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Heritage Technologies in Space Programs – Assessment Methodology and Statistical Analysis

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Abstract

An established approach to cost and risk reduction in system development programs is the use of heritage technologies. A heritage technology is defined as a proven technology, reused in a new use context, in an unaltered or adapted form. Heritage technologies are particularly relevant for space systems development programs, as their development costs are usually high and stakeholders risk-averse. Nevertheless, numerous space programs encountered problems linked to improper ‘management’ of heritage technologies when reused, i.e., improper use, implementation or adaptation. Improperly managed heritage technologies can lead to cost and schedule overruns, or even failure in the reuse application. Currently, the applicability of heritage technologies is mostly assessed ad-hoc. The existing assessment approaches are deemed to be insufficient for providing decision-makers and analysts with ample guidance on the applicability of heritage technologies.

This thesis presents a methodology for assessing heritage technologies in the early phases of development, taking the new use context of the technology, its necessary adaptations and modifications, as well as technological capabilities of the implementing organization into consideration. For illuminating the relationship between the use of heritage technologies and the performance of space programs empirically, a statistical analysis is performed.

The methodology focuses on the early phases, where most of the technology selection takes place. A 3-component framework is developed that serves as the theoretical basis for the statistical analysis and the methodology. The framework consists of a systems architecting framework, a technology framework, and a verification, validation, testing, and operation framework.

Based on the concepts developed in the framework, a statistical analysis is performed. Using multiple regression with control variables, a statistically significant relationship between heritage technology and specific development cost / development duration was confirmed. No statistically significant relationship between heritage use and development cost overrun / schedule overrun could be confirmed.

Based on the framework and results from the statistical analysis, a methodology for assessing heritage technologies in the early phases is developed. It allows for identifying potential compliance issues of the heritage technology with respect to changed requirements and constraints. Estimating the impact of modifications is performed via design structure matrices and a graph-edit-similarity algorithm. Furthermore, a heritage metric is presented that can be used for measuring heritage with respect to a new application. Finally, the methodology also allows for assessing technological and organizational capabilities.

The methodology is validated by three space system case studies: 1) a CubeSat component technology, 2) a high-pressure tank technology for the Ariane 5 launcher, and 3) the Saturn V and Space Launch System technology.

From the presented work it can be concluded that the methodology can be systematically applied to various types of space systems at different levels of decomposition. The heritage metric provides a rough estimate of the heritage of a technology for a new application and context. The statistical analysis confirmed that *in general* using heritage technologies significantly reduces specific development cost and development duration. As future work, the developed methodology could be extended to other domains such as automotive engineering, aeronautics, and medical engineering, where heritage also plays an important role.

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Zusammenfassung

Ein etablierter Ansatz Kosten und Risiken in der Systementwicklungsprogrammen zu senken ist der Einsatz von Heritage Technologien. Eine Heritage Technologie ist definiert als eine erprobte Technologie, welche in unveränderter oder veränderter Form, in einem neuen Kontext wiederverwendet wird. Heritage Technologien sind besonders relevant in Entwicklungsprogrammen für Raumfahrtsysteme, da deren Entwicklungskosten besonders hoch sind und deren Stakeholder besonders risikoscheu. Jedoch traten in zahlreichen Raumfahrtprogrammen Probleme im Zusammenhang mit unangemessener Handhabung von Heritage Technologien auf, einschließlich in deren Übertragung, Implementierung, und Verwendung. Eine unangemessene Handhabung kann zu Überschreitungen des Budgets und der Projektdauer, oder sogar zum Ausfall in der neuen Anwendung führen. Derzeit wird die Übertragbarkeit von Heritage Technologien größtenteils ad-hoc bewertet. Es wird festgestellt, dass die existierenden Bewertungsansätze unzureichend sind um Entscheidungsträger und Analysten bei der Bewertung von Heritage Technologien zu unterstützen.

Diese Arbeit präsentiert eine Methodologie für die Bewertung von Heritage Technologien in den frühen Phasen der Systementwicklung, unter Berücksichtigung des Kontexts der Technologie, deren notwendigen Anpassungen und Modifikationen, und technologischen Fähigkeiten der Organisation welche die Technologie entwickelt und hergestellt hat. Um den Zusammenhang zwischen der Verwendung von Heritage Technologien und der Performanz von Raumfahrtprogrammen zu beleuchten wird eine statistische Analyse durchgeführt.

Die Methodologie zielt auf die frühen Phasen der Systementwicklung ab, in denen ein Großteil der Technologieauswahl stattfindet. Ein aus drei Elementen bestehendes Rahmenwerk wird entwickelt, welches die theoretischen Grundlagen der Methodologie bereitstellt. Das Rahmenwerk besteht aus einem Systemarchitekturrahmenwerk, einem Technologierahmenwerk, und einem Verifikations-, Validierungs-, Test-, und Betriebsrahmenwerk.

Auf der Grundlage der Konzepte die in den Rahmenwerken entwickelt wurden, wird eine statistische Analyse durchgeführt. Unter Verwendung multipler Regression und der Einführung von Kontrollvariablen wurde ein statistisch signifikanter Zusammenhang zwischen der Verwendung von Heritage Technologien und den spezifischen Entwicklungskosten, sowie der Entwicklungsdauer festgestellt. Kein statistisch signifikanter Zusammenhang konnte zwischen der Verwendung von Heritage Technologien und der Überschreitung von Entwicklungskosten und Entwicklungsdauer festgestellt werden.

Aufbauend auf dem Rahmenwerk und den Resultaten der statistischen Analyse wird eine Methodologie zur Bewertung von Heritage Technologien in den frühen Phasen entwickelt. Diese ermöglicht potentielle Konformitätsprobleme der Heritage Technologie bezüglich veränderter Bedürfnisse und Anforderungen zu erkennen. Den Einfluss von Modifikationen auf die Heritage wird mit Hilfe von Design Struktur Matrizen und einem Graph-Edit-Similarity Algorithmus bewertet. Darüber hinaus wird eine Heritage Metrik eingeführt mit deren Hilfe die Heritage bezüglich einer neuen Anwendung gemessen werden kann. Die Methodologie erlaubt darüber hinaus das Vorhandensein von entsprechenden technologischen und organisatorischen Fähigkeiten abzuschätzen.

Die Methodologie wird durch drei Fallstudien verschiedener Raumfahrtsysteme und Komponenten validiert: 1) eine CubeSat Komponententechnologie 2) eine Hochdrucktanktechnologie für die Ariane 5 Trägerrakete, und 3) die Saturn V und die Space Launch System Technologie.

Aus den Ergebnissen der Arbeit wird geschlussfolgert, dass die Methodologie systematisch auf verschiedene Typen von Raumfahrtsystemen auf unterschiedlichen Ebenen der Systemhierarchie eingesetzt werden kann. Die Heritage Metrik ermöglicht eine grobe Abschätzung der Heritage einer Technologie in einer neuen Anwendung und einem neuen Kontext. Die statistische Analyse bestätigt, dass im Allgemeinen die Verwendung von Heritage Technologien zu wesentlichen Senkungen der spezifischen Entwicklungskosten und der Entwicklungsdauer führt. Zukünftige Arbeiten könnten darauf abzielen die entwickelte Methodologie auf andere Anwendungsbereiche wie der Automobil-, Luftfahrt-, und Medizintechnik zu übertragen, in denen Heritage Technologien ebenfalls eine wichtige Rolle spielen.

Contents

Abbreviations & Acronyms

ADCS	Attitude Determination and Control System
AIT	Assembly Integration and Testing
CDR	Critical Design Review
ConOps	Concept of Operations
DCSS	Delta Cryogenic Second Stage
DoD	Department of Defense
DoDAF	Department of Defense Architecture Framework
DSM	Design Structure Matrix
EDL	Entry, Descent, and Landing
ESA	European Space Agency
ESO	European Southern Observatory
ET	External Tank
EUS	Exploration Upper Stage
FPGA	Field-Programmable Gate Array
GEO	Geostationary Orbit
ICPS	Interim Cryogenic Propulsion Stage
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
INCOSE	International Council on Systems Engineering
ISO	International Organization for Standardization
LEO	Low Earth Orbit
LRO	Lunar Reconnaissance Orbiter
MBSE	Model-Based Systems Engineering
MEO	Medium Earth Orbit
MER	Mars Exploration Rover
MIT	Massachusetts Institute of Technology
MSL	Mars Science Laboratory
NASA	National Aeronautics and Space Administration
OCO	Orbiting Carbon Observatory
OECD	Organization for Economic Co-operation and Development
PC	Personal Computer
PDR	Preliminary Design Review
R&D	Research and Development
RTG	Ratioisotope Thermal Generator
SCAF	Spacecraft Architecting Framework
SLS	Space Launch System
SRAM	Static Random-Access Memory
SRBs	Space Shuttle Solid Rocket Boosters
SRL	System Readiness Level
SysML	Systems Modeling Language
TCP/IP	Transmission Control Protocol / Internet Protocol
TEA	Transversely Excited Atmospheric
TRIZ	Theory of inventive problem solving (Translation from Russian)
TRL	Technology Readiness Level
VVT	Verification, Validation, and Testing
VVTO	Verification, Validation, Testing, and Operations

1 Introduction

1.1 Motivation

The history of technology can be interpreted as a successive introduction of new technologies. At the same time, it can be interpreted as a successive inheritance of existing technologies for new applications (Basalla, 1988; Bijker et al., 1987; Constant, 1980). Almost all newly developed systems, to some degree, rely on inherited technologies. Such inherited technologies are called "heritage technologies" in the following. In systems engineering, the use of heritage technologies is an established approach to cost and risk reduction for complex technical systems. Heritage technologies can be defined as "hardware, software, and systems developed for previous projects that are adapted for use on other projects." (NASA, 2013a)

Heritage technologies are relevant for various engineering domains. In the automotive sector, proven parts, modules, and technologies used in one vehicle are often used in a newly developed vehicle. The process is called "carry-over" (Schoeller, 2007). Fig. 1-1 shows schematically how parts from a predecessor product generation are used in the subsequent generation. "Commonality" indicates that aspects of products are "common". "Temporal commonality" is commonality across generations of products, whereas "simultaneous commonality" is commonality across products at a specific point in time. Schoeller (2007) also introduces the term "carry-back part", where a part developed for a subsequent product generation is integrated into a predecessor product generation.

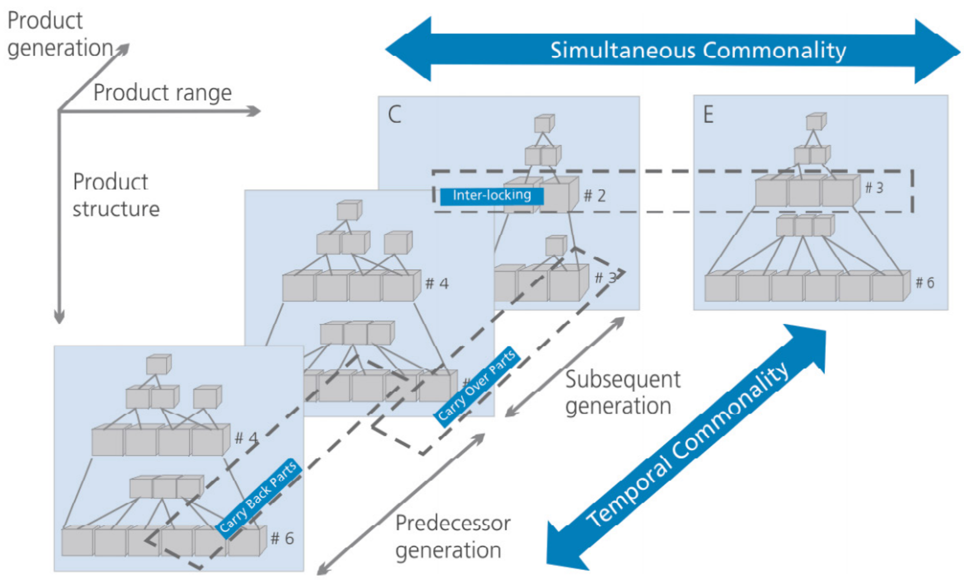


Fig. 1-1: The use of carry over pars in automotive engineering taken from Schoeller (2007)

In software engineering, proven software modules are used for developing new software. This branch of software engineering is called "component-based software engineering" (Chaudron and Crnkovic, 2008; Hasselbring, 2002; Heineman and Councill, 2006; Lan and Young, 1996). Fig. 1-2 shows an exemplary component-based software engineering approach. The domain-model describes the problem domain, for which the software is developed. The reference architecture provides a solution to the problem. The reference architecture is realized by reusable components.

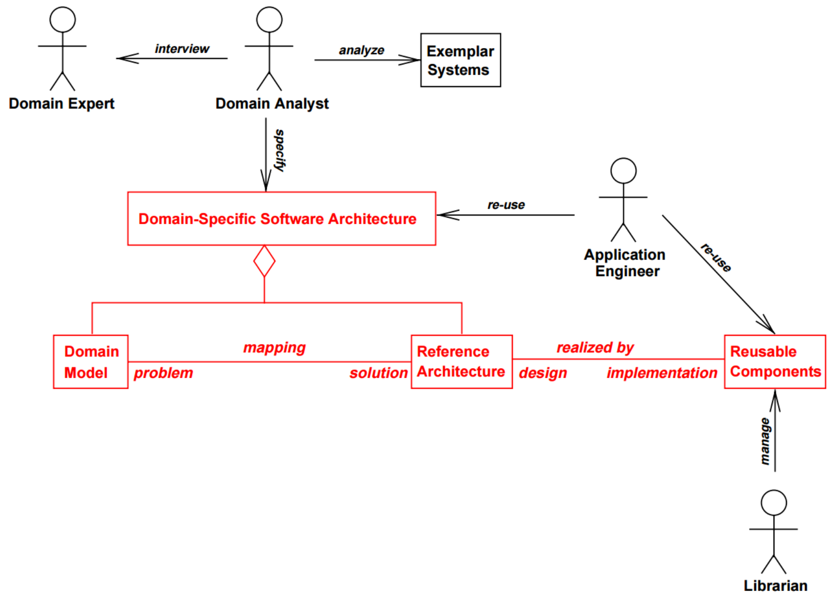


Fig. 1-2: Roles and artifacts in a component-based software engineering approach (Hasselbring, 2002)

Despite their use in various engineering domains, heritage technologies are particularly important in aerospace engineering and defense. In these domains, systems are produced in low quantities, they have long lifecycles, along with high quality and reliability standards. In fact, the term "heritage technology" is today only used in space systems engineering and appears in major guidelines and standards (ESA, 2009; Kapurch, 2010). Nevertheless, terms with similar meaning are used in other domains. The term "carry-over part" is an equivalent to "heritage technology" in automotive engineering and aeronautical engineering (Boas, 2008).

This thesis focuses on the use of heritage technologies in the space domain, where heritage technologies play a traditionally important role. To showcase the benefits and risks of using heritage technologies, two space programs for Mars exploration are presented. Both programs made extensive use of heritage technologies. However, the way heritage technologies were adapted lead to very different consequences.

In November 2013, NASA's Mars Volatile and EvolutioN Mission (MAVEN) was launched on schedule and within budget (GAO, 2014a; NASA, 2013a).[1] An artist's impression of the MAVEN spacecraft is shown in Fig. 1-3. The spacecraft has successfully reached Mars and is sending back data of the Martian atmosphere. The success of the program was attributed to an experienced leadership, the use of heritage technologies, and stable funding (NASA, 2013a). MAVEN managers "emphasized the use of heritage, flight-qualified hardware and software flown on eight previous interplanetary missions, thereby avoiding the cost and schedule challenges often associated with developing new technologies." (NASA, 2013, pp.ii-iii) Furthermore, "Project management's adherence to original specifications meant that in most cases the heritage technologies required minimal modification to meet the form, fit, and function requirements of the MAVEN mission." (NASA, 2013, p.iii)

[1] GAO (2014a, p.1) mentions that the mission was accomplished with $35 million less than expected.

Fig. 1-3: Artist's impression of the MAVEN spacecraft (NASA, n.d.)

During the 80s, the Mars Observer spacecraft was developed for observing the Martian surface, atmosphere, climate, and magnetic field. An artist's impression of the Mars Observer spacecraft is shown in Fig. 1-4. The spacecraft was successfully launched on the 25th of September 1992. On August 21 1993, communications with the Mars Observer spacecraft were lost. The investigation board concluded that the most probable source of the failure was a leaking check valve in the propulsion system (Investigation Board, 1993). The propulsion system was a heritage technology, previously used on a satellite in Low-Earth Orbit (LEO). For a LEO mission, leak-proof operations of the valve over extended periods were not required. However, for the Mars Observer mission, the valve had to operate flawlessly after 11 months, in a cold environment (Investigation Board, 1993, p.D-35). The failure investigation board concluded that "Too much reliance was placed on the heritage of spacecraft hardware, software, and procedures, especially since the Mars Observer mission was fundamentally different from the missions of the satellites from which the heritage was derived." (Investigation Board, 1993, p.B-5) The investigation board goes on and argues that "In fact, many of the spacecraft systems had been so extensively modified for Mars Observer that their heritage had been lost; others, whose heritage remained intact, should have been requalified to verify that they would function properly on an interplanetary mission of three years duration (an environment for which they were not designed)." (Investigation Board, 1993, pp.D-2, D-3)

Fig. 1-4: Artist's impression of the Mars Observer spacecraft (Wikipedia, 2016a)

In the case of MAVEN, the program's success was attributed to a proper use of heritage technologies, such as avoiding modifications to existing specifications. In the case of Mars Observer, the program's failure was attributed to an inappropriate application of heritage technologies: Components were significantly modified and verification activities were insufficient for the application at hand.

The challenges of properly applying heritage technologies are mentioned in major guidelines within the space sector such as the NASA Systems Engineering Handbook (Kapurch, 2010) and failure investigation reports. The NASA Systems Engineering Handbook remarks that "a frequently overlooked area is that associated with the modification of "heritage" systems incorporated into different architectures and operating in different environments from the ones for which they were designed." (Kapurch, 2010, p.62) Failure investigation reports repeatedly mention the need to rigorously test heritage technologies, such as the failure investigation report of the crash-landed Genesis mission (NASA, 2005). Its failure was attributed to insufficient verification activities of a heritage component. Similar remarks are made by a failure assessment case study for the Lewis mission, where a failure of the attitude control system lead to the loss of the spacecraft (NASA, 2007). One of the underlying issues was deemed to be the "inadequate test and verification of heritage hardware/software". However, are these issues isolated cases or recurring?

In fact, issues and benefits related to the management of heritage technologies seem to be recurring across NASA space projects. The yearly U.S. Government Accountability Office (GAO) report assessing large NASA space projects repeatedly attributed both, staying within budget / schedule *and* cost / schedule overruns to the use of heritage technologies (GAO, 2015). In the GAO reports, issues associated with heritage technologies are termed "complexity of heritage technology". For identifying this issue in a program, GAO members asked program managers "what heritage technologies were being used, what effort was needed to modify the form, fit, and function of the technology for use in the new system, whether the project encountered any problems in modifying the technology, and whether the project considered the heritage technology as a risk to the project." (GAO, 2010, p.73) Based on the collected data, Fig. 1-5 shows that the "complexity of heritage technology" was an issue for over 60% of 20 large NASA programs assessed in 2010 (GAO, 2010, p.15). It is thereby the most prevalent issue.[2]

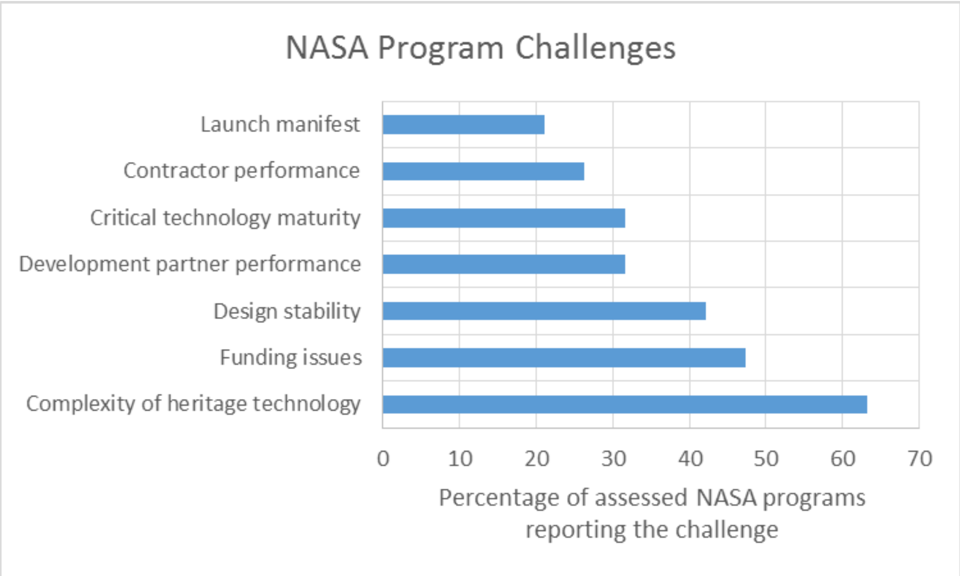


Fig. 1-5: Challenges for 20 large NASA programs (GAO, 2010, p.15)

To conclude, the benefits and risks of using heritage technologies depend on its appropriate adaptation to a new application. Before these benefits and risks are assessed in more detail, the term "heritage" and "heritage technology" need to be defined more precisely.

[2] These challenges are not unique to the space domain. The well-known software engineering failure case, the Therac-25, can be attributed to an inappropriate adaption of software to a new application (Leveson and Turner, 1993). The Therac-25 was a medical device for radiation therapy. Malfunctions of the device lead to six accidents of radiation overdose. According to the statement of a manager, the device was successfully proven in operation over a duration of 2700 hours (Leveson & Turner, 1993, p.20). According to Leveson and Turner (1993), one of the underlying problems leading to the accidents was the transfer of the software from the predecessors Therac-6 and Therac-20 to the Therac-25. The Therac-6 and Therac-20 both had a physical shut-down mechanism in case of a malfunction. This shut-down mechanism was replaced by a software-based mechanism in the Therac-25. The original physical safeguard no longer existed and already existing errors in the software now lead to a failure of the overall system. Hence, at least partly, the change in context was not sufficiently taken into account when the software was adapted to the new application.

1.2 Defining Heritage

Several definitions for heritage are given in the literature. According to the Merriam-Webster-Dictionary, "heritage" refers to "*something transmitted by or acquired from a predecessor*" (Merriam-Webster Inc., 2004). This is a general definition and is also applicable to cultural heritage and natural heritage. A definition specific to heritage technology is given by GAO (2009). It defines heritage technology as

*"**proven components** that are being modified to **meet new requirements**" (highlights added).*

Barley et al. (2010) present a more detailed definition of heritage (highlights added):

*"Heritage technology includes hardware or software subsystems or components with previous flight history that are used as part of a **new mission system**. The heritage of the component includes not only the **previous flight history**, but the **previous function**(s) for which the component was used, the **environment** in which it was used, and physical, thermal, and data **interfaces** with other elements of the mission system. Heritage also includes the **availability of documentation**, **support equipment, and personnel experienced in its design, implementation, and operational use.**"*

A similarly elaborate definition can be found in the NASA Systems Engineering Handbook (highlights added) (Kapurch, 2010, p.76):

*""Heritage" refers to the original manufacturer's level of **quality** and **reliability** that is built into parts and which has been proven by (1) time in service, (2) number of units in service, (3) mean time between failure performance, and (4) number of use cycles. High-heritage products are from the **original supplier**, who has **maintained the great majority of the original service, design, performance, and manufacturing characteristics**. Low heritage products are those that (1) were not built by the original manufacturer; (2) do not have a significant history of test and usage; or (3) have had significant aspects of the original service, design, performance, or manufacturing characteristics altered. An important factor in assessing the heritage of a COTS product is to ensure that the use / application of the product is relevant to the **application for which it is now intended**. A product that has high heritage in a ground-based application could have a low heritage when placed in a space environment."*

What is common to these definitions? The following aspects are mentioned in at least two of the three definitions:

- *New application:* Heritage technologies need to meet "new requirements", are used in a "new mission system", or "new application".
- *Usage and test history:* The component has a history of usage and testing in which its function, performance, and integration into a system has been proven.
- *Similarity between former application and new application:* This includes the natural environment and the system into which the component is integrated. Furthermore, the functions that were performed in the application are relevant.
- *Original manufacturer:* The original manufacturer's capability to develop, manufacture, and support the component plays an important role. This capability is based on the "availability of documentation, support equipment, and personnel experienced in its design, implementation, and operational use." (Barley et al., 2010)

Furthermore, there is a distinction between "heritage" and "heritage technology". Table 1-1 shows what is considered heritage and heritage technology according to the literature.

Table 1-1: Heritage and heritage technology definitions

	What *is* "heritage"?	What *is* "heritage technology"?	Applied to
Merriam-Webster	Something	No explicit definition	-
GAO	Something proven	Component	New requirements
Barley	Previous flight history, function, interfaces, documentation, support equipment, experienced personnel	hardware or software subsystems or components	New mission system
NASA	Level of quality and reliability that is built into parts	Parts	New application

Although several definitions exist, they lack internal consistency and sufficient theoretical underpinnings. Table 1-2 gives an overview of these issues and how they are addressed by a heritage conceptual model presented in Fig. 1-7.

Table 1-2: Aspects missing in existing heritage and heritage technology definitions and how they are addressed by a novel heritage conceptual model in Fig. 1-7

Missing aspect	Addressed in this thesis by
Technology definition	Technology conceptual model (Section 1.3)
Instance – design distinction	Distinction between heritage system and proven system design
Unit of heritage technology	Can be applied to different levels in system hierarchy
Organizational capabilities as part of a heritage technology	Organizational capabilities are considered part of a heritage technology
Evolution of heritage	Organizational capabilities

First, the existing heritage definitions lack a proper definition of "technology". A "technology" is referred to as a component, part, hardware, or software subsystem. However, I argue that the notion of "technology" goes beyond the concrete component. Such a limited interpretation of "technology" is missing the distinction between an instance of a technology and its type, the main entity under analysis (unit of analysis), and its relationships to organizational capabilities. Each of these points is explained in the following.

There is a distinction between an instance and the type of a component. An instance is a concrete manifestation of a type.[3] An "instance" is the manufactured component that can be operated. In the case of software I can talk about an implemented piece of software that can be executed. In the following, I claim that the "type" of a component is its design. An instance of a Ford-T car can be driven. What is common to all instances of the Ford-T is that they are based on the same design. In principle, an infinite number of instances can be built from a design (Eden and Kazman, 2003). This distinction is often obscured in the existing literature on heritage technologies. For example, heritage technologies according to Barley et al. (2010) are "components with previous flight history that are used as part of a new mission system". However, it is not the component that is reused. It is rather the design of the component that has previous flight history. The component's design has accumulated flight history *via* its instances. Flight history is accumulated in the sense that the flight history has *proven* the component design to a certain degree. It is, hence, the design that is an important carrier of heritage in the form of flight history. However, it is not the only carrier, as is shown later.

Moreover, the unit of analysis for heritage technologies is too narrowly defined in existing definitions. They limit the unit of analysis to the subsystem or component level. The main reason is that heritage assessments usually take place

[3] For a philosophical introduction into the so-called type-token distinction, the reader is referred to Wetzel (2014).

at the subsystem or component level. However, there is no reason why heritage should not pertain to the system level. A proper heritage definition should be generic and be applicable to all hierarchical levels of a system.

Furthermore, the unit of analysis for a heritage technology can be extended to organizational capabilities. When I talk about "technology" I may not only refer to an implemented system and its design but also to the capabilities that are necessary for its development, manufacturing, and operation. Existing heritage technology definitions refer to these capabilities but it is not clear if they are considered part of a technology or not. The shortcoming of allocating heritage to the design alone can be illustrated by the following example: Imagine a situation in which a design, which contains all the necessary construction drawings is handed out to two manufacturers. One manufacturer has considerable experience with manufacturing this type of system and the other has not. It is clear that the first manufacturer is more likely to produce a product with a higher quality. Hence, heritage is also embodied by the organization(s) that develop(s), manufactures, integrates, operates, or conducts other operations with the technology. What is inherited here is the knowledge, experience, and all the entities in which these are embodied, such as personnel, documentation, tools, etc.

Another aspect which is not considered is the evolution of heritage. The built-up of heritage does not only depend on "*(1) time in service, (2) number of units in service, (3) mean time between failure performance, and (4) number of use cycles*", as mentioned in Kapurch (2010, p.76). These factors only address operational history. The amount of verification, validation, and testing activities is also important. For example, the extent to which off-nominal conditions were covered by tests and simulations increases heritage, although these conditions might never occur during operation. Usually, these activities go along with more mature organizational capabilities with respect to a specific technology, as more experience is gained by performing these activities.

Up to this point I have rather addressed the shortcomings of existing heritage definitions. In the following, I will propose definitions for heritage and heritage technology. As a starting point, it needs to be decided what "heritage" *is*. The definitions in Table 1-1 diverge quite significantly in what heritage *is*. In order to stay close to ordinary language, I adapt the definition from Merriam-Webster Inc. (2004) for a general notion of heritage.

Definition: Heritage

Heritage refers to something transmitted by or acquired from a predecessor that is considered increasing the successor's quality.

The main difference between the dictionary definition and the definition above is that the aspect of "quality" has been added. I will explain the reasoning behind this decision in the following. In general, it can be said that something has "high heritage" if a lot of aspects of a thing have been inherited and "low heritage" if only a few things have been inherited. For example, a house has high heritage, if it has been preserved without a lot of modifications. Its original substance has been preserved, its walls, roof, doors and windows as well. It has low heritage if many original elements have been modified, such as the roof, walls, windows etc. However, I assert that something is considered heritage if it pertains to *positive* attributes of a technology. A component that has failed several times without operating successfully would not be considered a heritage technology. Hence, "heritage" refers to things inherited that (promise) to be valuable in a new context. This distinguishes "heritage" from "legacy" as used for legacy systems. The notion of "legacy system" is mostly used in the context of software systems but "legacy" rather pertains to the *negative* aspects of the system which, e.g. decrease its maintainability (Bennett, 1995; Bisbal et al., 1999).[4]

For a technical system, the crucial question is what is transmitted or inherited. At first sight, the following aspects are important to be inherited:

- <u>*The design of the system:*</u> The design on which the system is based is important, as it specifies its characteristics.
- <u>*All things that make a system "proven":*</u> The evidence that provides someone with the confidence that the system works as intended.

[4] Another difference between a heritage technology and a legacy system is that legacy systems in computer science refer to instances of software or information systems and not the design.

- *All things necessary for each of the life cycle phases of a system:* All the knowledge about processes, methods, etc. and their embodiment in documentation, tools, machinery, organizations etc. that enable the development, implementation, assembly, integration, and testing, verification, validation, testing, deployment, operation, maintenance, and disposal. The triplet "verification, validation, testing" is often abbreviated as "VVT". A generic system life cycle model is depicted in Fig. 1-6. System development results in a system design. The system design is then used for implementing the system. "Implementation" can be the production of a physical system or the implementation of a software system. VVT activities result in a tested system. Of course, VVT activities often take place all along system development and implementation. However, it is assumed that VVT activities reach a peak after the first system is implemented. The system is then deployed, is operated, and maintained. Experiences from this phase inform the system development and implementation phase. When the system has reached its end-of-life, it is disposed.

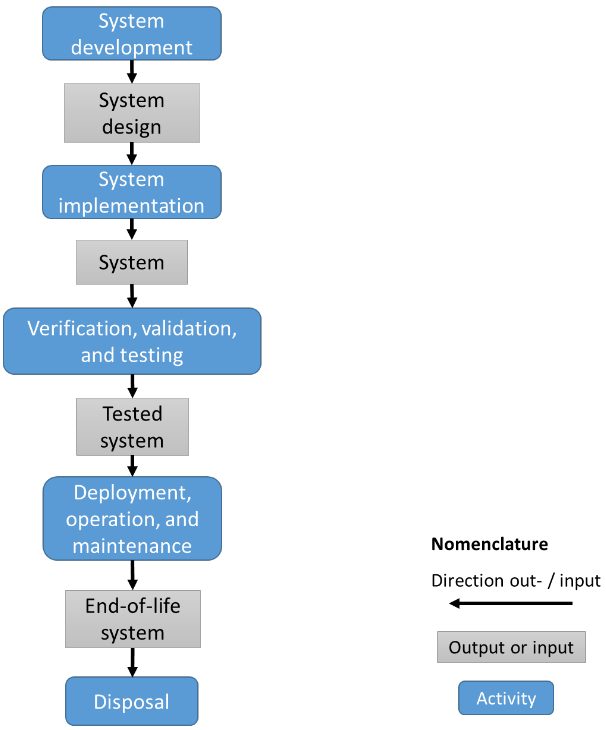


Fig. 1-6: Generic system life cycle model

Definition: proven

Something is called "proven", if it has a *successful* history of verification, validation, testing, and operation.

The notion "successful" in the definition for "proven" is important, as there are cases where systems have been flown but failed. One example is the Soviet N-1 launcher that was launched four times. All four launches resulted in catastrophic failure. Such a system would not be considered "proven". "Successful" means that the system was able to satisfy needs, requirements, and exhibited a certain level of reliability. Note that "successful" does not exclude that the system initially failed. The Ariane 5 launcher is considered a proven launcher today, although it initially had to deal with three failed or partially failed launches. Between its last failed launch in 2002 and 2015, it has now over 60 consecutive successful launches under its belt.

To summarize, the following inherited elements are considered to improve the quality of a technology:

- *System:* Has a higher quality and reliability due to a proven design on which it is based, and the knowledge and experience in designing, manufacturing, integrating it etc.
- *Design:* The knowledge and experience with verification, validation, and testing results in design improvements.
- *Organizational capabilities:* Organizations carry the knowledge and experience they have gained with a technology. This knowledge and experience can result in better processes that enable the development and manufacturing of instances with a higher quality and reliability.

At this point I introduce a conceptual model for heritage. Fig. 1-7 shows the heritage conceptual model which incorporates the missing aspects of current heritage definitions. Note that this model does not yet include the notion of "technology". The definition for "heritage technology" will be introduced in Section 1.3. "Heritage" in this model consists of a proven system design, organizational capabilities, and verification, validation, testing, and operation history.

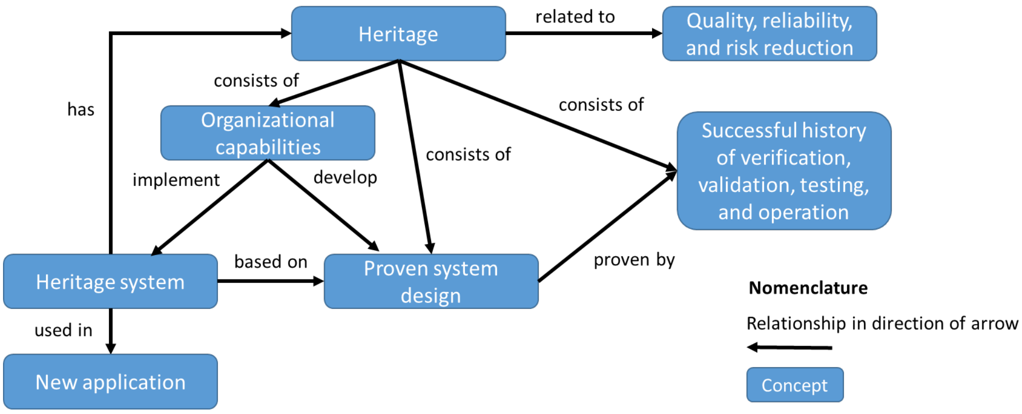


Fig. 1-7: Heritage conceptual model

A heritage system is used in a new application which differs from its past application(s). A heritage system has heritage, which consists of organizational capabilities, verification, validation, testing plus operational history, and a proven system design. Organizational capabilities are often left out in practice, as they are considered difficult to assess. Organizational capabilities here are associated with one or more lifecycle phase of a system. For example, a company may have the capability to develop, manufacture, and deploy a satellite system. Another organization may have the capability to operate the satellite. Capabilities that are related to the lifecycle phase of a technology are in the following called *technological capabilities*.

Definition: Technological capability

A technological capability is a capability that is related to the lifecycle phase of a technology.

In Fig. 1-7, the capabilities are related to developing a system design and implementing it. A proven system design is a system design that has been proven by VVT and possibly operations. A satellite system design is usually proven by a qualification program. Last but not least, heritage, if properly applied, is related to increased quality, reliability, cost and risk reduction. Empirical evidence from the software domain confirms that heritage components have a lower defect density and reduce development effort (Mohagheghi and Conradi, 2004). Cost, schedule, and risk reduction can also be expected from a proper use of heritage systems.

The heritage conceptual model is compared with the heritage product categories defined by the European Space Agency (ESA). The four product categories A, B, C, D shown in Table 1-5 can be used for distinguishing systems with respect to their heritage (ESA, 2009). These categories are used for proven system designs where instances have already been flown. Two aspects play a crucial role:

- The degree of Verification, Validation and Testing (VVT)
- The degree to which the design, supplier, manufacturing processes have changed

It can be seen that the conceptual model covers the areas of the ESA heritage product categories.

It is important to point out that the system design does not completely constrain the manufactured system. This is the reason why existing heritage definitions stress that the heritage system is manufactured by the original supplier. A complete set of design drawings still has multiple degrees of freedom, resulting in different manufactured systems. This is the reason why products based on the same design but manufactured at different companies can have large differences in quality. A famous example are TV sets, manufactured in Japan and the US with large differences in customer satisfaction (Taguchi, 1986). The different degrees of customer satisfaction had its origin in how the color density was distributed for TV sets produced by Sony-Japan and Sony-USA. In all cases the parameter value was within the required tolerance range. In general, inappropriate or changing manufacturing and quality assurance processes can lead to a system with low quality and low reliability, even with the same design. For example, electronic components often have different characteristics from one production lot to another. The design of the components is identical but variations in the used materials can lead to large variations in component quality. Thus, a heritage system design can only play out its advantages if appropriate manufacturing and quality assurance processes are in place.

Furthermore, the quantity of systems produced and the surrounding culture plays a role. There is a difference between mass produced systems and small lot / one-off systems. Mass produced systems are extensively specified, as designers and manufacturers are often different. Thus, it has to be guaranteed that the manufactured system is according to specifications. Within the Soviet Union, production drawings for artillery and rifles had to be very accurate and extensive, in order to be understandable, even for manufacturing personnel with low qualification (Interview I17). The reason was that most designing activities took place in and around Moscow. However, manufacturing was often undertaken in remote areas of the Soviet Union, far away from Moscow. Thus, engineering students in these domains were extensively educated in drawing precise drawings and adhering to the drawing standards. For small lot systems, designs are often not extensively specified and often rely on handicraft. Rolls Royce cars still rely extensively on handicraft. Spacecraft and rocket engines also highly depend on the qualification of the manufacturing personnel. One example where the retirement of a member of the manufacturing personnel of the Aestus upper stage rocket engine lead to an unexpected pressure drop in the combustion chamber. Only after extensive investigations, it was discovered that the way the worker chamfered a part of the injector was responsible for the performance of the previous engines. Thus, the person was hired again out of retirement (Interview I1). Another example is the failed attempt to replicate the RD-180 manufacturing capability in the US, as the following excerpt illustrates:

"However, Amross had great difficulty getting the detailed specifications for materials and machining processes, because although the Russian documentation was truly meticulous (each part had a 'passport' that accompanied it through every step in manufacture), it was very different from U.S. practice. Moreover, much of the detailed materials information and 'tricks' of the machining processes were in the heads of the skilled Russian workmen, to which Amross did not have access." (Grey, 2013)

This is a clear indication that tacit knowledge (know-how) could not be transferred from the Russian workmen to their US counterparts. But even for mass-production tacit knowledge plays a vital role. (MacKenzie and Spinardi, 1995)

A common strategy for heritage systems is to sacrifice VVT and instead enhance the existing technological capabilities for producing an improved modified system. One example is the five-segment booster for the Ares V and Space Launch System. The original four-segment boosters of the Space Shuttle had insufficient performance for these new applications. Thus, modifications were necessary, which required an extensive qualification program. However, using existing technological capabilities was still an attractive strategy.[5] The required effort depends on the extent of the modifications and the extent of the VVT program.

Heritage is embodied in organizations. Only organizations with technological capabilities, together with verification, validation cycles can lead to improvements in the design of a heritage system and thus increase its heritage. The distinction between the heritage system and the heritage system design can be explained by the common distinction between qualification testing and acceptance testing. Whereas qualification testing tests the design, acceptance testing is performed on each produced system. In principle, a design that has passed qualification testing should lead to a functioning system. Thus, if the design is passed to a manufacturer with the capability to manufacture the system according to the design specifications, the resulting system should work. In reality the line between "system design" and "system" is blurred. First, there is a fundamental difficulty to test a design. The design can only be tested if a

[5] Political reasons for choosing a specific supplier are also acknowledged. The interested reader is referred to Heppenheimer's reconstruction of the original Space Shuttle solid rocket booster decision (Heppenheimer, 2002)

system, e.g. a prototype, is manufactured and tested. Thus, it depends on an implementation of the design. A system design improves by verification and validation but also from its real-world operation. It is a well-known phenomenon that all new systems exhibit teething problems. This is reflected by the so-called "infant mortality" in the bathtub curve of systems reliability. Fig. 1-8 illustrates how the three aspects, design, implementation, and verification, validation, testing, and operation (VVTO) work together in increasing the degree to which a system is "proven".

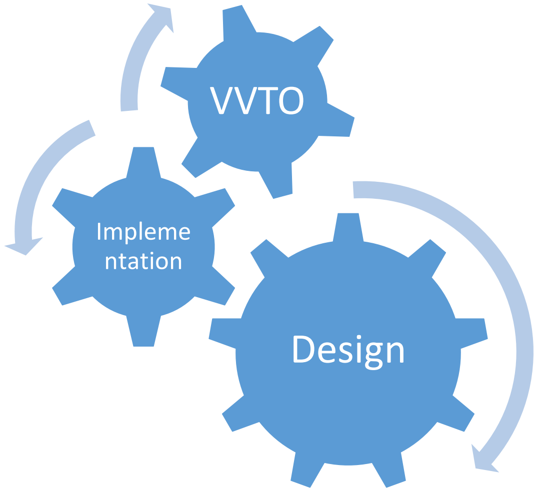


Fig. 1-8: Design, implementation, and verification, validation, and testing result in a proven design when properly combined.

Moreover, heritage comes at different degrees. A higher degree of heritage is associated with higher quality. A communication satellite where satellites with similar designs have been successfully flown over a dozen times in the same orbit is considered a system with a high degree of heritage. In such a case, it is assumed that the design and technological capabilities have not changed significantly. By contrast, if the same satellite would be flown in an orbit with considerably different environmental conditions, it would have a low degree of heritage with respect to this environment.

If a system design is proven also depends on its use context. Within the use context are stakeholders, regulations, standards etc. but also other systems which interact with the system under consideration. For example, a car interacts with other cars in the traffic. Use contexts usually change over time. For example, standards and stakeholder acceptance evolve. NASA's standards for human spaceflight are much stricter today than they were in the 60s. Partly, this is due to gained experience with the design of human spaceflight missions, which is then codified in the form of standards. Another example for standards incorporating past experience is the series of accidents related to the Comet aircraft, the first operational passenger jetliner. One of the reasons for the accidents were square-shaped windows, which created dangerous stress-peaks at the corners, leading to a structural failure of the window panels. Since then, passenger aircraft windows are oval-shaped (Wanhill, 2003). This is also the reason why already proven systems with long lifecycles are frequently recertified and reengineered to meet new standards. Apart from accidents, another source of contextual change is the acceptance of technologies. For example, nuclear thermal propulsion has been thoroughly tested during the 60s but has been abandoned since then (Dewar, 2004). Mothballing the German nuclear power plants is also mainly due to the declined public acceptance of nuclear energy. Thus, although a system has been operated and gained heritage in one context does not necessarily mean that it can be operated in another.

To summarize, "heritage" in the context of space systems consists of the system's design, successful verification, validation, testing, and operational history, and technological capabilities. The degree of heritage can change, depending on the context in which it the system is used. In the next step, this concept of heritage will be extended to heritage technologies.

1.3 Defining Heritage Technology

A still open question is how to define "heritage technology". This subject is covered briefly in this section and more elaborately discussed in Section 2.1.4. At first sight, a technology can be at least a system or part of a system. A system can be understood as a number of interacting components. On the other hand, a technology is *not only* the actual system such as a satellite or rocket launcher but includes the underlying technological capabilities that enable its development, production, modification, operation etc. Hence, developing a technology also means the development of the capabilities that allow for producing, modifying, and further evolving the technology. I even argue that for a technology to exist, concrete instances of the system are not necessary. For example, rocket launchers are manufactured and launched. A situation can be imagined in which a concrete launcher is not manufactured and no instance of a rocket launcher exists at that moment. Such a technology would still be deemed to be existing, as it *could* be manufactured.

A "technology" in the following is therefore primarily understood as a set of technological capabilities pertaining to a system. In this thesis, I define capabilities broader than for a specific system (Hein et al., 2012, p.125). For example, a company that is able to develop tanks for spacecraft can usually develop tanks of different sizes and using different materials. I use the notion of "design" of an artifact to specify the heritage technology more precisely. A "design" is understood as a set of attributes of an artifact such as its geometric dimensions, materials, parts, etc. An artifact is an object "that has been intentionally made or produced for a certain purpose." (Hilpinen, 2011) Based on the design the artifact can be manufactured.

Definition: Design

A set of attributes of an artifact such as its geometric dimensions, materials, parts, etc. that can be used for manufacturing an artifact.

The design of an artifact is selected as another necessary element of a technology. When I say the Clyde Space EPS board is a heritage technology, I mean that the company Clyde Space is able to manufacture instances of the EPS board and the design of the board has been proven on various space missions. I also assume that Clyde Space is able to produce EPS boards with different designs. Hence, a heritage technology is a combination of a set of technological capabilities and the system's design. This interpretation of technology can easily be extended to materials, software etc. by replacing "system" by "artifact". "Technology" can now be defined in the context of heritage technologies.

Definition: Technology

A technology is a set of technological capabilities, an artefact's design, and optionally artifacts based on the design.

Based on this definition of "technology", the definition of "heritage technology" is introduced.

Definition: Heritage technology

A heritage technology is a technology that has inherited a successful verification, validation, testing, and operations history, technological capabilities, its design, and optionally artifacts based on the design.

This interpretation of technology is illustrated in Fig. 1-9. In the following, a part of a system is called a "component". A component can again be a system in case it consists of further interacting components. A technology is called a "heritage technology" if the technology or elements of the technology are inherited. Inherited elements may include the technology's design, technological capabilities, or the technology's history of verification, validation, testing, and operation. Especially the last aspect of verification, validation, testing, and operation increases the confidence that the technology can be used in a similar context and functions as intended. To define "technology" at this level allows for assessing all heritage technology aspects in the literature as a bundle. Each of these aspects is elaborated in more depth in Chapter 2 and 3.

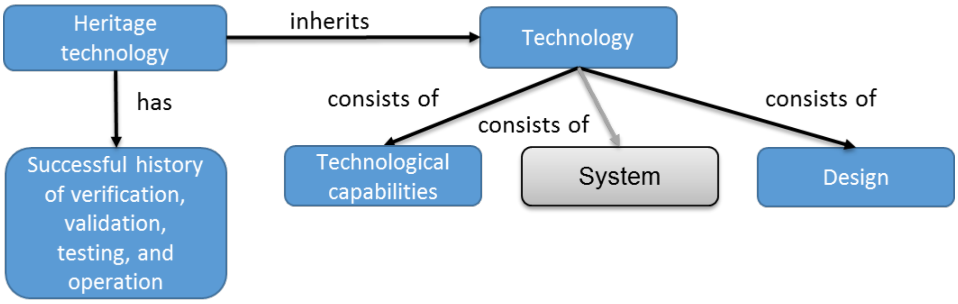


Fig. 1-9: Concept map of "technology" and "heritage technology"

"Heritage" as introduced in Fig. 1-7 and "heritage technology" in general express which *successful* elements of a technology are inherited. Whereas Fig. 1-7 illustrates what "heritage" is, Fig. 1-9 illustrates what elements are specifically inherited for a heritage technology. A system is called "heritage system" if it is part of a heritage technology. The literature on technologies is introduced in Section 2.1.4 and a more detailed conceptual model of technologies is developed in Section 3.2.

"Heritage technology reuse" is distinguished from other forms of reuse. "Reuse" indicates the use of something existing in a new context, for which it was not originally intended for (Hein and Brandstätter, 2010). First of all, heritage technology reuse is a form of technology reuse. However, it is a specific form of technology reuse, namely, the reuse of a proven technology. "Proven" means here that by a successful history of verification, validation, testing, and operation, the technology has improved its quality. Although a large number of definitions exist for "quality", it can be understood as how well a product satisfies the needs of stakeholders or a set of requirements. Quality is therefore strongly related to engineering activities that are used to check if requirements and needs are satisfied. These activities are usually associated with verification, validation, and testing. Hence, a heritage technology is usually a technology that has a history of successful verification, validation, testing, and operation. It has therefore been confirmed that the technology satisfies needs and requirements. Note that most publications dealing with "reuse" do not deal with the aspect of quality and how it might be altered by the changed context, as elaborated in Section 2.2.1.

Furthermore, "technology reuse" and "design reuse" can be distinguished. "Design reuse" is concerned with reusing a certain system or product architecture, configuration, and design parameters. It is a widespread approach in product development. "Technology reuse" is additionally concerned with the underlying technological capabilities behind the design. It asks questions such as: "If this component's design is modified, which dates back to the 1960s, are the people in the company still understanding the design to make the modifications?"

The different forms of reuse are depicted in Fig. 1-10. The three rectangles encompass elements of a reuse category. For design reuse, the design is the primary object under consideration. Technology reuse encompasses all aspects of a technology such as technological capabilities and optionally the system. Heritage technology reuse furthermore encompasses the aspect of the successful history of verification, validation, testing, and operation.

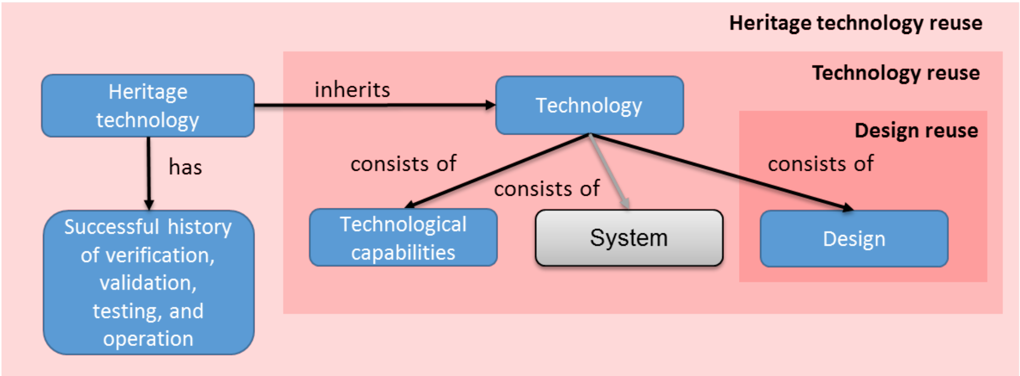


Fig. 1-10: Various reuse categories

How this terminology can be used for describing different forms of heritage is illustrated in the following. Recent examples for heritage technology use within the space domain are NASA's Space Launch System (SLS), and the Ares V and Ares I vehicles for the Constellation program, as shown in Fig. 1-11. Note that the indicated heritage technologies pertain to the initial concepts of the Ares I and V. The selection of heritage technologies was subject to significant changes during the program.

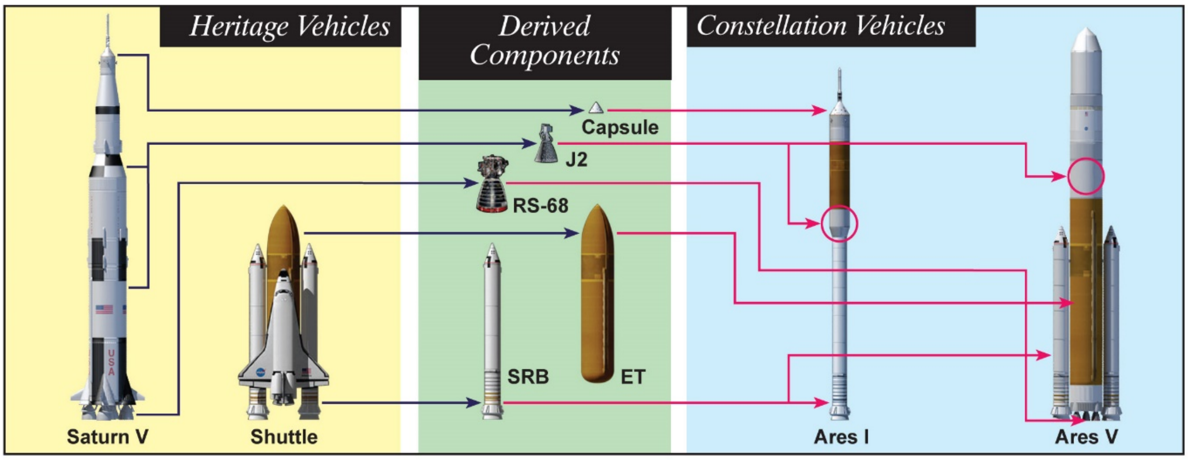


Fig. 1-11: Saturn V and Space Shuttle heritage technologies for Ares I and Ares V vehicles. Image taken from Campbell, (2011)

All these vehicle designs use component designs from the Space Shuttle[6] program, such as modified solid rocket boosters (SRB) and the external tank. The designs were more or less modified. The external tank (ET) has also undergone significant structural modifications, as the load profiles for the Shuttle and the Ares V are considerably different. Furthermore, its diameter was increased from 8.4m to 10m. It is expected that the suppliers of these technologies have retained the capability to modify the design and manufacture the systems.

The use of the Shuttle solid rocket booster for the Ares I vehicle required significant modifications of the original design. Instead of the four segments the original booster consisted of, five segments were now needed. Materials such as the Asbestos liner have been replaced due to changed safety regulations. These changes required considerable redesign and testing of the booster.

These examples show that the system designs are changed by existing technological capabilities along with verification, validation, and testing activities.

To summarize, heritage technologies extend the scope of design reuse by considering the following aspects in addition:

- *Quality:* How well the technology satisfies requirements and needs, proven by a successful history of verification, validation, testing, and operation.
- *Technological capabilities:* The underlying competencies, required for manufacturing, modifying, and evolving a technology.

After having introduced "heritage" and "heritage technology" the benefits and issues of their application are elaborated.

[6] Note that the actually correct terminology for the whole launch system is "Space Transportation System". Only the orbiter is called "Space Shuttle".

1.4 Heritage Technology: Pros and Cons

In the following, the benefits and issues of using heritage technologies are elaborated. The following heritage technology benefits can be found in the literature:

- *Potentially large savings in development cost and schedule:* reuse of existing design, reduction of verification, validation, and testing efforts (Boas, 2008; Fallon, 1997; GAO, 2015; Hofstetter, 2009). These efforts are not necessarily reduced by not performing tests but by passing them with a higher probability (GAO, 2009; NASA, 2013a).
- *Reduction of programmatic risks:* Properly used heritage technologies are expected to lead to a lower risk of cost and schedule overruns during systems development. This expectation is reflected by lower cost and mass margins for heritage technologies (Brown, 1998; Larson and Wertz, 1999).[7]
- *Higher confidence in the quality and reliability of a system:* It is expected that if heritage technologies are properly applied, they exhibit a better quality and higher reliability than newly developed technologies (Kapurch, 2010).

As mentioned before, these benefits only materialize if heritage technologies are properly adapted to a new application context (Goodman, 2002). If the heritage technology is not properly adapted, it may instead introduce new risks to the program, as elaborated by Goodman (2002) for various cases of aviation navigation units for space applications.

Although the relationship between the use of heritage technologies and reductions in cost, schedule, and risk makes intuitive sense, a statistical analysis of whether or not these benefits exist in general does not seem to have been attempted yet. Only Coonce et al. (2009) explore the effect of heritage technologies implicitly in a regression equation for space program cost. The regression equation includes a variable for the percentage of the space system that has been newly developed. The results of the analysis show that this variable has a statistically significant relationship with space program cost. The higher the percentage, the higher the cost. However, it is unclear how the percentage is determined. One reason why there is a lack of statistical analyses taking heritage technologies into account could be the lack of a precise definition of heritage (Larson & Wertz, 1999, pp.798-799). Larson & Wertz (1999, pp.798-799) and Coonce et al. (2009) both use the fraction of a system's design that has been reused or newly developed as a proxy for heritage technology.

Hence, the question whether or not using heritage technologies is benefitial in general has not been sufficiently answered yet.

Next, the issues linked to adapting heritage technologies are considered, as shown in Fig. 1-12. Two types of issues are distinguished. First, issues that are of technical nature and second, issues that are cognitive.

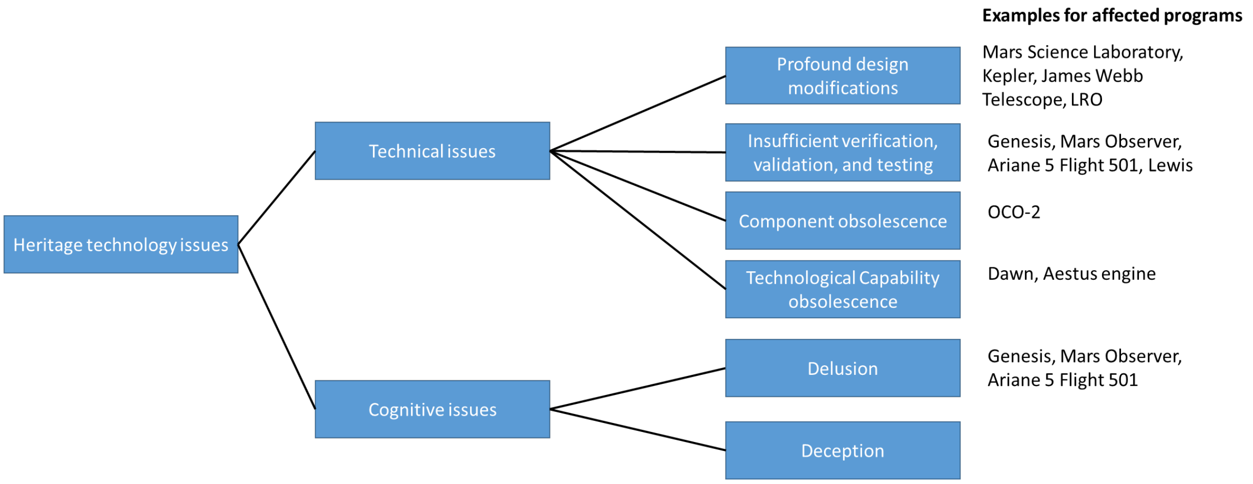


Fig. 1-12: Heritage technology issues breakdown and examples

[7] Mass overruns are strongly related to cost overruns in case the spacecraft mass exceeds the capacity of the launcher. The subsequent effort to reduce mass leads to cost increase. Shortly before launch, the cost of mass reduction may reach $200,000 per kg (1990 dollars), according to a report published by the U.S. Congress (U.S. Congress, 1990).

Several technical issues related to properly adapting heritage technologies can be found in the literature:

- *Profound design modifications:* Profound design modifications usually follow, when a heritage technology is not applicable in its existing form. The modification of the design can lead to a loss of its heritage. An extreme case of a technology modification occurred during the development of the Mars Science Laboratory (MSL) Entry-Decent-Landing (EDL) system's heat shield. The design was initially based on a material used for the Mars Exploration Rover (MER) and Pathfinder missions. However, testing showed that the material was inadequate. As a consequence, it had to be replaced by a material with a lower level of maturity. According to the project office, the consequence was a delay of 9 months and $30M in additional costs (GAO, 2010). An example where heritage was preserved, despite modifications, is the Pathfinder parachute system. The system design was first used for the Viking lander. The development team made deliberate efforts to keep the Viking heritage by preserving basic geometric parameters of the parachute (Fallon, 1997).
- *Insufficient verification, validation, and testing:* For several cases, insufficient verification, validation, and testing of heritage technologies was based on the assumption that some of these activities can be skipped for heritage technologies. However, if heritage technologies are used in a different context, required testing may significantly change. Hence, skipping testing introduces risks that can lead to mission failure. In the case of the Mars Observer mission, vital testing of heritage technologies was skipped. It was believed that previous testing and operation was sufficient to prove that these technologies would work again. However, as the technologies were only flown on LEO missions, they were not proven for interplanetary missions (Investigation Board, 1993). Another prominent example is the Ariane 4 avionics software which was reused in the Ariane 5. Important test cases were not covered, leading to an error when the software was used within the new context. The Ariane 5 flight 501 got off course due to this error and the rocket had to be destructed (Dowson, 1997).
- *Component obsolescence:* Components used in the original design get obsolete and are no longer available. Electronic components are particularly prone to obsolescence. Examples are the Orbital Carbon Observatory (OCO) spacecraft's RAD-6000 on-board computer. The computer's static random access memory (SRAM) was no longer available for its carbon copy, OCO-2, leading to a considerable redesign of the computer (eoPortal Directory, 2015a).
- *Technological capability obsolescence:* A supplier no longer possesses the capability to develop and/or manufacture a certain technology. An example is the Dawn mission's electrical propulsion system. The supplier had previously delivered the ion engine and the power processing units for the Deep Space 1 mission. However, after a 6-year lag between the development of the Deep Space 1 engine, the supplier had lost considerable parts of its capability (NASA, 2010). Capability loss can occur when contracts are awarded to a different supplier than before. Acquisitions, mergers, and other profound organizational changes are also associated with capability loss. Capability loss can also occur when the original development team is no longer available (Szajnfarber, 2011).

Table 1-3 gives an overview of a number of NASA space missions along with relevant heritage technologies used in these missions and the outcome of using heritage technologies.

Table 1-3: Space missions with the outcome of using heritage technologies, adapted from Hein (2014)

Mission	Relevant heritage technology	Comment on benefits / risks of technology
Spirit and Opportunity	Landing airbags	Last minute redesign and retest
Mars Express		Heritage as risk / cost strategy
JWST		Underestimation of heritage complexity
Stardust	Acceleration sensor	Failure due to insufficient testing, underestimation
Mars Observer	Spacecraft bus	Failure due to change in operational environment
MAVEN		Success: attributed to heritage by project officials
OCO-2	Spectrometer	Success: 95% drawings ready for CDR

SMAP		Failure: Heritage technology not matured for PDR
Mars Phoenix		Contributed to success
MSL	Avionics heritage architecture, entry, decend, and landing system based on Viking heritage	Cost overruns

The literature refers to these issues that prevent heritage benefits to materialize as a "heritage trap" (Investigation Board, 1993; NASA, 2013b, 2007). The heritage trap "occurs in making flawed assumptions regarding the applicability of a specific technology to another operating environment or another hardware configuration." (NASA, 2007). These "flawed assumptions" can be understood as cognitive biases that pertain to heritage technologies. One of these cognitive biases is the overestimation of resource savings by using heritage technologies. The annual GAO report (GAO, 2010, p.42) observed for the Kepler mission that contractor representatives "underestimated the complexity and the effort required to modify the existing heritage technologies." The consequence was a 25% ($78 million) cost overrun and a delay of 9 months (GAO, 2009a, p.14). A similar observation was made in the context of the Lunar Reconnaissance Orbiter (LRO) mission:

"The project did not identify any critical technologies. Each of the project's major instruments is based significantly on heritage technology. However, the project manager said the project had underestimated the difficulty of the modifications needed." (GAO, 2010, p.46)

Another quote illustrates how the risks of adapting heritage technologies is underestimated:

"According to NASA officials, heritage technologies are not the same as critical technologies because, in their opinion, critical technologies are not based on existing—or heritage— technology. Generally, the project officials said that the technology they were using was not considered "new" if it had been demonstrated in a test environment or used on a prior mission, even if there needed to be a change or customization in configuration or design. Yet, these projects all failed to build in the necessary resources for technology modification." (GAO, 2009a, p.14)

Furthermore, the NASA Systems Engineering Handbook remarks that there *"is a tendency on the part of technology developers and project management to overestimate the maturity and applicability of a technology that is required to implement a design. This is especially true of "heritage" equipment. The result is that critical aspects of systems engineering are often overlooked."* (Kapurch, 2010, p.57)

A similar statement is made in the Genesis Mishap Investigation Report (NASA, 2005, p.38):

"An erroneous belief that the SRC-AU was a heritage, or partially a heritage design, and unfounded confidence in heritage designs in general led to five errors that contributed to the mishap".

NASA training material stresses that heritage technologies need to be tested as rigorously as newly developed systems (NASA, n.d.). Nevertheless, there is a prevailing conviction that heritage technologies that have been flown in space are considered de-facto proven for a different context. For example, NASA's Deep Space Habitat is based on International Space Station (ISS) component technologies that have only been flown in LEO. Although there are considerable differences between the LEO environment and the deep space environment, an average TRL of 7.7 is attributed to the system (Smitherman and Griffin, 2014; Smitherman et al., 2012). An engineer from a large German space company confirmed that a technology is considered a heritage technology when it has been flown in space and questions about the specific context are usually not asked.

"Projects often take the simplistic approach during early formulation that a piece of hardware has flown before and therefore has been proven to work, without taking into account the environments in which the technology was flown in the past and will be flown in the new mission." (Barley et al., 2010, p.4)

Such overestimations of benefits and underestimation of risks can be explained by a cognitive bias pertaining to heritage technologies. Flyvbjerg et al. (2009) looked into large-scale engineering projects and discovered that the overestimation of benefits and underestimation of risks is a common phenomenon. They call the overestimation of benefits and the underestimation of risks "delusion". They explore the role of delusion in explaining cost and schedule overruns in large-scale engineering projects. They call delusion an "honest mistake", as the decision-maker is not aware of committing mistakes (Flyvbjerg et al., 2009, p.172). Delusion is commonplace in a range of planning tasks and prevalent in estimating the cost and schedule of projects (Buehler et al., 1997; Flyvbjerg et al., 2009, 2004; Malmendier and Tate, 2008; Newby-Clark et al., 2002). For the case of design reuse Busby (1999) observes that engineers tended to underestimate the effort of reusing designs, as "they underestimated the ramifications of design changes" (Busby, 1999, p.284).[8] Within the space domain, Bitten and Freaner (2010) and Freaner et al. (2008) have demonstrated that cost overruns and delays can often be traced back to initial optimism regarding the complexity of the spacecraft. Subsequent design changes would lead to a higher complexity and consequently to cost overruns and delays.[9] Looking at the heritage technology concept map in Fig. 1-9, delusion seems to pertain primarily to the design and the history of verification, validation, testing, and operation and less to technological capabilities. However, technological capabilities could play a role in delusion, as design modifications require technological capabilities and difficulties to modify the design may stem from an overestimation of existing technological capabilities.

Another cognitive bias is deception. Deception is the purposeful overselling of benefits and underselling of risks (Flyvbjerg et al., 2009). Deception is commonplace in large public projects, as resources are usually scarce and projects have to compete for them. Hence, there is an incentive for deception. Public space projects are not an exception. McCurdy (2007) and Heppenheimer (2002) meticulously reconstruct the approval process for today's ISS and the Space Shuttle. For both systems, benefits were grossly overstated and risks understated. As a consequence, both programs suffered from significant cost overruns. Other, more recent programs such as the Constellation program probably suffered from a similar fate (Augustine Commission, 2009). With respect to heritage technologies, the Ares I, Areas V, and SLS programs can be considered as overselling heritage technologies. For example, initial versions of the Ares V implied that only few components needed to be newly developed. All rocket engines would be based on existing technologies such as the Space Shuttle Main Engine, the RS-68, and the J-2. The J-2X, intended for powering the upper stages of the Ares I and V, is in essence a new engine development. However, the notion "J-2" in its name invokes that it is a variant of the J-2. Whether or not this is an attempt of deception cannot be answered. However, similar naming issues are known from the Soviet navy, where names were reused in order to suggest that a development program was rather a variant of an existing system. In reality, these vessels were new developments (Interview I17).

To summarize, three key advantages of a proper application of heritage technologies can be identified: potentially large savings in development cost and schedule, reduction of programmatic risks, and a higher confidence in the quality and reliability of the developed system. Issues that impede the proper application of heritage technologies have their origin in profound design modifications, insufficient verification, validation, and testing, component obsolescence, and the obsolescence of organizational capabilities. I argue that delusion and deception are the cognitive root causes of some of the technical issues. Statistical evidence that draws general conclusions on the effects of using heritage technologies is lacking and has only be implicitly considered.

[8] Another case where delusion played an important role is in software engineering. Software was assumed to be inherently fault-free, as in the case of the Therac-25 case (Leveson and Turner, 1993).

[9] The complexity metric used is based on component counts for each subsystem (Bearden et al., 2012).

1.5 Heritage Assessment

As demonstrated in the preceding sections, the proper adaptation of heritage technologies to a new application is crucial for reaping its benefits. What existing approaches exist for helping decision-makers to assess the potential benefits and risks of using a specific heritage technology? Existing approaches for assessing heritage are mostly based on heritage categories with certain criteria assigned to them. In the following, six approaches are presented.

Technology Readiness Levels (TRL)

Technology Readiness Levels (TRL) are a set of nine categories, called "levels", to classify technologies according to their maturity and readiness. The levels are hierarchical. A TRL of one is the lowest level and nine the highest. In order to advance from a lower level to a higher level, a set of conditions needs to be satisfied. Table 1-4 shows the TRL definition and explanation used by the European Space Agency (ESA) (ESA, 2008).

Table 1-4: TRL definition and explanation from ESA (2008)

TRL	Definition	Explanation
1	Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development.
2	Technology concept and/or application formulated	Once basic principles are observed, practical applications can be invented and R&D started. Applications are speculative and may be unproven.
3	Analytical and experimental critical function and/or characteristic proof-of-concept	Active research and development is initiated, including analytical / laboratory studies to validate predictions regarding the technology.
4	Component and/or breadboard validation in laboratory environment	Basic technological components are integrated to establish that they will work together.
5	Component and/or breadboard validation in relevant environment	The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment.
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)	A representative model or prototype system is tested in a relevant environment.
7	System prototype demonstration in a space environment	A prototype system that is near, or at, the planned operational system.
8	Actual system completed and "flight qualified" through test and demonstration (ground or space)	In an actual system, the technology has been proven to work in its final form and under expected conditions.
9	Actual system "flight proven" through successful mission operations	The system incorporating the new technology in its final form has been used under actual mission conditions.

The TRL 1 to 5 can be interpreted as *maturity levels* in the sense that they indicate whether or not a technology, in the sense of a component, is able to perform a certain function in a given environment. Levels 6 to 9 are *readiness levels*, in the sense that the technology works when integrated into a system. Different agencies such as NASA and the Department of Defense (DoD) use slightly different TRL definitions (Kapurch, 2010).

TRL are in widespread use, despite their qualitative nature. One of the reasons is that technology maturity problems have repeatedly lead to significant cost and schedule overruns. TRL is one of the approaches to identify maturity-related risks. A study of 62 Department of Defence programs showed that development programs that started with all technologies at TRL 7 did virtually not suffer from cost and schedule overruns. Programs that did not meet this condition suffered from an average cost growth of 30% and a schedule overrun of 20 months (Francis, 2007). An overview of the current state of practice of TRL is provided in Olechowski et al. (2015). Other maturity metrics have been introduced such as the System Readiness Level (SRL) (Sauser et al., 2006). However, they have been criticized for being mathematically flawed (Jimenez and Mavris, 2014; Kujawski, 2013) and of limited use in practice (Olechowski, 2015, pp.13-14).

TRL can be used for assessing heritage technologies. In most cases, heritage technologies can be put into one of the levels between five and nine, depending on how the operating environment and the system into which the technology is integrated. As Kujawski (2013) remarked, TRL only addresses the current state of a technology. It does not take other important maturity areas into account, such as programmatic maturity, developer maturity, and customer maturity (Kujawski, 2013, p.981). For example, the ESA TRL Handbook (ESA, 2008) does not explicitly mention technological capabilities, although in practice engineers seem to take them into consideration during TRL assessments (Interview I8).

ESA heritage categories

The ESA heritage product categories are widely used within the European space industry (Interview I10, I19). They are part of the European Cooperation of Space Standardization (ECSS) standard, to which all space projects conducted for the European Space Agency (ESA) have to adhere to. Table 1-5 depicts the four product categories A, B, C, and D. The four levels can be distinguished by whether or not the product has been modified, the extent of past qualification programs, whether or not the supplier has changed or the supplier uses different tools, manufacturing processes etc. Similar to the heritage conceptual model presented in Fig. 1-7, the aspect of design, supplier, and the extent of verification, validation, and testing is taken into consideration.

Table 1-5: ESA heritage product categories. Image taken from (ESA, 2009b)

Table 5-1: Product categories according to heritage

Category	Description	Qualification programme
A	Off-the-shelf product without modifications and • subjected to a qualification test programme at least as severe as that imposed by the actual project specifications including environment and • produced by the same manufacturer or supplier and using the same tools and manufacturing processes and procedures	None
B	Off-the-shelf product without modifications. However: It has been subjected to a qualification test programme less severe or different to that imposed by the actual project specifications (including environment).	Delta qualification programme, decided on a case by case basis.
C	Off-the-shelf product with modifications. Modification includes changes to design, parts, materials, tools, processes, procedures, supplier, or manufacturer.	Delta or full qualification programme (including testing), decided on a case by case basis depending on the impact of the modification.
D	Newly designed and developed product.	Full qualification programme.

The ESA heritage product categories have the purpose to help categorizing heritage technologies and to estimate the extent of the qualification program needed. They do not provide any assessment process or methodology. They also lack sufficient conceptual underpinnings. For example, it is not clear whether or not further assessment criteria have to be taken into consideration such as how much time has passed since the last qualification campaign. Furthermore, similar to TRL, the categories cannot be used for assessing the difficulty of getting from one category to another.

Advancement Degree of Difficulty methodology

The Advancement Degree of Difficulty (AD²) methodology is a risk assessment methodology for technologies (Bilbro, 2008). AD² addresses a shortcoming of TRL. TRL does not provide any support for assessing how difficult it is to get from one TRL to another. For assessing the difficulty of advancing on a TRL, AD² asks the question "Have we done this before?". Depending on the answer, one of the AD² levels shown in Table 1-6 is selected. Nine AD² levels are defined, which are linked to risk percentages. The higher the level, the higher the corresponding risk. AD² focuses on how far modifications or new development is required. In case new development is required, it assesses, how far it is within the existing experience base. AD² is used for technology assessment in general. Besides the AD² levels, AD² also provides various capability-related questions for design and analysis, manufacturing, software development, test and evaluation, and operations.

Table 1-6: AD² levels from Bilbro (2008)

AD² level	Uncertainty	Description	Risk
9	Chaos	Requires new development outside of any existing experience base. No viable approaches exist that can be pursued with any degree of confidence. Basic research in key areas needed before feasible approaches can be defined.	90+%
8	Unknown unknowns	Requires new development where similarity to existing experience base can be defined only in the broadest sense. Multiple development routes must be pursued.	80%
7		Requires new development but similarity to existing experience is sufficient to warrant comparison in only a subset of critical areas. Multiple development routes must be pursued.	70%
6		Requires new development but similarity to existing experience is sufficient to warrant comparison on only a subset of critical areas. Dual development approaches should be pursued in order to achieve a moderate degree of confidence for success. (desired performance can be achieved in subsequent block upgrades with high degree of confidence.	50%
5	Known unknowns	Requires new development but similarity to existing experience is sufficient to warrant comparison in all critical areas. Dual development approaches should be pursued to provide a high degree of confidence for success.	40%
4	Well understood	Requires new development but similarity to existing experience is sufficient to warrant comparison across the board. A single development approach can be taken with a high degree of confidence for success.	30%
3		Requires new development well within the experience base. A single development approach is adequate.	20%
2		Exists but requires major modifications. A single development approach is adequate.	10%
1		Exists with no or only minor modifications being required. A single development approach is adequate.	0%

AD² provides a starting point for heritage technology assessment as it deals with technological capabilities. Similar to the ESA heritage categories, it does not provide proper conceptual underpinnings.

NASA subsystem inheritance review

NASA's "inheritance review" defines broad criteria for assessing heritage such as environmental changes or changes in the spacecraft architecture (NASA, 1999a). Furthermore, typical program management criteria such as cost, schedule, and risk are mentioned. Compliance of the technology to requirements and constraints of the new application are assessed via a compliance matrix. However, the relationship between these criteria and heritage is not clarified. Furthermore, the review guidelines mostly list the assessment criteria without providing an assessment process or a supporting framework that ensures that all relevant aspects were taken into account.

Top-down TRL assessment method

The "Top-down TRL assessment method" by Fragola et al. (2010) aims at assessing heritage technologies in the early phases of development. It is based on the TRL scale and takes the cost and performance uncertainties of using technologies with a low TRL into account. However, important aspects of heritage technologies, such as the availability of suppliers are not taken into account. Furthermore, changes in the system context that might lead to significant modifications, such as changes in system standards, are also not taken into account.

NASA heritage grading scale

The NASA heritage grading scale provides a list of criteria and to what degree a technology needs to fulfill these in order to claim full or partial heritage (NASA, n.d.). The grading scale is shown in Table 1-7. Similar to the ESA heritage product categories, criteria such as design, manufacture, and supplier / provider are considered. Although not included in the ESA heritage product categories, "use" and the referenced mission are considered. Furthermore, software is explicitly mentioned whereas it is not mentioned in the ESA heritage product categories. With respect to the heritage technology concept map in Fig. 1-9, "design" is represented by "design" together with "software" in the NASA grading scale. "Technological capabilities" are represented by "manufacture" and "provider". "Verification, validation, testing, and operation" is represented by the last three elements in the grading scale: use, operating environment, and referenced mission.

Table 1-7: NASA heritage grading scale taken from NASA (n.d.)

	Full Heritage	*Partial Heritage*	*No Heritage*
Design	Identical	Minimal modifications	Major modifications
Manufacture	Identical	Limited update of parts and processes necessary	Many updates of parts or processes necessary
Software	Identical	Identical functionality with limited update of SW modules (<50%)	Major modifications (>=50%)
Provider	Identical provider and development team	Different however with substantial involvement of original team	Different and minimal or no involvement of original team
Use	Identical	Same interfaces and similar use within a novel overall context	Significantly different from original
Operating Environment	Identical	Within margins of original	Significantly different from original
Referenced Mission	In operation	Built and successfully ground tested	Not yet successfully ground tested

As in the case of the ESA heritage product categories, the NASA heritage grading scale does not provide an evaluation process or sufficient conceptual underpinnings. This is reflected in the differences in assessment criteria.

Table 1-8 summarizes the existing heritage assessment approaches and to what extent they can be used for assessing different aspects of heritage systems and technologies. Note that the assessment dimensions are partly derived from the heritage technology concept map from Fig. 1-9. Changes to requirements and constaints, mission risk, program management indicators, and development phases have been added. Existing approaches from the literature seem to address the relevant assessment dimensions incompletely. Most of the approaches in the literature only mention the listed criteria but do not provide any method for assessing them. Changes in requirements and constraints with respect to a new application are only addressed by the NASA inheritance review in the form of the compliance matrix.

Table 1-8: Existing heritage assessment methods and heritage-related aspects from Fig. 1-7 and Fig. 1-9 they cover

Assessment dimension \ heritage-related aspect	**TRL**	**ESA heritage categories**	**NASA heritage grading scale**	**AD2**	**NASA inheritance review**	**Top-down TRL assessment method**	**Conclusions**
Verification, validation, testing aspects	Criteria mentioned	Criteria mentioned			Testing history		**Not addressed**
Operational history	Criteria mentioned		Criteria mentioned				**Not addressed**
Design modifications			Criteria mentioned		Criteria mentioned		**Not addressed**
Technological capabilities		Criteria mentioned	Criteria mentioned	Multi-dimensional criteria			**Not addressed**
Changes to requirements and constraints					Compliance matrix		**Partial coverage**
Mission risk					Reliability / failure history		**Partial coverage**
Program management indicators						Schedule risk	**Not addressed**
Applicable to development phases	all	all	all	all	From phase B onwards	Phase 0/A	**Addressed**

To summarize, existing heritage assessment approaches are based on broad heritage categories such as the ESA heritage categories or TRL. Most approaches are rather suited for later stages of systems development, where detailed information about the system into which the heritage technology is integrated is already available. Approaches that can be used in the early stages of systems development do only cover the aspect of programmatic risk such as cost and schedule overruns (Fragola et al., 2010). Above all, no existing approach links heritage characteristics to mission and programmatic risks and benefits.

1.6 Research Gaps

In the following, the research gaps with respect to existing heritage assessment approaches are identified. In order to identify these research gaps, first, the use cases for a heritage assessment methodology are elicited. Second, it is evaluated how far these use cases are satisfied by the existing heritage assessment approaches.

The rationale for using heritage technologies is driven by the *programmatic objectives* of a space program such as reducing cost and shortening development duration. It is furthermore driven by the *requirements* for the technologies used in the space system, for example their functions, performance, interfaces, and operating environments. Finally, the *context* of the program is of relevance, as it may influence which technologies can actually be used.

The potential benefactors of a heritage assessment methodology are depicted in Fig. 1-13. Note that benefactors of the methodology are not necessarily users of the methodology. Users may generate results with the methodology and present them to potential benefactors.

One of the main benefactors are program managers. Program managers may work in space agencies or industry. Their primary concern is to plan and execute a space program within budget and schedule. Furthermore, they need to identify and mitigate programmatic risks. A heritage assessment methodology may support their heritage-related decision making in identifying potential benefit and risk areas. Furthermore, they can use the methodology for supplier audits in order to verify heritage claims.

Another benefactor is an organization concerned with space program assessment. In the U.S., GAO provides independent audit, evaluation, and investigation services for the United States Congress (Strotz, 2015, p.314). It assesses large NASA space programs on a regular basis. GAO focuses on the same issues as program managers, but their perspective is audit and controlling. Cost, schedule, and risk play a fundamental role and the prospects of a space program are estimated (GAO, 2015, 2009). Within the ESA context, no independent agency for program evaluation exists. However, independent advisory boards provide recommendations on space programs. The heritage assessment methodology may help assess claims about heritage technologies made by program managers. As program managers may have an incentive to oversell the advantage of heritage technologies in cutting cost and schedule, validating such claims may reduce programmatic risks. On the other hand program managers may have the opposite incentive to undersell their heritage in order to get a technology development program funded. In both cases, providing an objective basis for the existing heritage could be advantageous to organizations assessing heritage technologies.

Systems engineers working in the early stages of a space program are usually concerned with assessing the feasibility of a mission, defining requirements, and selecting technologies (Kapurch, 2010). Technology selection is usually accompanied by an ad-hoc assessment of heritage technologies, looking at the flight history of a technology. A heritage assessment methodology or metric may allow for a more reliable assessment of heritage technologies and identify its potential loss or inappropriateness.

Finally suppliers may be benefactors of a heritage assessment methodology, as they usually have to integrate a section on existing heritage into their proposals, for example for ESA. Although there is a difference between the results of an internal assessments and what is put into a proposal, at least the internal assessment can be improved, avoiding heritage claims that are not defensible.

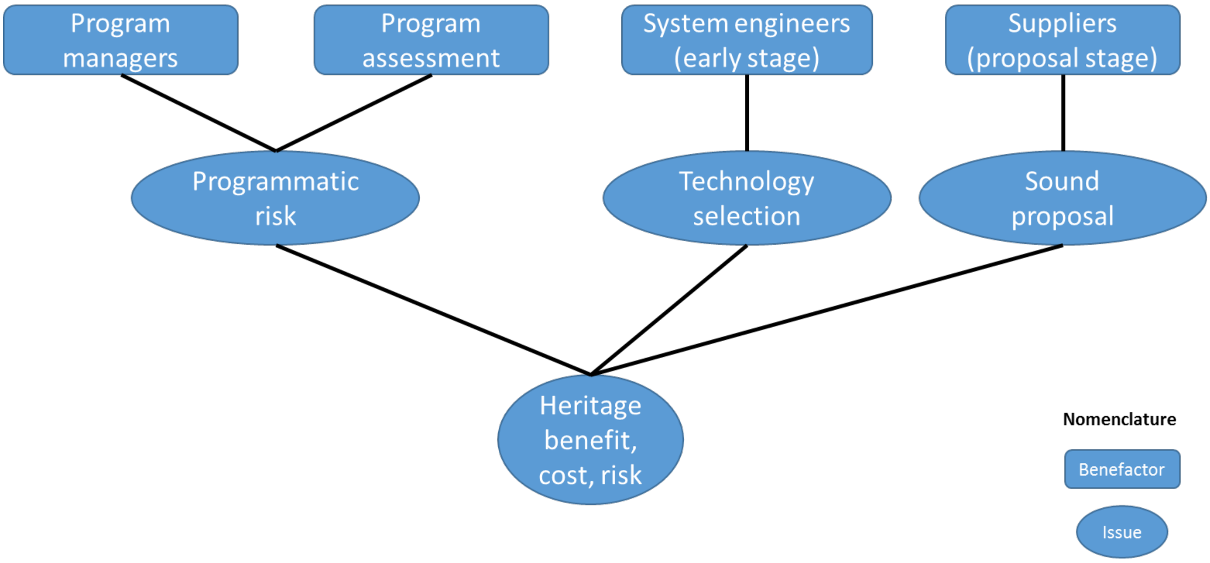


Fig. 1-13: Methodology benefactor issues and links to heritage technology characteristics

A heritage assessment approach's primary objective is to improve the way heritage technology-related decisions are made. More specifically, such an approach should address the following points:

- *Assess adequateness at an early stage:* Assess early on if the use of a heritage technology for a proposed application is adequate. As demonstrated in Section 1.3, most problems associated with heritage technologies can be traced back to their inadequate application. The decision for using heritage technologies starts early, often during concept development (Wessen et al., 2013). As Barley et al. (2010, p.3) indicate, existing heritage technology assessment approaches work well in detecting issues in later phases. However, "for both heritage and new technology, by the time the technical issues were identified and addressed, the corrections to or mitigation of the issues resulted in schedule delays and cost increases." They go on and explain that "significant changes late in the formulation process (phase B or early phase C) may not allow adequate time for long lead procurements identified as mitigations." Hence, the approach needs to address the early phases in particular, where decision making has the largest leverage and issues can be mitigated without adverse impact on the program (Schulz et al., 1999; Waiss, 1987; Whelton et al., 2002).
- *Enable comparison between alternatives via a heritage metric:* Compare between different options for heritage technologies and newly developed technologies.
- *Assist decision making:* The needs of the decision-maker(s) are addressed and the approach can be used in practical contexts. This means that the effort spent in using the approach needs to be justified with respect to the insights generated by applying the approach (Keeney & Winterfeldt, 2009, p.233).
- *Meaningfulness of assessment results:* In order to assist the decision-maker(s), the results of the assessment need to be easily interpretable. Furthermore, they need to make sense for a decision-maker.
- *Reliability of assessment results:* The adequateness or inadequateness of heritage technologies with respect to an application can be assessed without generating results that violate sound engineering judgement.
- *Grounded in sound theory:* The approach needs to be grounded in a conceptual framework or theory. The framework explains the relevant concepts and relationships between these concepts such as "heritage", "technology", and "capability". Furthermore, the approach should be consistent with basic concepts from decision theory. However, it should seek a compromise between theoretical soundness and practical usability (Keeney & Winterfeldt, 2009, p.233). An approach that is theoretically sound but without applicability and vice-versa need to be both avoided.

Table 1-9 gives an overview of the assessment criteria versus existing heritage assessment approaches.

Table 1-9: Comparison of existing heritage assessment approaches with criteria (Yes: satisfies criteria; No: does not satisfy criteria)

	TRL	***ESA heritage categories***	***NASA heritage grading scale***	***AD2***	***NASA inheritance review***	***Top-down TRL assessment method***
Assess adequateness at an early stage	Yes	No	No	Yes	No	Yes but only uses TRL
Enable comparison between alternatives via a heritage metric	No	Heritage categories	Heritage categories	No	No	Only TRL used as metric
Assist decision making:	Yes	No methodology	No methodology	Yes	Yes	Yes
Meaningfulness of assessment results	Yes	Yes	Yes	Yes	Yes	Yes
Reliability of assessment results	In use	In use	unknown	unknown	In use	unknown
Grounded in sound theory	No	No	No	No	No	No

As a result of comparing existing approaches with the criteria, several gaps can be identified:

- *No sound theory:* There is no conceptual framework that defines what heritage and heritage technology is. Furthermore, there is no framework for factors that affect them, such as contextual and capability changes.
- *No assessment of adequateness at an early stage:* An assessment of heritage technologies in the early stages of systems development is lacking, taking all identified aspects into account. Common practice is listing on which missions a heritage technology has been flown before.
- *No heritage metric:* A proper metric or measure for heritage does not exist, besides the ESA heritage product categories (ESA, 2009). TRL as a measure for heritage is insufficient, as argued by Kujawski (2013), as it does only take into account the current state of the technology. Other dimensions such as programmatic maturity, developer maturity, and customer maturity are left out.

Note that a further gap is the assessment of mission risks with respect to heritage technology. Mission risk is more related to the reliability of heritage technologies. However, in the following the focus is rather on the programmatic risks of using heritage technologies, although mission risk is considered in the form of "confidence" that the system works as intended.

1.7 Research Questions and Thesis Objectives

The main objective of this thesis is to develop a holistic heritage assessment methodology for the early stages of space systems development. The focus is on the early stages of development, as heritage-related risks can be mitigated easier if they are identified early on. In order to arrive at a validated and theoretically sound heritage assessment methodology, the following objectives need to be addressed in this thesis:

1. Provide a general **definition** of heritage technologies;
2. Provide a **conceptual framework** for heritage technologies within a general technology framework;
3. Provide **statistical evidence** for heritage benefits;
4. Enable the **assessment** of heritage technologies with respect to a new set of requirements, constraints, and environments;
5. Enable evaluating the effects of **modifications** on heritage technologies;
6. Enable assessing **capabilities** related to the development, manufacturing, and operation of a heritage technology;
7. Enable the **measurement** of heritage in order to compare technology options;
8. **Validate** the methodology by application to case studies.

Fig. 1-14 illustrates how the thesis objectives address various research questions related to heritage technologies. A definition for "heritage technology" is needed for answering the question what heritage technology is. A conceptual framework for heritage technologies within a general technology framework provides a theoretical background for developing a theory of heritage technologies. Statistical evidence for the benefits and issues using heritage technologies has been cursory to date. The statistical evidence informs the development of the heritage assessment methodology and the heritage measurement approach. Furthermore, one of the main challenges of heritage technologies is to assess if the technology can be used in a changed context. Such an assessment has to take into account changed requirements, constraints, and environment. Another important aspect is the modification of a technology. How is the heritage affected by such a change? An essential element of a technology are the capabilities of organizations associated with it. A way to quickly estimate if a capability is existing or not is required. Finally, the heritage assessment methodology needs to be supported by a quantification of heritage. With a quantification, different technologies can be compared with respect to their heritage.

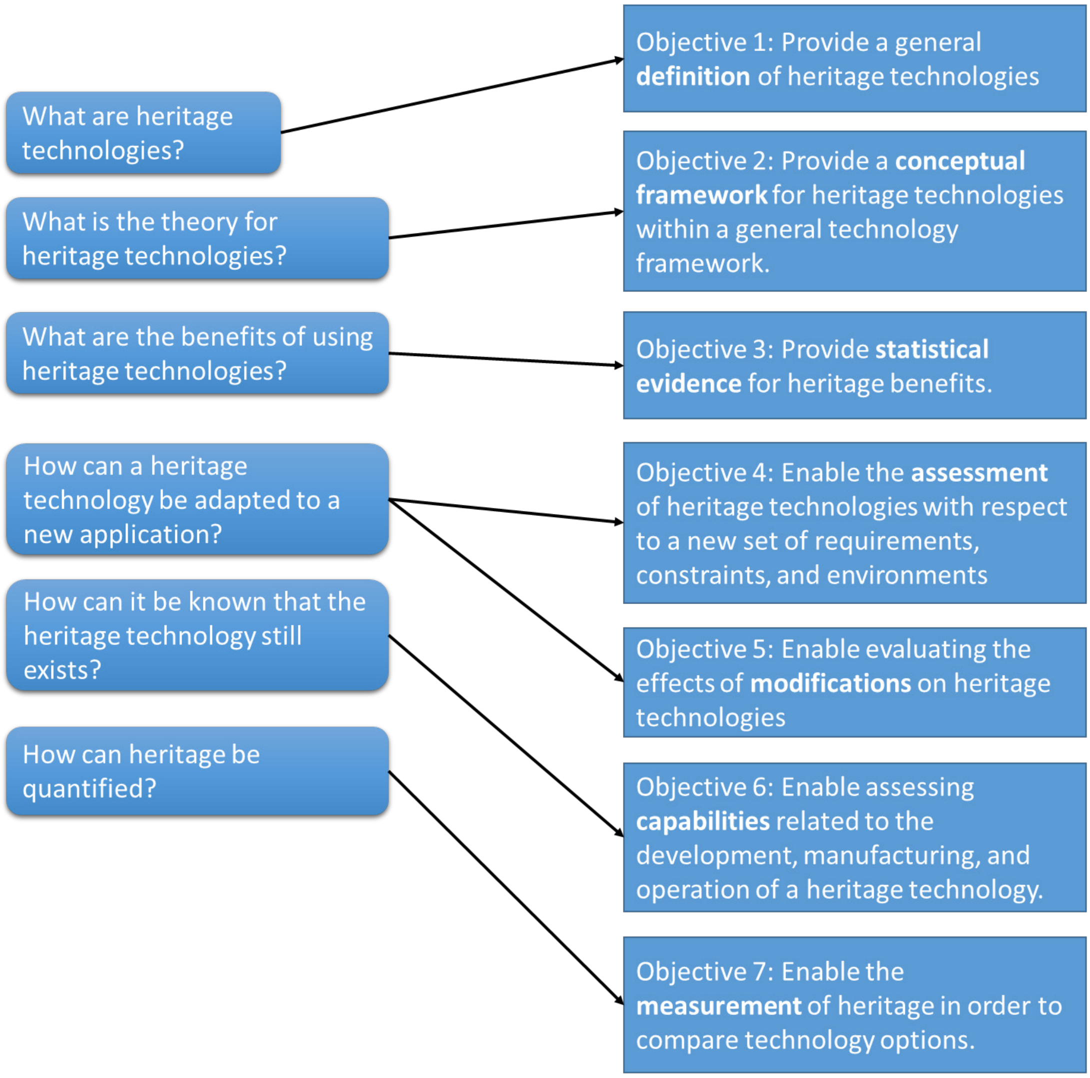


Fig. 1-14: Research questions and how they are addressed by the thesis objectives

1.8 Thesis Structure

Fig. 1-15 provides an overview of the chapters of this thesis and how they address the thesis objectives presented in the introduction.

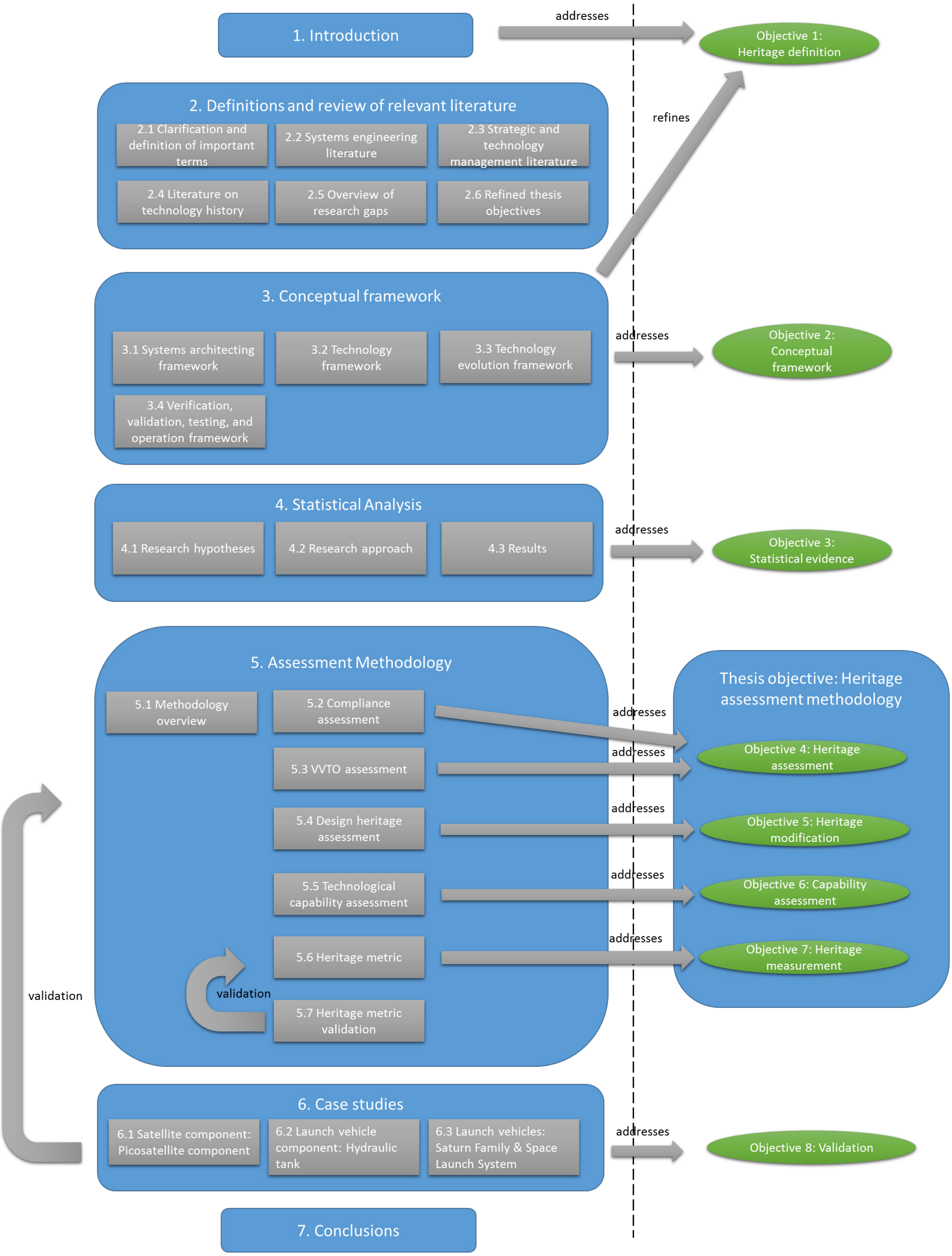


Fig. 1-15: Thesis structure and how specific chapters address the thesis objectives

The content of the chapters and their logic is described in the following:

Chapter 1 provides a brief introduction into the topic of heritage and heritage technologies and their relevance to space systems engineering and to other domains. The main research questions and the objectives for the thesis are defined.

Chapter 2 provides key definitions for important terms used in this thesis. In case suitable definitions from the literature do not exist, they are developed. Moreover, the relevant literature that forms the basis for Chapter 3, 4, and 5 is presented.

Chapter 3 presents three frameworks that form the basis for the statistical analysis in Chapter 4 and the methodology presented in Chapter 5. The frameworks are kept sufficiently general to be applicable to capability and technology assessments in various domains.

Chapter 4 presents a statistical analysis for quantifying the programmatic benefits of using heritage technologies in space programs. The results form the basis for in selecting proper heritage metric elements in Chapter 5.

Chapter 5 presents the heritage assessment methodology based on the frameworks from Chapter 3. The methodology consists of four steps covering the areas: compliance, VVTO, design heritage, and heritage measurement.

Chapter 6 presents three case studies, each covering different types of space technologies. The case studies are used for validating the applicability of the heritage assessment methodology to a wide range of space technologies.

Chapter 7 summarizes the results and contributions of this thesis, formulates conclusions and suggests topics for future work.

2 Definitions and Review of Relevant Literature

Chapter 2 presents definitions and literature from relevant domains. Literature from four major domains are relevant for this thesis, as shown in Fig. 2-1: systems engineering, strategic management and technology management, technology history, and measurement and decision theory. Systems engineering is relevant, as this thesis develops a systems engineering methodology. The systems engineering literature covered pertains mostly to systems architecting, various forms of reusing existing technologies, and verification, validation, and testing. The strategic management and technology management literature is relevant, as it deals with organizational capabilities, i.e. what an organization "can do". The analysis of what an organization can do is associated with the resource-based view of the firm, core competencies, and capabilities. Furthermore, literature on technology history is covered. The technology history literature is relevant, as it presents various models for the evolution of technologies and the role knowledge plays in this process. Heritage technologies change over time and the change affects its heritage. Finally, measuring heritage requires a grounding in measurement and decision theory. Basic concepts such as scales, metrics, measures, and indicators are introduced. The concept of "value function" is introduced, as it allows for quantifying and aggregating preferences.

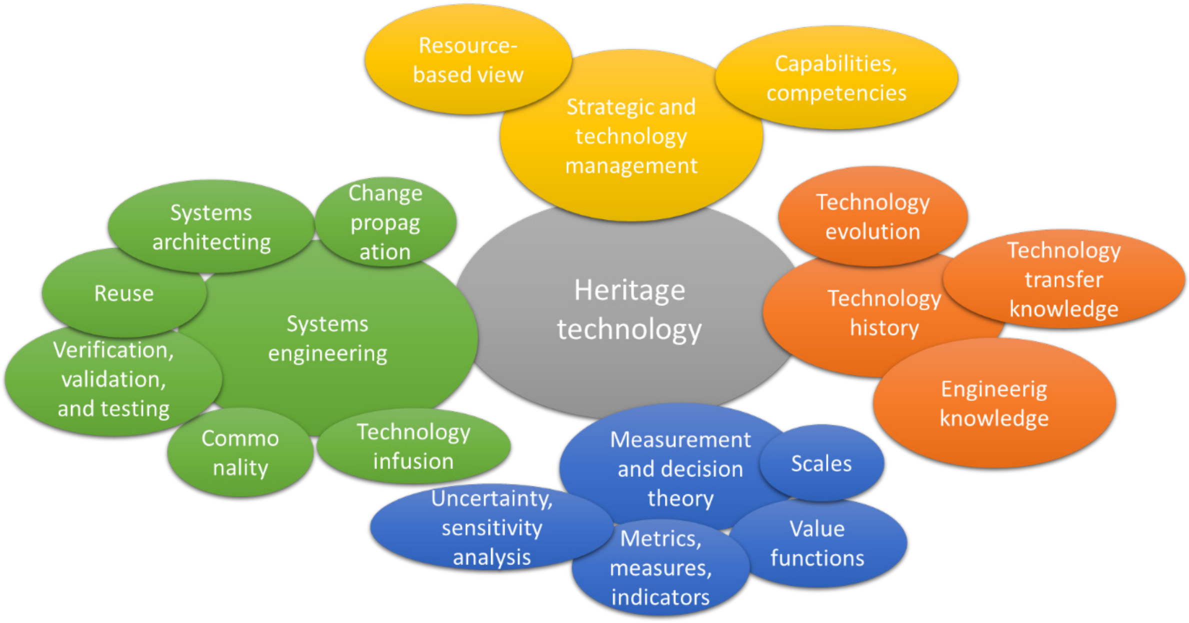


Fig. 2-1: Relevant literature for the assessment of heritage technologies

2.1 Terminology

In the following, essential terms for this thesis are defined.

2.1.1 Systems Engineering

The research in the context of this thesis falls into the domain of systems engineering. Before definitions of systems engineering are presented, the notion of "system" needs to be defined. There exists a large number of definitions for "system". A system in general can be defined according to the Merriam-Webster dictionary as "a set of interacting or interdependent components forming an integrated whole." (Merriam-Webster Inc., 2004) This definition pertains to both, natural and artificial systems. In the context of this thesis, the focus is on artificial systems and more specifically on technical systems.

In this thesis, a technical system is defined as "an integrated set of elements, subsystems, or assemblies that accomplish a defined objective." (Hamelin, 2010, p.5)

Definition: System

An "integrated set of elements, subsystems, or assemblies that accomplish a defined objective." (Hamelin, 2010, p.5)

The main difference between a general system and a technical system is that technical systems have objectives, purposes, or goals. For systems in general, this is not necessarily true. Whether or not, for example, biological systems have an underlying purpose is a matter of debate (Nagel, 2012).

In the following, the definition of "systems engineering" of the International Council on Systems Engineering (INCOSE) is used.

Definition: Systems engineering

"Systems Engineering" is "an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem: operations, cost and schedule, performance, training and support, test, manufacturing, and disposal. SE considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs." (Haskins et al., 2007)

The former NASA administrator Michael Griffin gives the following definition:

„System engineering is the art and science of developing an operable system capable of meeting requirements within imposed constraints." (Griffin, 2007)

These definitions cover a broad range of engineering activities and there is a lack of specificity what systems engineering activities actually are. At least in the context of this thesis, a distinction is made between what is understood as "systems engineering" in industry and in an academic context. In industry, roles such as "systems engineer" are mostly domain-specific, which is often indicated in titles such as "software systems engineer", "propulsion systems engineer". A software systems engineer is usually responsible for coordinating the technical aspects of a software development project such as defining the software architecture and tracing the software requirements. A propulsion systems engineer manages the various aspects that are relevant for developing a rocket or jet engine. These roles are technological leadership positions and require deep domain-specific knowledge.

Research in systems engineering is more concerned with the generic, domain-independent aspects of systems. For example, the principles of system decomposition or functional analysis are intended to be applicable to all engineering domains (Dori, 2002). Further aspects are development processes, interface management, requirements elicitation, and engineering decision theory. Deep domain knowledge in a specific engineering domain is helpful but not essential in understanding these aspects. This thesis is no exception and aims at contributing to the domain-independent body of systems engineering. However, the space domain is used as an entry point with the option to extend the methodology to other domains.

2.1.2 Systems Architecting

According to Crawley et al. (2015, p.16) systems architecting translates stakeholder needs into a first systems architecture. A systems architecture can be understood as a high-level design of a system (Selva Valero, 2012). It bridges the gap between customer needs and detailed design. The term originated in software engineering but is also used in other engineering domains. Rechtin and Maier (2000) list several points that distinguish architecting from engineering, depicted in Table 2-1.

Table 2-1: Architecting – engineering continuum taken from Rechtin & Maier (2000, Table 1.1)

Characteristic	Architecting	A & E	Engineering
Situation/goals	Ill-structured	Constrained	Understood
	Satisfaction	Compliance	Optimization
Methods	Heuristics	↔	Equations
	Synthesis	↔	Analysis
	Art and science	Art **and** Science	**Science** and Art
Interfaces	Focus on "mis-fits"	Critical	Completeness
System integrity maintained through	"Single mind"	Clear objectives	Disciplined methodology and process
Management issues	Working for Client	Working with Client	Working for Builder
	Conceptualization and certification	Whole waterfall	Meeting project requirements
	Confidentiality	Conflict of interest	Profit vs. cost

Emes et al. (2012) present the to-date most comprehensive survey of the term "system architecting". Based on a thorough literature survey and interviews with system architects, they derive a number of different, partly contradictory interpretations for systems architecting. In the context of this thesis, the following definition is used:

Definition: Systems architecting

"SA (systems architecting) is a subset of [systems engineering], focusing on the top-level structure (or top-level design) of the system;" (Emes et al., 2012, p.389)

2.1.3 System / Product Architecture

System architecture can be understood as the way how elements of a system are related to each other. For example, a car can have a front drive, back drive, or both. For a front drive, the transmission drives the front wheels. The transmission therefore interacts with the front wheels. For the back drive, the transmission drives the back wheels. In this case, the transmission interacts with the back wheels instead of the front wheels. Therefore, cars with front and back wheel drives have different architectures, as the way their components interact is different.

Two prevalent definitions for "system architecture" are presented. The first definition from the ISO/IEC/IEEE standard defines system architecture as "fundamental concepts or properties of a system in its environment embodied in its elements, relationships, and in the principles of its design and evolution." (ISO/IEC/IEEE, 2011, p.2). The definition is prevalent in software engineering and has also been used in (general) systems engineering. Although it is widely used, it is too abstract in order to be fruitful in the context of this thesis. Due to the lack of detail, a second, more specific definition was selected.

Crawley and Cameron (2012) define system architecture as "the embodiment of concept: the allocation of physical/informational function to elements of form, and the definition of interfaces among the elements and with the surrounding context"."

Definition: System architecture

A system architecture is "the embodiment of concept, and the allocation of physical / informational function to elements of form, and definition of relationships among the elements and with the surrounding context." (Crawley and Simmons, 2006)

Concept can be understood as the basic idea for the system or product which performs a function. For example, the function "transport passengers" can be performed by a car, bus, train, ship, or airplane. Defining the system architecture for an airplane is the next step in further refining these concepts. The allocation of function to elements of form can be understood as the mapping between functions and system elements. For example, a car has a motor. The motor generates torque. "Generate torque" is its main function. The transmission has the function "transmit torque". The wheels have the function "transmit traction force to road". Each of the system's elements has one or more functions allocated to it. Usually, there are different ways of how functions can be allocated to system elements. For example, the Soviet N-1 lunar rocket has spherical propellant tanks and a supporting structure that holds the rocket together. The spherical tanks have the function "contain propellant" and the supporting structure the function "provide structural integrity to rocket". The Saturn V by contrast has propellant tanks that serve at the same time as the supporting structure. In this case, two functions are allocated to the tanks which are allocated to different system elements in the case of the N-1.

Interfaces play a crucial role in system architectures. Properly defined interfaces enable modular architectures (Baldwin and Clark, 2000). Modular architectures allow for the exchange of system modules, which can have significant technological and economic implications. Baldwin & Clark (2000) elaborate on the IBM 360 personal computer for how a modular architecture helped to develop a personal computer industry. They argue that one important mechanism was the ability of companies to develop modules for the personal computer, given precise interfaces.

Modular architectures also allow for the implementation of flexibility (Gershenson et al., 2003; Neufville and Scholtes, 2011). In case changes in a system's context occur, modules can be exchanged. In the context of heritage technologies, modular architectures may enable the smooth modification of systems.

Ulrich (1995, p.419) defines "product architecture" as "the scheme by which the function of a product is allocated to physical components." This definition is similar to a part of Crawley's system architecture definition. The relationship between the product architecture and the performance of a manufacturing firm is stressed. The paper explores different types of product architectures. These product architecture types are distinguished by their pattern of mapping of product functions to the product's components. A one-to-one allocation of a product's functions to its components is defined as a "modular architecture" whereas the allocation of several functions to one module and / or the mapping of one function to several components is defined as an "integral architecture" as shown in Fig. 2-3.

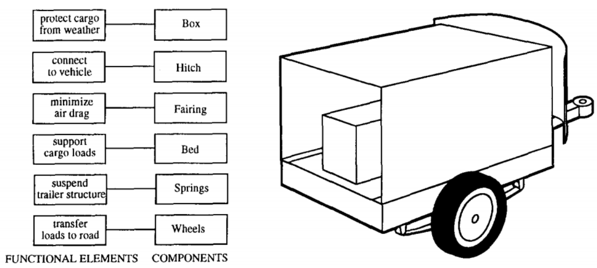


Fig. 2-2: Example of modular architecture. Image taken from Ulrich (1995)

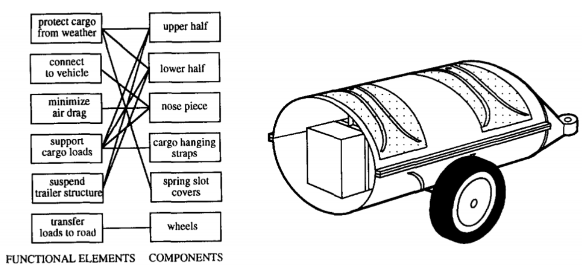


Fig. 2-3: Example of integrated architecture. Image taken from Ulrich (1995)

Traditionally, the product architecture literature has been close to the management literature. This becomes clear by looking at the journals in which highly-cited papers in this area were published, e.g. Research Policy, Administrative Science Quarterly, and Management Science (Henderson and Clark, 1990; Sosa et al., 2004; Ulrich, 1995).

Two seminal contributions are Henderson and Clark (1990) and Ulrich (1995). Henderson and Clark (1990) elaborate on the architecture of a product in the context of product innovation. The term "architectural innovation", which they coined, is a type of innovation which redefines the relationships between a product's components. They focus on the relationship between product architecture and the communication patterns within an organization. Henderson and Clark (1990) conclude that a misalignment of a product with a new architecture with an organization's architecture might have profound consequences for its competitiveness. The concept of architectural innovation is related to the concept of the "mirroring hypothesis" where the product architecture mirrors the organizational architecture (MacCormack et al., 2011). For example, a modular organization implies a modular product architecture. Sosa et al. (2004) introduce an approach for identifying the misalignment between the product architecture and the organizational architecture.

To conclude, the system / product architecture literature provides approaches for modeling heritage system designs at a high level of abstraction. In particular, the mapping between functions and components is relevant for assessing changes to a heritage system design at an early stage of development. Furthermore, the notion of architectural innovation links the product architecture to the architecture of an organization. Architectural innovation and the mirroring hypothesis seem to be ways how a system's design and technological capabilities interact.

2.1.4 Technology

One of the central concepts of this thesis is „technology". The notion of "technology" in the context of heritage technologies was introduced in Section 1.3. In this section, a general definition of technology is introduced, based on definitions from the literature. The general definition aims at grounding the previously introduced technology definition to the existing literature on technology.

The importance of technology is self-evident. Technology is considered an integral part of civilization and an economic driver (Bijker et al., 1987; Liebowitz and Margolis, 1995; Malecki, 1997; Pierson, 2000). Although it is easy to find an example for a technology, it seems notoriously difficult to define (Blomström and Kokko, 1998). It is therefore not surprising that there is a plethora of definitions for technology (Reddy and Zhao, 1990). Wahab et al. (2012) provide an overview of definitions from the literature since 1968. They conclude that technology definitions are multifaceted and depend on the perspective from which they are defined. The specific perspective here is to find a definition that is relevant in the context of systems engineering and more specifically space systems engineering.

Having introduced the perspective on technology, two criteria that a definition of "technology" needs to fulfill are introduced:

- *Sound theory:* The existing literature on technology shall provide sufficient theoretical underpinnings for the definition.
- *Usefulness:* The definition shall be in line with how engineers commonly use the term.

How is "technology" defined in prevalent handbooks and standards in systems engineering? Important elements of a technology are identified in the ESA Technology Readiness Level (TRL) Handbook (ESA, 2008)[10]. The ESA TRL Handbook describes in detail each TRL and provides guidelines for their application. The handbook does not provide an explicit definition of technology. However, as an ESA handbook, it is a valuable resource that may provide clues for what is considered a technology from the perspective of space systems engineering. Furthermore, TRL is an established approach for evaluating technologies and in widespread use in various engineering domains.

[10] Other handbooks such as the NASA Systems Engineering Handbook or the DoD Technology Readiness Assessment (TRA) Deskbook could be used analogously for this purpose (Department of Defense, 2009; Kapurch, 2010).

Looking into the ESA TRL Handbook, the following technology attributes can be identified (ESA, 2008). A technology includes:

a) Application of science and knowledge (TRL 1 description);
b) Aspects addressing the technology lifecycle, e.g. maturity-related aspects, development, manufacturing, and use. (TRL 1, 3 descriptions and implicitly in all other steps);
c) Purpose-oriented: It delivers a service, capability, solves a problem, or intends to do so. Some technologies are conceived for a purpose but fail to address it. (TRL 2 description and different requirements for individual TRLs).

In the next step, technology definitions from the literature are surveyed and compared to the attributes identified in the ESA Handbook. Bijker, Hughes, & Pinch (1987, pp.3-4) propose three definition categories:

- Physical objects or artifacts: bicycle, lamp
- Activities or processes: steel making, molding
- What people know as well as what they do: “know-how”

As a definition for “process” has not yet been provided, I will introduce it in the following.

Definition: Process

A process can be defined as a sequence of activities or tasks to achieve an objective or function (Eppinger & Browning, 2012, p.130; Estefan, 2008, p.2)

According to Hammer (2001), a process is “an organized group of related activities that work together to create a result of value”. According to Estefan (2008, p.2), a process “defines “WHAT” is to be done, without specifying “HOW” each task is performed. The structure of a process provides several levels of aggregation to allow analysis and definition to be done at various levels of detail to support different decision-making needs.”

Table 2-2 shows some of the technology definitions from Wahab et al. (2012). The definitions were screened with respect to the question what a technology “is” and its purpose according to the definition. Furthermore, the definitions in the table satisfy the three technology attributes from the ESA TRL Handbook: science and knowledge application, technology lifecycle aspects, purpose-oriented. The definitions in Burgelman et al. (1996), Hawkins et al. (1981), Maskus (2004), and Merrill (1968) are compatible with the technology attributes from the ESA TRL Handbook. Three of the four definitions have in common that a technology has the purpose of producing goods. This limitation seems to be inadequate to cover the breadth of technologies in engineering.

Table 2-2: Technology definitions from Wahab et al. (2012) that satisfy the three technology attributes.

	What technology is	Purpose
(Burgelman et al., 1996)	Theoretical and practical knowledge, skills, and artifacts	Develop products and services as well as their production and delivery systems
(Hawkins et al., 1981)	Specialized knowledge	Production of goods and services, manage processes
(Maskus, 2004)	Combining / processing production processes, intra-firm and organizational structures, management techniques, means of finance, marketing methods	Achieve production outcome
(Merrill, 1968)	Skills, knowledge, procedures	Making, using, doing things

A definition focused on the physical objects or artifacts category of Bijker, Hughes, & Pinch (1987, pp.3-4) is presented by Sahal (1981). He introduces the “system’s” view of technology. According to this view, a technology is defined by its main function and its performance characteristics. An example would be the function “generate thrust” for aircraft engines. In this case, a crucial performance characteristic would be the thrust-to-weight ratio. This definition seems to be well suited for describing technology evolution, for example in the form of the technology S-curve.

One takeaway from analyzing these definitions is that technology has a purpose and knowledge is an important element of a technology. More specifically, knowledge as part of technology is knowledge with a purpose, used for achieving a goal, performing a task, or solving a problem. Bozeman (2000, pp.628-629) refers to Sahal (1981) to argue that technology and knowledge are inseparable. Knowledge is for example required for the use and application of a product.

Fig. 2-4 shows a conceptual model for "technology" in general, based on the knowledge, process, and system interpretation of technology. Based on the conceptual model, the following general technology definition can be derived:

Definition: General technology

A technology in general can be a method, artifact, process, and knowledge or a combination of these. It uses resources for the purpose or intended purpose of realizing a function, solving a problem or performing a task.

As previously defined, an "artifact" is "an object that has been intentionally made or produced for a certain purpose." (Hilpinen, 2011) An artifact can be a system, a tool, etc. The crucial point in this definition is that technologies can be composed of many different elements. This interpretation of technology is consistent with the view that technologies can be aggregated (Arthur, 2009). Furthermore, they serve or are intended to serve a purpose. Some technologies are developed but never used for their intended purpose, for example due to not addressing customer needs, non-compliance, etc.

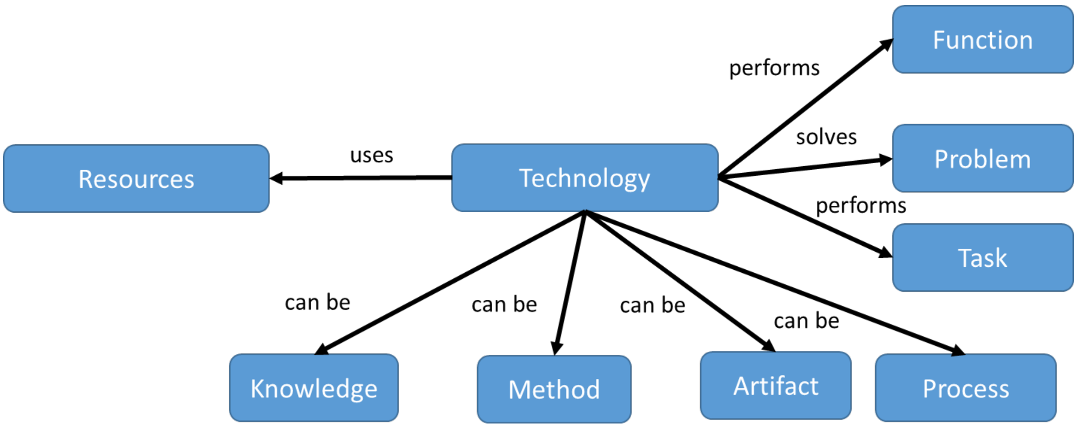


Fig. 2-4: Conceptual model of a general technology

For example, one of the most ancient technologies is the control of fire. Note that the definition of this technology is functional and its solution not specified. Fig. 2-5 shows a model of this technology. The technology "control fire" breaks down into the activities "ignite fire", "maintain fire", and "extinguish fire", covering the whole life cycle of fire, which is necessary for controlling fire. In this case the technology is a process, which requires wood, straw, and flint as resources. Flint could be further classified as a tool, whereas wood and straw are consumables. The purpose of controlling fire is to provide warmth in cold climate or at night, to protect people from insects and animals, and to cook raw food. The technology "control fire" is only partly solution-neutral. For example, a fire can be ignited by a lighter instead of using flint stone and straw. However, this would result in a different input to the process "ignite fire" and thus change the technology. Thus, there are degrees of freedom how the resources are used in order to ignite fire, which is consistent with how technologies are adapted to different contexts.

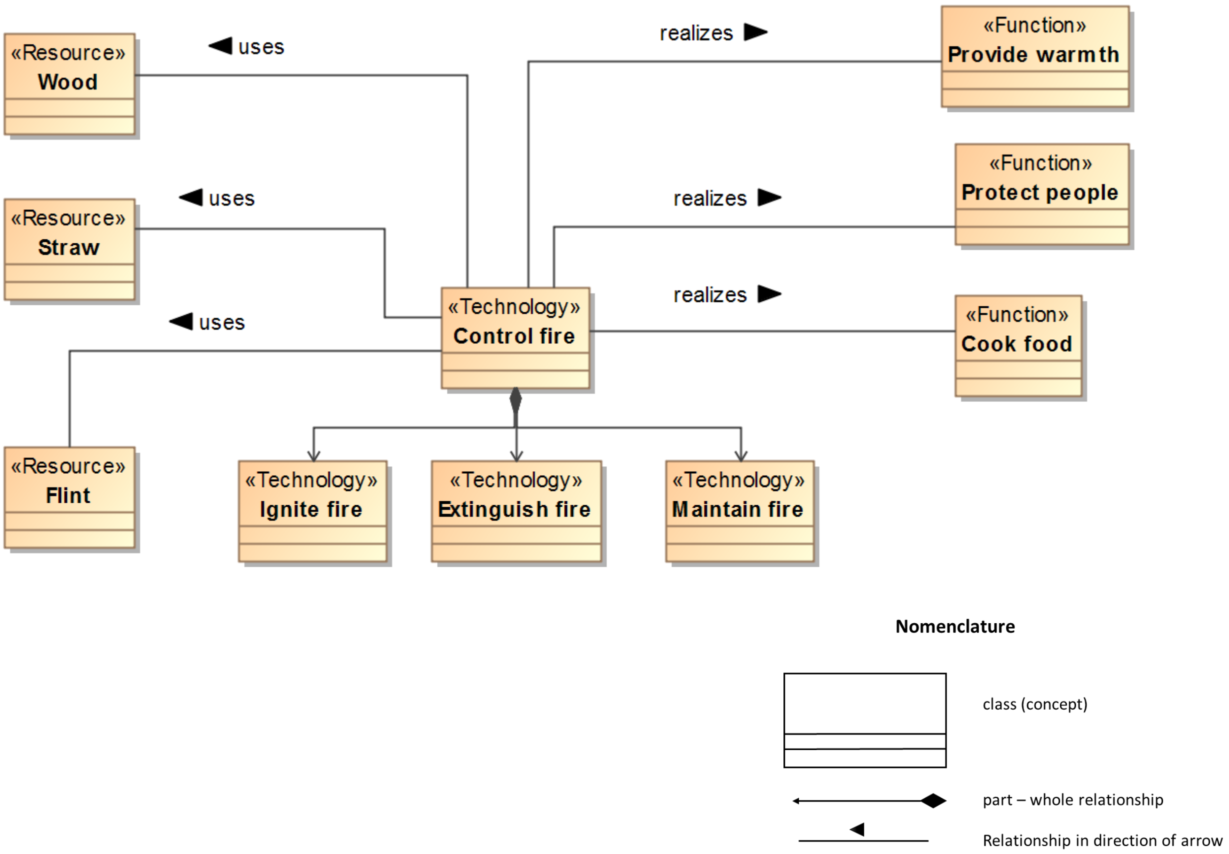


Fig. 2-5: "Control fire" as an example for a general technology

Knowledge is used by an *agent* to perform an activity. An agent is an entity capable of action. Knowledge is stored in a medium such as the human brain, a book, etc. In the case of controlling fire, the agent knows how to collect wood or straw and how to find flint stones. Furthermore, the knowledge for igniting, maintaining, and extinguishing fire must be present. Igniting fire with flint stones is not trivial and depends on how the stones are cut, the angle of hitting them, and where to put the straw in order to spark the fire. In this case, tacit knowledge plays an important role. Tacit knowledge is knowledge which is difficult to externalize (Gorman, 2002; Polanyi, 1964). Schön (1984) argues that tacit knowledge plays an important role for professionals in fields such as engineering that are concerned with the creation of technologies. Explicit knowledge is knowledge that can be externalized. In the case of explicit knowledge, knowledge does not depend on an agent. A textbook contains a lot of knowledge which can be internalized by an agent and used for a purpose. Thus, knowledge is either embodied in an agent or in artifacts such as text, code, items, and systems. Note that knowledge that pertains to a certain activity is also called "know-how" or "knowledge how" in contrast to "knowledge that" which stands for factual knowledge (Stanley and Williamson, 2001).

A common problem in identifying individual technologies is how to define what belongs to a technology and what not. This is called the demarcation problem (Bozeman, 2000, p.629). This problem is similar to selecting adequate boundaries for systems in systems engineering. For example, the boundaries of a satellite system can be defined as the satellite as deployed in orbit. The rocket launcher that transports the satellite into space and the ground station that communicates with the satellite are not part of the satellite system but belong to the larger "space mission system" that is required in order to operate the satellite. Other systems are neglected in this model, as they are not considered relevant. In this thesis, the demarcation problem is treated as a modeling problem. A model is used for a purpose. Thus, for the model of a technology, the boundaries of the technology are defined such that the model is adequate for its purpose. A technology model is also restricted to the aspects of a technology that are important for the purpose of the model.

At this point, the general and specific technology definitions can be related. Technology in the context of heritage technologies was defined as a set of capabilities, the artifact's design, and optionally instances of the artifact. All elements of the set are general technologies. As each of the elements is a technology in general, the set of technologies is also a technology in general. Hence, the specific technology definition for heritage technologies has been grounded in the general technology definition.

2.1.5 Technological Capability

For finding an adequate definition for "capability" in this thesis, the starting point is the literature on capabilities. Regarding dictionary definitions, a "capability" according to Fowler and Fowler (1995) is:

1. The power or ability to do something
   1.1 The extent of someone's or something's ability: 'the job is beyond my capabilities'
   1.2 A facility on a computer for performing a specified task: 'a graphics capability'
   1.3 Forces or resources giving a country the ability to undertake a particular kind of military action: 'their nuclear weapons capability'

Alternatively the Merriam- Webster dictionary lists the following definitions (Merriam-Webster Inc., 2004):

1. The quality or state of being capable; also : ability
2. A feature or faculty capable of development : potentiality
3. The facility or potential for an indicated use or deployment <the capability of a metal to be fused> <nuclear capability>

These definitions can be separated into two categories: Capability as an *ability* and capability as a *potentiality*. An ability can be understood as an attribute of an agent that "can" perform an action. Maier (2014) elaborates on the notion of "ability". According to him, an ability can be understood as a specific form of "powers". Powers are properties that "(i) are possessed by agents and (ii) are typically expressed by the modal auxiliary 'can'" (Maier, 2014). A powers is only an ability "just in case it relates an agent to an action." (Maier, 2014, Section 1.2) Hence, abilities are a subset of powers, as depicted in Fig. 2-6.

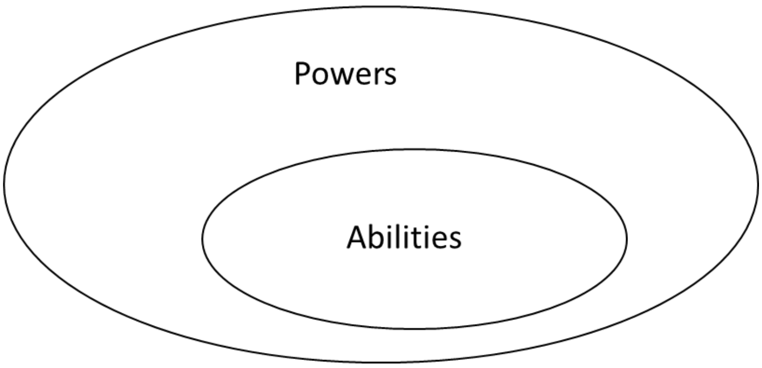


Fig. 2-6: Capability defined as an ability which is a subset of powers

Typical actions are speaking and walking, whereas understanding is typically not. Thus, to understand French is a power, whereas speaking French is an ability. Note that commonly an agent is ascribed some form of decision-making power. In this thesis, the notion of "agent" is used in the widest sense. An artifact that performs a function is categorized as an agent as well as groups and organizations. Groups and organizations can have the status of "agents" and they are capable of collective actions (Roth, 2011). This generous interpretation facilitates the later treatment of capabilities. In the following, "ability" and "capability" are in general used interchangeably. If "capability" is used in the sense of potentiality, this will be specifically indicated.

Definition: Capability

The attribute of an agent which can perform an action.

An ability has a more or less defined object on which the ability acts upon. A person running uses its body to run. A piano player needs a piano to play piano. The relationship between an agent, ability, and object of ability is depicted in Fig. 2-7.

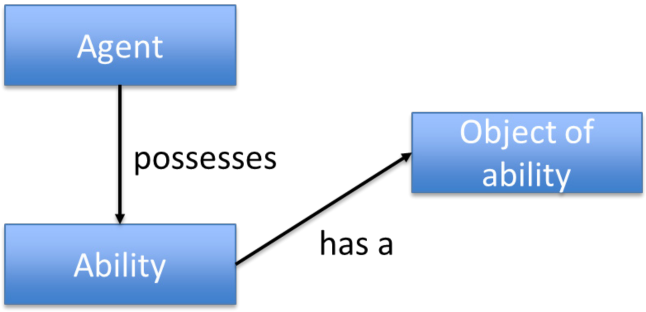


Fig. 2-7: Relationship between actor, ability, and object of ability

A key question with respect to the object(s) of an ability is whether or not they need to be present for claiming an ability to exist. This question leads to the distinction between specific and general abilities. For example, a piano player sits in front of the piano and has all prerequisites for playing the piano. A piano player in such a situation has the *specific* ability to play the piano. A specific ability is bound to a specific context (Vetter, 2015, p.127).

Definition: Specific ability

A specific ability is an ability that is bound to specific external circumstances to exist.

The piano player that is able to play the piano in a given context does not necessarily have the ability to play the piano in a different context. In many cases specific abilities are volatile. A piano player does not sit in front of a piano all the time. A country with the ability to defend itself is not always fully mobilized. A less volatile definition of ability is one which is independent of its context. It is independent in the sense of: If the context would be adequate, the action can be performed. Such a definition of ability is independent of its context (Vetter, 2015, p.127). A piano player who is away from a piano still has the ability to play the piano. Such a piano player has *the general* ability to play the piano.

Definition: General ability

A general ability is an ability that does not depend on external circumstances to exist.

This definition of ability presupposes that abilities are present, even without the external circumstances in which the action can be performed. Such a player lacks the specific ability to play the piano, as not all prerequisites for playing the piano are present, for example the piano at first place.[11]

This distinction between specific and general ability is important in how capabilities are treated in this thesis. Let's assume an organization has all the resources to develop a certain system. Such an organization has the specific ability to develop the system. For assessing the specific ability of the organization, it would be necessary to assess the presence of each of the external circumstances that allows for the development of the system such as the supply chain. Such an analysis is quite extensive and can only be done with respect to a short time horizon (days, weeks, months), as many factors are frequently changing. By contrast, for assessing general ability, it is not necessary to analyze the existence of

[11] The following example illustrates the difference between these two types of abilities. There are cases where a specific ability is present but the general ability is not. Maier (2014, Section 2.2) illustrates this by the case of a golf player who accidentally sinks a difficult put (Honoré, 1964, pp.466-468). Such a case would qualify as a case of the specific ability "sink a difficult put", as the action was actually performed by the golfer. However, it would not count as a case of general ability, as a sense of robustness and control is missing. Actually performing the action is a sufficient condition for a specific ability but is not sufficient for a general ability.

each and every external factor. It is sufficient to assess if these external factors could *in principle* be present. Such an analysis is oriented towards a longer time horizon of months to years.

As the focus of this thesis is in assisting long-term decision making for technologies and technological capabilities, opposed to short-term issues such as dynamic resource allocation and logistics, "capability" is used in the following in the sense of "general ability". For example, a firm that temporarily runs out of material needed for manufacturing a product has lost its specific ability to manufacture the product but retains its general ability to manufacture the product.

The second type of "capability" is that of a potentiality as in definition 2 from Merriam-Webster Inc. (2004). Potentiality can be understood as the ability to acquire an ability.

Definition: Potentiality [12]

"Potentiality" is the ability of an agent to acquire an ability.

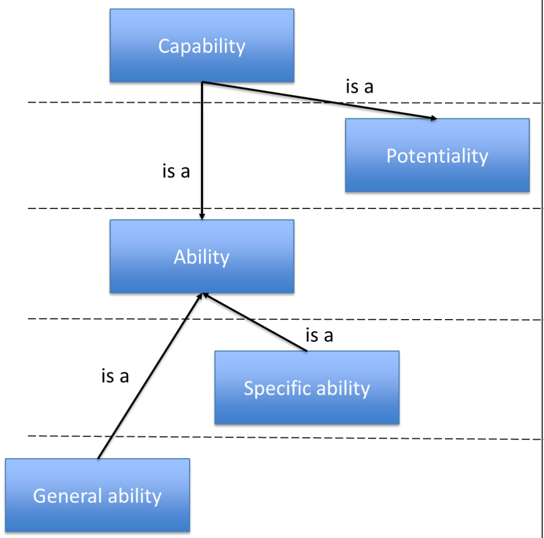
Capability in terms of ability is defined with respect to an existing ability and capability in terms of potentiality with respect to an ability that can exist in the future.

For example, a company that is manufacturing gasoline cars may have the potentiality to manufacture electric cars if they acquire the necessary manufacturing technology. In this case "manufacture electric cars" is the future ability and "acquire manufacturing technology" the necessary acquisition step to develop the ability. By definition, the action associated with a potentiality (manufacture electric cars) cannot be performed now. Potentiality is important, as decision-makers are often not interested in what an organization is capable of doing today but what it is capable of doing in the future.

Note that one of the main challenges in measuring capabilities is that they are not directly observable. A general ability is by its very nature not directly observable. It is only the action that is observable. The crucial question is, what can be considered as evidence that a capability exists. The literature provides a hint: A capability is often associated with a "normal" performance (Honoré, 1964, p.468), i.e. the performance given nominal circumstances. A performance is considered "normal" if it has already been repeatedly performed by an agent. The question is then, how past actions can demonstrate that future actions of the same kind can be performed. To answer this question, two aspects need to be taken into consideration. First, each past action has to comply with some performance criteria that are considered "normal". It is therefore necessary to define what is considered a "normal" performance. Defining conditions for "normal" include criteria for how repetitions are taken into consideration. An action performed several times is better than an action performed once. Second, each past action has taken place in a specific context. Hence, some criteria for what is considered a nominal context has to be defined. By assessing these two aspects, it can be inferred if a capability exists.

Fig. 2-8 shows the relationships between the concepts capability, ability, and potentiality as they are defined in this thesis, their relationships, and how their existence can be demonstrated in a systems engineering context.

[12] This definition of potentiality is similar to the notion of "iterated potentiality" from Vetter (2010, pp.81-84) and Vetter (2015, pp.158-161).



Definition	Approaches to demonstrate existence
Ability of an agent to acquire an ability	- Demonstration that acquisition steps can be undertaken. - Demonstration that similar acquisition steps have been undertaken in the past. - Similar actions have been or are performed.
Power to perform an action	
Ability that depends on external circumstances.	- Demonstration(s) in a specific context.
Ability that is independent of external circumstances.	- Demonstration that action can be performed in different contexts. - Demonstration of similar actions

Fig. 2-8: Taxonomy for ability, definitions and approaches to demonstrate their existence

Up to this point I have not distinguished between capabilities pertaining to specific types of agents. In this thesis, I am particularly interested in capabilities of organizations in general and capabilities of organizations associated with technologies in particular.

> **Definition: Organizational capability**
>
> An organizational capability is a capability of an organization.

An example for an organizational capability is to recruit and manage human resources. Another typical organizational capability is to conduct research and development.

It is useful to introduce another notion of capability that focuses on the technology that is the object of a capability instead of an organization. The "object" of a capability is the thing that is used, created, or modified by a capability. Such technology-specific capabilities are called "technological capability". Technological capabilities were introduced in Section 1.2. A technological capability is always related to a technology that is object of that capability and an organization being the agent to whom the capability belongs. For example, Airbus developing the A380 has the technological capability to develop the A380. Airbus is the agent and the A380 the object of the capability. An airline has the technological capability to operate the A380.

Another aspect of technological capabilities is that they can be considered as general technologies. This allows for aggregating technological capabilities and other technologies into a higher-level technology. For example, the A380 as a technology is not only a specific instance of the A380 but could be understood as the design of the aircraft along with all the technological capabilities that are needed for its development and manufacturing. I argue that the technology definition I have introduced in Section 2.1.4 can be extended to capabilities. By taking one of the oldest technological capabilities, "make a wooden spear", it is tested if this capability can be represented as a *method, system, process, and knowledge or a combination of these.*

- Knowledge (Pruetz and Bertolani, 2007):
  - How to identify and collect straight limbs that can be used as a spear.
  - How to break the limb and stripping them of leaves and side-branches.
  - How to use trimming to sharpen the limb.
- Method:
  - How the steps are combined into a process to achieve the desired outcome of a wooden spear.

The technological capability of Airbus to develop the A380 can be, in principle, represented as a collection of *methods, systems, processes, and knowledge,* although it would be a vastly larger collection than for creating a wooden spear. One of the challenges is to delineate the boundaries for such a complex capability. At the most fundamental level, it can be argued that the capability is mainly embodied in the various business units of Airbus and its supply chain. The specific technological capabilities are the development capabilities of Airbus and its suppliers along with the manufacturing capabilities of Airbus and its suppliers.

Further theoretical background regarding capabilities will be gradually developed in subsequent sections. In Section 2.3 the existing management literature is consulted that has treated capabilities extensively. A specific framework for technological capabilities is developed in Chapter 3.2.

To summarize, a capability is the power to perform an action. A capability is defined two-fold: As a general ability, i.e. an ability that exists even if the action cannot be performed immediately but could be performed once all preconditions are satisfied and "capability" as a potentiality, i.e. the ability to acquire an ability. An organizational capability is an ability of an organization and a technological capability an organizational capability that has a technology as its object.

2.1.6 System – Technology Relationship

At this point I have defined the notions of "system" and "general technology". How are the two related to each other? First, a technology is not necessarily a system and vice versa. The Solar System is certainly not a technology. However, technical systems can be considered a subset of general technologies. A car is certainly a technical system as well as a technology. The opposite is not true. A toothpick is a technology but it is not a technical system as it only consists of one element.

If the general technology definition from Section 2.1.4 is used, the definition includes the notion of "system". Furthermore, it includes the notion of "function". Hence, the general technology definition subsumes the definition of a system.

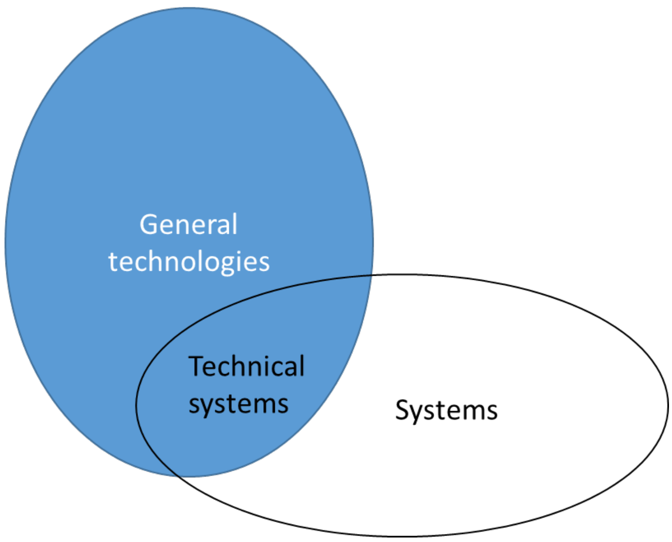


Fig. 2-9: Venn diagram showing the sets for technologies, systems, and technical systems. Technical systems are the set of elements which are both technologies and systems.

Note that in the following, instead of "technical systems", the shorter term "system" is used. Furthermore, note that within the space domain, a "system" is often used as a synonym for "product". A "technology" is often considered an element of a product.

2.1.7 Verification, Validation, Testing, and Operation

In the following, definitions for verification, validation, testing, and operation from systems engineering references are presented.

Verification

System verification ensures that the system, its elements, and its interfaces conform to their requirements. In other words, verification ensures that "you built it right." (Haskins, Forsberg, & Krueger, 2007, p.126). Table 2-3 shows the various approaches to verification in two major systems engineering publications: The INCOSE Systems Engineering Handbook and the NASA Systems Engineering Handbook (Haskins et al., 2007; Kapurch, 2010). "Analysis" is basically the use of calculations, estimations, modeling, and simulation. "Demonstration" can be understood as showing the customer that the system works. It is a rather informal approach to verification. "Testing" is more formal in the sense that good testing involves a careful testing setup, error estimation, and careful control of testing conditions. "Certification" is the confirmation that a system has certain characteristics. Commonly, certification is conducted by certification bodies. Certification experts are assessing the compliance with the certification requirements.

Table 2-3: Types of verification

INCOSE SE Handbook (Haskins et al., 2007, p.128)	NASA SE Handbook (Kapurch, 2010, p.86)
Analysis	Analysis
Demonstration	Demonstration
Inspection	Inspection
Test	Test
Certification	

Furthermore, ESA (2008) lists "experiments" as a verification approach at low TRLs. Kass (2008) elaborates on the difference between a "test" and an "experiment". Whereas a test is more related to verifying a requirement, an experiment is concerned with the feasibility of a technology. Thus, experiments are more related to TRLs 1-4, as ESA (2008, p.7) indicates.

The ESA TRL Handbook lists the following aspects for the quality of verification (ESA, 2008, p.5):

- *Similarity of testing environment:* "The environment in which testing of the new technology has occurred, and the degree to which that environment is similar to, or the same as the environment in which technology will be used in operations."
- *Surrounding system:* "The degree of similarity of test articles incorporating the new technology to an actual systems application."
- *Performance in environment:* "The degree to which required levels of performance are achieved, and in the needed environment."

Hence, the closer the environment in which testing occurs resembles the actual environment, the better. "Environment" denotes not only the natural environment but also the system into which the technology is integrated.

Validation

According to Haskins et al. (2007, p.133), the "purpose of the Validation Process is to provide objective evidence that the services provided by a system when in use comply with stakeholders' requirements, achieving its intended use in its intended operational environment." System validation confirms that the system, as built (or as planned to be built), satisfies the stakeholders' needs. Validation ensures the requirements and the system implementation provide the right solution to the customer's problem. In other words, it confirms that "you built the right thing". (Haskins et al., 2007, p.136)

Testing

Haskins et al. (2007, pp.128-129) list the following types of tests:

- *Development test:* “Conducted on new items to demonstrate proof of concept or feasibility.”
- *Qualification test:* “Tests are conducted to prove the design on the first article produced, has a predetermined margin above expected operating conditions, for instance by using elevated environmental conditions for hardware.”
- *Acceptance test:* “Conducted prior to transition such that the customer can decide that the system is ready to change ownership status from supplier to acquirer.”
- *Operational test:* “Conducted to verify that the item meets its specification requirements when subjected to the actual operational environment.”

Putting these types of tests into the context of TRL, the most relevant tests are development and qualification tests as they pertain to the development of a new technology. Qualification testing is usually performed for qualifying the *design* of a particular system. Acceptance tests are usually conducted on a system *instance*.

Operation

System operations is an important phase for getting verification and validation data. There are many aerospace examples where only operations revealed design errors or validation errors. Examples include:

- *Reaction wheels for OCO-2 mission:* A GEO communication satellite mission revealed the design error before OCO-2 was launched (GAO, 2015)
- *Boeing Dreamliner battery and electronics incident:* Lithium-ion batteries caught fire during operations in five different cases leading to a temporal grounding of the Dreamliner by the Federal Aviation Administration (FAA).

There are several sources for continued verification, validation, and testing activities after the system has been put into service. These are error corrections, for example due to teething problems and bug fixes. “Teething problems” are usually errors that are minor, for example small manufacturing defects that do not compromise the safety of the system. The Boeing Dreamliner incident is not a teething problem, as the error was serious, impacting the safety of the system. Requirements changes due to contextual changes are another source of continued verification, validation, and testing after the system has entered operations. Sources are for example new regulations, standards, and technologies. Examples are the mandatory use of seat belts in cars. The various sources of modifications are introduced in Section 3.2.3.

2.2 Systems Engineering

2.2.1 Reuse

A concept closely related to heritage technologies is reuse. Reuse can be understood as the use of something in a different context than the one for which it was originally intended (Hein and Brandstätter, 2010). The use of a heritage technology can therefore be understood as a form of reuse. According to Ong et al., (2008) several types of reuse are possible during the systems development process.

- *End-of-life product reuse (Type I):* Components and materials from a used product are reused or recycled. This is reuse of product instances.
- *Reuse of existing manufacturing resources (Type II):* The equipment used for manufacturing a product can be reused for manufacturing a different product.
- *Reuse of product information and design knowledge (Type III):* Product data such as geometric models, circuit drawings, etc. along with their documentation is reused.

According to Sivaloganathan and Shahin (1999), “design reuse” “is aimed at maximizing the value of design efforts by reusing *successful* past design information in whole or in part for future designs.” However, they do not explain what “successful” actually means.

Busby (1999) conducted an empirical analysis of factors that inhibit the design reuse of process plants and production equipment. The results are based on a number of interviews in two companies supplying process plants and production equipment. He concludes that the difficulties associated with reuse are multiple:

- *Engineering:* For example, integral design makes it difficult to trace the design rationale;
- *Cognitive*: For example, preferences of the current designer that differ from the ones of the original designer;
- *Motivational:* For example, designers want to innovate;
- *Organizational:* For example, existing designs are considered deficient;
- *Environmental*: For example, different local standards to which previous designs do not adhere to, interface incompatibility with client systems, rapid technology change, etc.

Fletcher and Gu (2005) present a state of the art overview of product design reuse and current and future research areas. They list the following challenges to design reuse:

- *Indexing and retrieval problems*: Difficulty to find relevant designs;
- *Misunderstanding:* Difficulty to understand prior designs;
- *Modification issues:* New technologies might render an existing design obsolete, as the new technology cannot be integrated into the existing design. The effort of modifying an existing design can also be underestimated;
- *Satisfying tendencies:* The designer does no longer search for innovative designs but is fixated on an existing design;
- *Organizational matters:* Lack of incentives for design reuse or designs are not available for reuse.

Within the software engineering reuse literature, Garlan et al. (2009, 1995) argue that despite extensive efforts in research and industry to reuse software, reuse is still difficult. One of the reasons why software reuse is difficult is that implicit assumptions about the software's context do not match the new context in which it is reused. This mismatch of assumptions about the context is called "architectural mismatch". This concept seems to be related to the environmental mismatches mentioned by Busby (1999) such as incompatibilities with local standards and interfaces.

The literature on design reuse provides important clues for properly managing heritage technologies. First, the context-sensitivity of designs has been highlighted by both, the hardware and software literature. Context-sensitivity can take several forms such as constraints imposed by other components (Busby, 1999), rationale for design such as justifications, alternatives, and trade-offs (Busby, 1999), assumptions about the systems the component is operating in (Garlan et al., 2009, 1995), and the goal for which the design was optimized (Busby, 1999).

There are also gaps in the reuse literature with respect to heritage technologies. There seem to be only few publications that deal with the quality of reused artifacts. Mohagheghi and Conradi (2004) analyse the defect-density in reused software components. They also study if reused components are stable and do not need to be modified. They conclude that reused software components exhibit a lower defect-density and higher stability. Similar literature in other domains seems to be missing.

2.2.2 Commonality

Boas (2008, p.12) defines „commonality" as "the reuse and sharing of assets such as components, processes, technologies, interfaces, and/or infrastructure, across a product family. A product family is defined as "products that share a common platform but have specific features and functionality required by different sets of customers." (Utterback & Meyer, 1993, p.30) To give an example, platforms in the automotive industry enable rapid customization of cars to address different market segments. An overview of the extensive product platform literature is given in Jiao et al. (2007). Fixson (2007) presents a comprehensive overview of the literature on commonality. He counts 76 publications on commonality between 1960 and 2005. Most of these publications deal with mathematical models of commonality. Commonality is often considered as a way to reduce the overall cost of the product family by reducing overall development effort and risk, reducing fixed recurring and variable recurring cost, decreasing operational risk of the portfolio, and reducing the number of dedicated spares required for system operation (Hofstetter, 2009, pp.27-28).

For this thesis, two aspects of the commonality literature are relevant:

- Empirical analyses of how commonality changes over the product lifecycle (Boas, 2008; Cameron, 2011);
- System architecting / System engineering methodologies for assessing commonality (Aliakbargolkar et al., 2013).

To start with the empirical analyses, Boas (2008) uses data from the Joint Strike Fighter program and other large engineering programs, in order to assess, how the degree of commonality within a product family changes over time. He observes that commonality tends to decrease over time. Thus, at a later stage of the program, product family members had less parts in common with other members than initially intended. This phenomenon is called “divergence” and is illustrated in Fig. 2-10. Point A represents the result of the initial product family planning effort in the early phases. The level of commonality is optimistic, as many factors that may impede the level of commonality are still unknown. Due to increased knowledge and reduced uncertainty, commonality levels fall from that point onwards. Point B represents a point where efforts are made to reestablish commonality. Divergence dilutes the initially intended benefits of commonality.

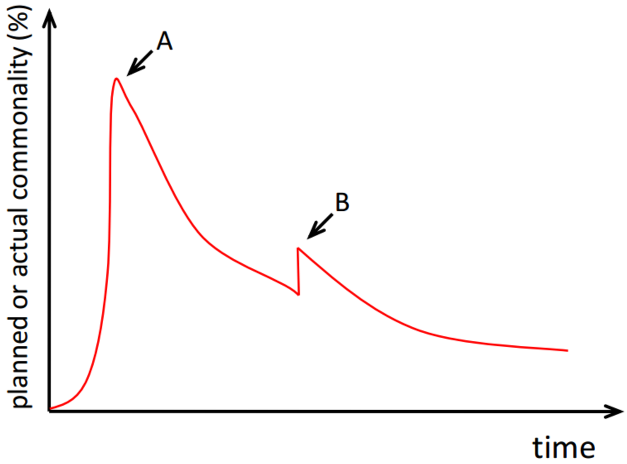


Fig. 2-10: Illustration of divergence from (Boas, 2008, p.127)

Boas goes on to investigate potential reasons for divergence (Boas, 2008, pp.129-135):

- Changing requirements;
- Learning in development, production, and operations;
- Availability of new technologies;
- Component obsolescence.

Divergence is relevant for heritage technologies, as the actual level of heritage technologies in a system can be significantly lower than initially anticipated, as the Mars Observer case has shown (Lambright, 2014, pp.101-102). Unanticipated modifications and component obsolescence are also factors that have been reported for heritage technologies, as mentioned in Section 1.4.

Cameron (2011) provides some empirical evidence for the link between divergence and cost growth. Cost growth from decreased commonality can be incurred by reduced inventory benefits, higher quality expenses, and additional manufacturing coordination. Furthermore, he proposes a framework for making commonality cost decisions.

Regarding systems architecting / systems engineering methodologies for assessing commonality, Hofstetter (2009) introduces a system architecting methodology for creating product portfolios, taking commonality into consideration. He defines different commonality types, as shown in Fig. 2-11.

Commonality type

Common feature	Functional commonality	Operational commonality	Technology commonality	Design commonality	System reuse	Variable functionality	Implementation commonality
Internal functions	X	X	X	X	X		
Operating processes		X	X	X	X		
Technology choices			X	X	X		
System form				X	X	X	X
System instance					X	X	

Fig. 2-11: Commonality types and their common features taken from Hofstetter (2009)

Functional commonality is the "identity in system internal functionality between two systems…" (Hofstetter, 2009, p.63) Hofstetter distinguishes between internal functionality and externally delivered functionality. Internal functionality is "what the system does specifically". (Hofstetter, 2009, p.39) External functionality delivers value to stakeholders. A car and a bicycle are both used for transportation. However, both function in different ways. Thus, their external functionality is identical but they have different internal functionalities.

Operational commonality "requires identity in the operating processes between two systems in addition to identity in internal functionality." (Hofstetter, 2009, p.64) Hofsetter gives the example of a car, which can be operated in a standardized way, independently of the underlying technology, such as internal combustion, hybrid, and electric.

Technology commonality "requires identity in the technology choices associated with the internal functions in addition to identity of the internal functions between two systems." (Hofstetter, 2009, p.64) The way Hofstetter uses the notion of "technology" corresponds to "working structure" in Pahl et al. (2007), as it refers to the working principles of the system, their mapping to system functions, geometry, and materials. It is also related to Polanyi's concept of "operational principle", as presented in Vincenti (1990, p.209). The choice of technology does not yet determine the exact values for the design parameters of the system. Only with design commonality, identity in "form structure and similarity in design parameter values" are required in addition to functional, operational, and technology commonality.

System reuse is the use of the same system instance for the same external functionality. The Space Shuttle Orbiter was reused several times for the external functionality of transporting payloads into space.

"Variable functionality" is the use of the same system instance for different purposes. The Skylab "wet workshop" concept was intended to reuse the Saturn V S-IVB upper stage in orbit as the habitable volume of the Skylab space station.

"Implementation commonality" is similar to variable functionality, but the same system instance is not necessarily used for different purposes. The actually implemented Skylab space station was based on the S-IVB upper stage, where the tank was converted into a habitable volume without being used as a rocket stage.

The last three forms of commonality can be interpreted as reuse on the instance level (system reuse, variable functionality) and type level (implementation commonality). The typology also takes the functional aspect of reuse into account, which is mostly neglected in the reuse literature. For system reuse, the external functionality does not change, whereas it changes for variable functionality and implementation commonality.

The commonality types form a hierarchy, as shown in Fig. 2-12 Functional commonality is a precondition for all other commonality types. Technological commonality is a precondition for design commonality and system reuse. For technology commonality to be present, operational and functional commonality have to be present.

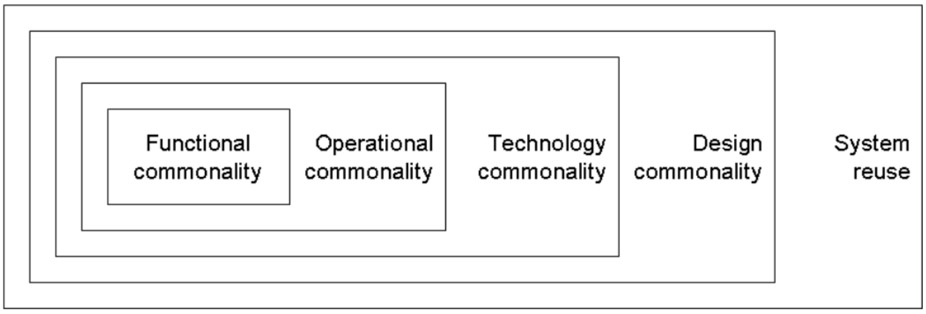


Fig. 2-12: A Venn diagram for commonality types taken from Hofstetter (2009, p.66)

Although the commonality literature seems to implicitly assume that commonal elements work as intended, this cannot be taken for granted. There is evidence that commonal elements increase the risk that an error in such an element has an adverse impact on the whole product family. However, to the author's knowledge, the literature has not yet dealt with these negative effects of commonality. Hence, the aspect of successful VVTO history has not yet been addressed. A heritage technology assessment methodology could therefore also contribute to the current literature and practice of commonality.

To conclude, the commonality literature provides important input to the assessment of heritage technologies such as the notion of divergence and a taxonomy for commonality types.

2.2.3 Technology Infusion

In this section, a form of technology change is introduced where the design of a new technology is integrated into an existing system design. This process is called "technology infusion". Whereas technology infusion is dealing with changing a design and to manufacture the changed system as a whole, it can be distinguished from retrofitting, which changes an existing system instance. Technology infusion occurs when a new technology promises to add value to an existing system design, for example the addition of more fuel-efficient engines to an aircraft. The literature on technology infusion is relevant for heritage technologies, as heritage technologies are also often subject to technology infusion.

Alzaharnah, Seering, & Yang (2012) give a concise overview of the existing literature on technology infusion, focusing on approaches based on the design structure matrix (DSM). Two key publications in this area are Smaling and de Weck (2007) and Suh et al. (2010). They present methodologies for assessing the risks and opportunities of technology infusion. The risks and opportunities are both represented in the form of utility curves. Smaling and de Weck (2007) use an automotive case study for validating their methodology, whereas Suh et al. (2010) use printers as a case study.

At the core of the methodology is a representation of the system architecture in the form of a DSM which takes physical, energy, information, and mass flow interactions between components into account (Smaling & de Weck, 2007, p.8). From the initial, existing system architecture, a new system architecture with the infused technology is derived. By comparing the new with the old DSM, a Delta-DSM is created, which only includes the changes made to the components and relationships between the new and the old DSM.

Suh et al. (2010) build on Smaling and de Weck (2007) but instead of using a utility-based risk-benefit assessment approach, a probabilistic risk-return curve is derived. The risk and the return are represented in the form of a net present value (NPV) analysis.

One limitation of the methodologies presented by Smaling and de Weck (2007) and Suh et al. (2010) is the lack of an empirical validation for the technology invasiveness metric which is used for quantifying design change. Such a validation would be helpful, as the different change types can each only be weighted collectively. However, some changes to a component or relationship might have a much higher impact on the overall system than others. This problem is addressed by the change propagation literature such as Clarkson et al. (2004).

Another limitation is that it is not clear for what the changes represented by the Delta-DSM actually stand for. The changes may stand for the effort to develop and testing changed interactions between components. However, changes in interactions have also an effect on the organizational architecture, as Henderson and Clark (1990) demonstrated. In such a case, the impact is less on engineering effort but rather on the risk that the organization might not be able to cope with the architectural changes.

In the context of heritage technologies, the technology infusion literature provides a useful basis for assessing changes to heritage design, based on architectural changes. However, the modeling approach and the technology infusion metric need to be aligned with measurement theory first.

2.2.4 Change Propagation

The literature on change propagation is relevant for heritage assessment, as changes to the system design lead to a decrease in heritage. The change propagation literature may provide insights into change mechanisms and may allow for predicting changes. The research on change propagation falls into two categories. One stream of research analyses actual change data from real world projects a posteriori such as Giffin and de Weck, (2009) and Siddiqi et al. (2011). The other stream of research develops a priori change assessment methodologies such as Clarkson et al. (2004) and Fricke and Schulz (2005).

Giffin and de Weck (2009) analyse change propagation in a complex sensor network using a graph theoretical approach. The data set consists of 41,500 change requests during the development of the network over 8 years. They discovered that some changes stay local but others "ripple" through the design and result in a cascade of changes. Certain components are found to be the source of cascading changes and are called "mulitpliers". Other areas seem to stop changes to propagate and are called "reflectors". Siddiqi et al. (2011) analyze data from an offshore infrastructure to explore the frequency of change requests over the system's lifecycle and their effect on cost.

The literature on a priori change assessment proposes methodologies for assessing the change propagation before changes happen. Clarkson et al. (2004) present a DSM-based representation of a system design, accompanied by a change likelihood DSM and a change impact DSM. By multiplying likelihood and impact for each potential component change that may affect another component, risk values for components are calculated. The risk values are not only calculated for direct change propagation between components but also indirect change propagation where changing a component changes another component which in turn propagates the change to yet another component and so on. Fricke and Schulz (2005) present four characteristics that systems need in order to react to a changing market place, environment, and evolving technologies that are integrated in them: flexibility, agility, robustness, and adaptability. They present design principles to enable these characterisics in systems. Clarkson et al. (2004) propose a compilation of design principles that can be used to address specific aspects of changeability. Both publications do not address how far changes are actually impacting the heritage of a system or technology.

Another stream of literature that is implicitly relevant for change propagation is about the degree distribution in complex systems. The degree is a measure for how many connections a component has with other components. The higher the degree, the more connections the component has. A high degree of a component implies that a change made to this component potentially affects a large number of other components. The degree distribution is the distribution of the degrees of components within a system. Sosa et al. (2011) assess the degree distribution of 105 systems. They conclude that the degree distribution follows a power law distribution. This means that in many systems, a small number of components has a lot of connections with other components. Such components are called "hubs". They find evidence that there is an optimal number of hubs with respect to system quality. This research is important with respect to heritage technologies, as it implies that some changes made to a few components in a system may have a significantly larger effect on its heritage than changes made to others.

2.2.5 Verification, Validation, and Testing

For this thesis, the literature on verification, validation, and testing in the early phases of development is of interest. More specifically, the relationship between verification, validation, testing and a technology's maturity.

The most prominent instrument for ranking technologies according to their maturity / readiness is TRL. The TRL has been introduced in order to rank technologies according to their level of verification, validation, and testing (ESA, 2008; Mankins, 1995). Each level ascribes certain verification, validation, and testing criteria. Kapurch (2010, p.297) presents a systematic procedure for assigning a TRL to a technology, as shown in Fig. 2-13. A particularly interesting step is the second from the top. If an "identical unit has been flown in a *different* configuration / system architecture" (emphasis added), the TRL drops by default to TRL 5 until a more detailed evaluation takes place. This step explicitly takes changes to the system architecture into account.

For the heritage assessment methodology presented in Chapter 5 this methodology is used for determining the TRL. Note that Olechowski et al. (2015) and (interview I6) remark that in practice this procedure is not necessarily followed.

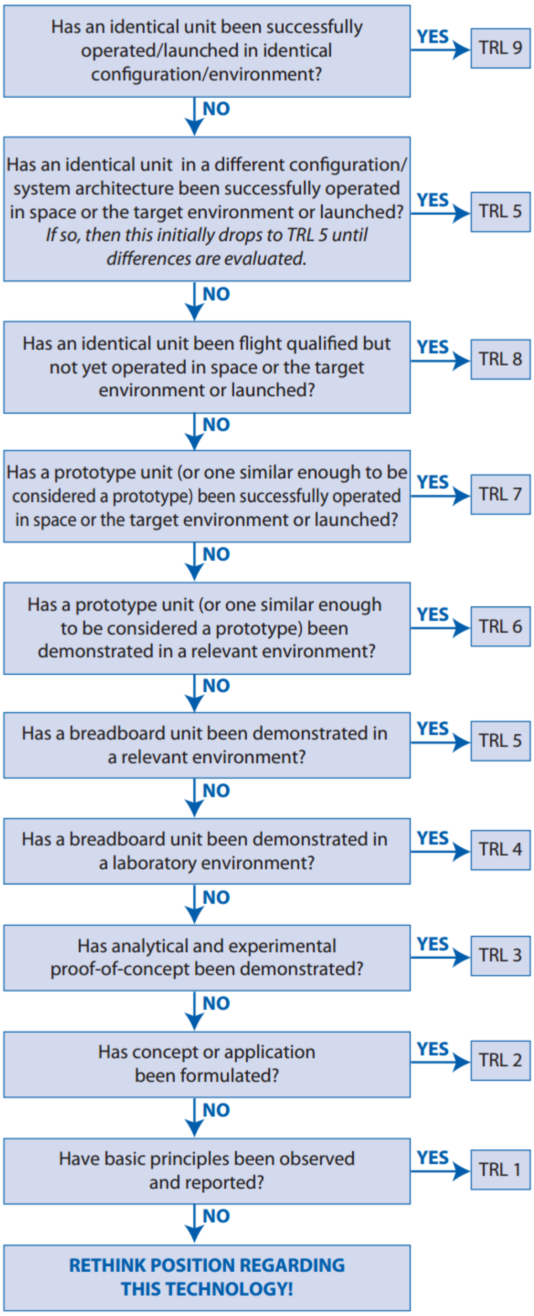


Fig. 2-13: NASA Technology Maturity Assessment process taken from Kapurch (2010, p.297)

Tetlay and John (2009) argue that the TRL is a combined maturity and readiness metric. According to their definition of "maturity" and "readiness", maturity is related to the verification of a system, whereas readiness is related to validation.[13] Tetlay and John (2009) interpret readiness as "ready for use", which depends on the context in which the system is operated. Therefore, "system readiness is context dependent." (Tetlay & John, 2009, p.3) Verification thus assesses the maturity of the system, whereas validation assesses the readiness of a system. System readiness is

[13] Note that this definition of "maturity" is different from the maturity definition given in the technology management literature, where a mature technology is a technology whose performance parameters became difficult to improve. Within the management literature, a technology has reached maturity at the plateau of the technology S-curve (Foster, 1986).

considered as a binary property: Either the system is ready or not. System maturity is considered as a gradual property. Using the classic TRL, TRL 8 and 9 would be related to readiness, as the actual system is flight-proven. TRLs below 8 are dealing with prototypes which are used for verification.

One limitation of Tetlay & John's concept of maturity and readiness is that it seems to be tightly related to the V-model of system development, which is still prevalent in the aerospace and defense sector. Agile development processes which emerged in software engineering initiate validation by prototyping as early as possible. Examples for agile processes include Scrum, extreme programming, the spiral model, and incremental prototyping. However, even for these processes, readiness can be used as "ready for use" in the narrow sense of a system that is delivered to the customer to be operated and deliver value. This is different from the use of a prototype, which is developed for improving the system during development.

TRL is often used without a clear reference to what it measures. In many cases, it is referred to as a substitute for programmatic and operational risk. However, it is also used as a proxy for development cost. Dubos et al. (2008) explore the quantitative relationships between TRL and cost / schedule slippage. They conclude that the lower the TRL, the higher the relative schedule slippage. This result has been confirmed by Katz et al. (2015).

Modifications made to a system are not explicitly treated in the TRL literature. The ESA heritage categories provide a way to classify mature systems with respect to a changing operational environment and modifications. In terms of Tetlay & John's framework, the ESA heritage categories are thus addressing the readiness of a system. The ESA heritage categories are used within the European space industry when technologies are already sufficiently mature (interviews I10, I19, I14). As mentioned before, the NASA Systems Engineering Handbook uses TRL directly and initially downgrades a modified system to a TRL of 5 (Kapurch, 2010, p.297).

For the sake of completeness, Nolte (2008) specifically deals with the measurement of technology maturity. Nolte's definition of technology maturity is along the lines of the classic technology S-curve literature. However, he goes on to explore the whole product / system life cycle and its relation to maturity.

To summarize, the most widespread approach for linking a technology's maturity / readiness and verification, validation, and testing is the TRL. The existing literature provides different interpretations of TRL and provides statistical evidence that a lower TRL is associated with higher schedule overruns.

2.3 Strategic Management and Technology Management

As introduced in Section 2.1.5, another important topic with regards to heritage technologies is an organization's capability to develop, modify, manufacture, and operate a system. For example, BMW has the capability to manufacture the i3 electric car. In addition, it has now the capability to change the design and produce derived electric vehicles, based on technologies developed for the i3. The strategic management and technology management literature deals with organizational capabilities, mostly on the firm and on the program / project level. In the following, I provide an overview of the relevant capability literature from these domains.

2.3.1 Resource-based View

The resource-based view of a firm is a concept from the strategic management literature. Strategic management is concerned with the competitiveness of firms. Competitiveness can be influenced by external and internal factors. Fig. 2-14 depicts these two perspectives on competitiveness that are widely known from SWOT analysis (Hill and Westbrook, 1997). SWOT is an abbreviation for strengths, weaknesses, opportunities, and threats. Whereas strengths and weaknesses pertain to factors internal to a firm, opportunities and threats pertain to external factors.

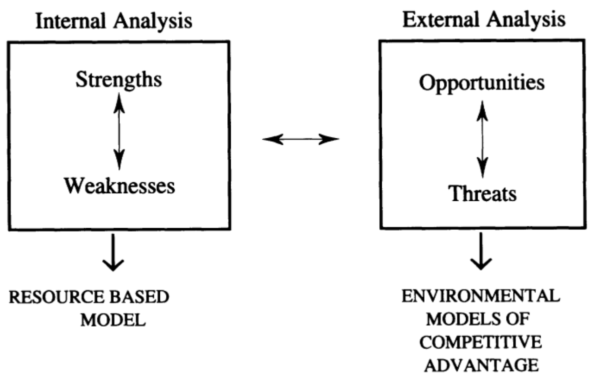


Fig. 2-14: Internal and external perspective on a firm's competitiveness taken from Barney (1991, p.100)

The resource-based view focuses on the internal factors of competitiveness.[14] More specifically, it argues that resources that are valuable, rare, in-imitable, and non-substitutable are an important factor of sustainable competitive advantage (Barney, 1991; Teece et al., 1997, p.517). The four criteria are often abbreviated as VRIN. Resources in this context can be tangible or intangible. Tangible resources can be capital, facilities, IT infrastructure etc. Intangible resources are for example knowledge and skills of personnel. Resources have not received a lot of attention in economics, as especially intangible resources are rather difficult to model, as Wernerfelt (1984, p.171) remarks. Another important aspect of resources that satisfy the VRIN conditions is that they are only transferrable with considerable effort or incompletely. For example, BMW's ability to define requirements for new cars is difficult to transfer, as it is tied to its personnel, organizational structure, IT infrastructure etc. Case studies from technology history confirm this perspective such as in Westrum (2013). The development of the Sidewinder missile, representing a quantum leap in air-to-air missile technology was bound to its unique organizational conditions at China Lake that could not be replicated. Another example is the effort to replicate the success of Silicon Valley at other places in the world. However, none of these efforts seems to have succeeded (Kenney and Burg, 1999; Kenney, 2000).

Resources are sometimes also called "firm-specific assets" (Teece, Pisano, & Shuen, 1997, p.516). Assets are economic resources that can create economic value (O'Sullivan & Sheffrin, 2007, p.272). Barney (1991, p.101) further categorizes "resources" into physical capital resources, human capital resources, and organizational capital resources. Physical capital resources "include the physical technology used in a firm, a firm's plant and equipment, its geographic location, and its access to raw materials." Human capital resources are related to characteristics of individual personnel, such as training, experience, judgment, intelligence, relationships and insights. Organizational capital resources are "a firm's formal reporting structure, its formal and informal planning, controlling, and coordinating systems, as well as informal relations among groups within a firm and between a firm and those in its environment." (Barney, 1991, p.101)

Wernerfelt (1984) is the first seminal publication on the "resource-based view". It presents the concepts of resource - position barrier and resource-product matrices as analogues to entry barrier and growth-share matrices. Both concepts are fundamental to traditional strategic management. A resource – position barrier originates from someone already having a resource. The acquisition of the resource by someone else at a later stage "affects the costs and/or revenues of later acquirers adversely." (Wernerfelt, 1984, p.173) Wernerfelt (1984, p.174) elaborates on the resource – position barrier by using examples for resources such as machine capacity, customer loyalty, production experience, and technological leads. Most of these resources are linked to lower costs, compared to a new entrant. A large machine capacity leads to economies of scale. Production experience leads to learning curve effects.

The resource – product matrix indicates the importance of a resource for a product and vice versa (Wernerfelt, 1984, pp.176-177). It can be used for visualizing patterns of resource development such as sequential entry, exploit and develop, and stepping stones. A sample matrix is shown in Fig. 2-15.

[14] External factors are captured by frameworks such as Porter's five forces analysis: bargaining power of suppliers, threat of substitutes, bargaining power of buyers, threat of new entrants, and industry rivalry (Porter, 2008).

Resource / Market	Production Skills	International Contacts	III	IV	Domestic Contacts
Domestic	X				X
International	X	X			
C		X		X	
D			X		X

Fig. 2-15: Example for a resource – product matrix taken from Wernerfelt (1984, p.177)

As the resource-based view originated from the strategic management literature, its unit of analysis is the firm. A gap exists between the firm-centric view of resources and a more product / system-centric view of resources. For example, the resource – product matrix remains at a product portfolio level, without details on specific product features or technologies. The resources also remain too high-level to inform concrete decision making for a specific product. For making the concept fruitful for decision making in systems engineering, more detail has to be added for modeling specific system lifecycle-related resources such as system development and manufacturing. Furthermore, other aspects are less interesting in this context, such as customer loyalty, as long as they do not translate into features of the system.

2.3.2 Capabilities and Competencies

Within the resource-based view, capabilities and competencies are a form of resource. A literature survey on capabilities and competencies has been presented in Hein et al. (2014). There is no consensus on how far capabilities and competencies differ and both terms are often used interchangeably (Schilling, 2013, p.117).[15] A prevalent concept is "core competency", introduced by Prahalad and Hamel (1990). "Core competencies" are "the company's collective knowledge about how to coordinate diverse production skills and technologies." (Prahalad & Hamel, 1990, p.2) They are vital for the competitive advantage of the company. Three criteria for identifying core competencies are introduced:

- It "provides potential access to a wide variety of markets" (Prahalad & Hamel, 1993, p.7);
- It "should make a significant contribution to the perceived customer benefits of the end product" (Prahalad & Hamel, 1993, p.7);
- It "should be difficult for competitors to imitate." (Prahalad & Hamel, 1993, p.7)

Prahalad and Hamel (1990) stress the importance of cross-cutting activities across business units as an essential element of a core competency. These activities remove thought-barriers of business units and facilitate the development of competencies on a company level. They introduce a matrix for mapping the product portfolio of a company to its core competencies. Recent research by Danilovic and Leisner (2007) and Bonjour, E., & Micaelli (2010) link core competencies to the domain of product design and project management. They use incidence matrices for mapping specific core competencies to a company's project and product portfolio. However, the core competency literature does neither address how low-level competencies aggregate and form core competencies nor does it show a way to elicit core competencies.

Leonard-Barton illustrates how "core capabilities" can also be obstacles in the face of a changing environment (Leonard-Barton, 1992). The notion "core capability" is used by Leonard-Barton as a synonym for "core competencies". The four dimensions of a core capability are shown in Fig. 2-16. As for a core competency, skills and knowledge are an essential element of a core capability. She specifically addresses the challenge of aligning product and process development projects with existing core capabilities.

[15] A further source of confusion is the use of the term "capability" in a systems engineering context, predominantly in the defense sector (Antunes, G., & Borbinha, 2013).

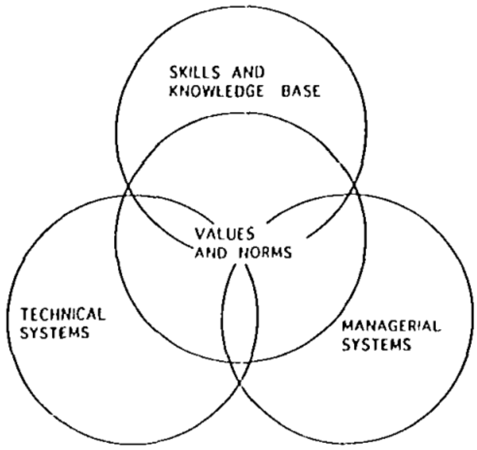


Fig. 2-16: Four dimensions of a core capability taken from Leonard-Barton (1992, p.114)

Over time, core capabilities that have originally contributed to the competitive advantage of a company can lead to a loss of competitive advantage when the environment changes. One source of a loss of competitive advantage is the introduction of a new technology. Tushman and Anderson (1986) present "technological discontinuities" as a source of competency enhancement and destruction. A competence-destroying discontinuity "renders obsolete the expertise required to master the technology that it replaces." (Tushman & Anderson, 1986, p.609) For example, the competency to develop and manufacture vacuum tubes was rendered obsolete by the introduction of integrated circuits. Competency-enhancing discontinuity "builds on the know-how embodied in the technology that it replaces." (Tushman & Anderson, 1986, p.609)

A second prevalent concept is the resource – process – value perspective on "capabilities" introduced by Christensen and Overdorf (2000) and Christensen and Kaufman (2006). The three capability elements "resource", "process", and "value" are introduced in the following:

- *Resources:* tangible (people, equipment, technologies, cash etc.) and intangible (product designs, information, brands, supplier relationships etc.).
- *Processes:* "the patterns of interaction, coordination, communication, and decision making employees use to transform resources into products and services of greater worth." (Christensen & Overdorf, 2000, p.2) Formal (explicitly defined and documented) and informal processes (e.g. routines) are distinguished. Christensen and Kaufman (2006) refer to Garvin (1998) for a comprehensive overview of process types, shown in Table 2-4.

Table 2-4: Organizational processes framework according to Garvin (1998)

	Work prcesses	**Behavioral processes**	**Change processes**
Definition	Sequences of activities that transform inputs into outputs	Widely shared patterns of behavior and ways of acting/interacting	Sequences of events over time
Role	Accomplish the work of the organization	Infuse and shape the way work is conducted by influencing how individuals and groups behave	Alter the scale, character, and identity of the organization
Major categories	Operational and administrative	Individual and interpersonal	Autonomous and induced, incremental and revolutionary
Examples	New product development, order fulfillment, strategic planning	Decision making, communication, organizational learning	Creation, growth, transformation, decline

- *Values:* “standards by which employees set priorities that enable them to judge whether an order is attractive or unattractive, whether an idea for a new product is attractive or marginal…” (Christensen and Overdorf, 2000, p.2)

Capabilities define what an organization can or cannot do. Christensen and Overdorf (2000) also point out that capabilities evolve along with the maturity of organizations. They argue that capabilities of start-ups are dominated by the resource component, mostly people. A few people leaving the organization can lead to its collapse. A mature organization by contrast draws its capabilities mainly from its processes and values. Processes are defined when tasks are recurring. Values set priorities in decision making. A shortcoming of this capability perspective is the lack of a distinction between the “capability” in the sense of the ability to perform an action and the action itself. If processes and values are interpreted as a form of knowledge, it can be argued that capabilities are embodied as knowledge in people and other agents and this knowledge can be transformed into action.

According to Teece et al. (1997) dynamic capabilities are defined as “the firm’s ability to integrate, build, and reconfigure internal and external competences to address rapidly changing environments." (Teece et al., 1997, p.516) Key to understanding dynamic capabilities are organizational processes. These are fed by a firm’s knowledge as well as evolutionary paths of this knowledge “it has adopted or inherited”. Organizational processes are understood as “the way things are done in the firm, or what might be referred to as its routines, or patterns of current practice and learning.” (Teece et al., 1997, p.518) “Paths” are understood as “the strategic alternatives available to the firm.” (Teece et al., 1997, p.518) They also deal with the aspect of replication and imitation of capabilities, as this has an effect on the sustainability of competitive advantage. Replication involves “transferring or redeploying competences from one concrete economic setting to another.” Imitation is defined as replication performed by a competitor (Teece et al., 1997, p.526). Replication is considered a precondition of imitation (Teece et al., 1997, p.525). Replication is furthermore not only information transfer, as this would require a full codification of knowledge, which is often not possible. The difficulty comes from the knowledge which is not codified and explicit, also called tacit knowledge. As tacit knowledge is embodied in people, replication is often accompanied by the transfer of people. They also stress the importance of contextual elements which have to be taken into account and make replication more difficult. One important factor with regards to imitation is the observability of what is imitated. Products can be reverse engineered rather easily as they can be observed or acquired. In order to benefit from the product, the product has to be exposed. Processes are less observable and they do not have to be exposed in order for the firm to benefit from them.

Another important aspect is path dependency, resulting from previous strategic choices. In short, “history matters” (Teece et al., 1997, p.522). Changes in strategy face inertia from the firm’s already followed path of capability development: “From the capabilities perspective, strategy involves choosing among and committing to long-term paths or trajectories of competence development.” (Teece et al., 1997, p.529). Thus, changes in capability tend to be rather incremental.

The dynamic capability literature stresses the role people play in the transfer of tacit knowledge. Furthermore, the notion of “path dependency” can be understood as the impact a firm’s heritage capabilities have on its present capabilities. The dynamic capability literature argues that firms are constrained by their heritage capabilities and limited in their present capability choices.

To summarize, the capabilities and competencies literature provides different perspectives on these concepts. The core competencies literature focuses on cross-cutting competencies of companies that are important for its competitivity. Moreover, there are publications that present ways to map core competencies to product and project portfolios in order to assess if the company is using and enhancing its core competencies. The resource-process-value perspective focuses on what a capability actually “is”. However, it seems to lack a proper distinction between the embodiment of the capability and action that can be performed due to the capability. I conclude that the existing publications in this area do not introduce a way to both represent the components of a capability and how they can be linked to specific products and programs.

2.4 Technology History

The third category of literature this thesis draws from is technology history. In the context of this thesis theories of technological evolution are of interest, as well as how technologies are transferred. A general tendency of the technology history literature is the focus on individuals and organizations and how they shaped technological development.

2.4.1 Technology Evolution

The evolution of technology is a core topic of technology history. Two prevalent theories of technology evolution exist. One stresses the role of revolutionary changes and the other denies the existence of "revolutions" and instead stresses gradual changes. Constant (1980) focuses on the former. He presents a history of the turbojet revolution. Constant focuses on two aspects. The first are communities of practice associated with a certain technology. These communities have an interest in a technology and are involved in its development, funding etc. Constant demonstrates that the communities of practice of the turbojet and the propeller engine were distinct. Furthermore, the idea of the turbojet emerged independently in Great Britain, Germany, and Austria. However, it was mainly driven forward to a first prototype by Frank Whittle and Hans von Ohain in parallel, without knowing of each other. The second aspect Constant focuses on is the evolution of the turbojet from existing technologies. The turbojet gradually evolved from predecessor technologies such as the water, steam, and gas turbine. However, the turbojet had nevertheless unprecedented capabilities, which had nothing to do with the individual technologies that were combined, such as turbo superchargers and gas turbines.

Basalla (1988) criticizes Constant on the basis of his proclaimed turbojet "revolution" in fact being a gradual evolutionary process. Basalla claims that nothing such as a technological "revolution" exists, where technological artifacts suddenly emerge without a predecessor.

These two contradictory perspectives on technology evolution can be resolved by distinguishing between individual technologies, their combination in a system, and the system's intended function. Basalla is right when he claims that sudden technological leaps do not occur "out of nowhere" and each technology is based on a predecessor (Basalla, 1988, pp.28-30). However, he seems to miss that technologies usually exhibit a hierarchy and are combined or disaggregated on various levels, as Arthur (2009) remarks. From combining different technologies, completely different capabilities can emerge that were not present in its individual constituting technologies. The turbojet was indeed based on various predecessor technologies but exhibited a completely new capability of being able to generate much larger thrust for propelling aircraft at unprecedented altitudes. From this system and capability perspective, the turbojet was indeed a revolution and cannot be traced to any direct predecessor.

Another important contribution is the work by Donald MacKenzie on the history of nuclear missile guidance and nuclear weapons development (MacKenzie and Spinardi, 1995; MacKenzie, 1993, 1987). The first two works focus on the relationship between technological evolution and the dynamics within and between different organizations. By exploring the history of inertial navigation, MacKenzie shows how different technological solutions to the inertial navigation problem have been adopted by the US and the Soviet Union. The Soviet solution can be traced back to the heritage of the German V-2 rocket, whereas the US solution has emerged from research being done at Draper Labs at MIT. MacKenzie's research on nuclear weapons technology is important in the context of this thesis, as he explores how technological knowledge is bound to geographic locations. Technological knowledge is difficult to move, as it is often tacit and embedded in organizational structures. MacKenzie demonstrates this by using Los Alamos Laboratories as a case study.

Another publication from the area of technology history which deals with the locality of technological knowledge is Westrum (2013). Westrum uses the case of the Sidewinder missile in order to illustrate the factors that lead to a technology with unprecedented capabilities. He attributes most of these factors to the unique organization structure at the Naval Ordnance Test Station (NOTS) at China Lake. The joint military and civilian leadership together with the close location of work and living quarters established an environment where highly innovative defense systems were developed quickly.

To conclude, the literature from technology history confirms empirically some of the tenets of the resource-based view from the management literature, for example the difficulty to move resources that constitute a unique organizational capability of which tacit knowledge is an essential element. Furthermore, the development of revolutionary technologies seems to be conducted by communities of practice that are distinct from the community of practice of the existing technology.

2.4.2 Engineering Knowledge

According to the Oxford Dictionary, "knowledge" is defined as: "Facts, information, and skills acquired by a person through experience or education; the theoretical or practical understanding of a subject…" (Fowler & Fowler, 2011) Knowledge is a key element of a capability. A specific form of knowledge, "know-how" or "skill", has been recently treated by Stanley and Williamson (2001) and Stanley (2011). Stanley and Williamson (2001) distinguish between "knowledge-that", which is knowledge about that something is the case, and "knowledge-how", which is an ability. Skills would fall into the latter category.

"Engineering knowledge" is the subset of knowledge which is used for engineering activities. Engineering activities mainly pertain to the creation of artifacts (Vincenti, 1990). These activities can be directly or indirectly related to the creation of artifacts. For example, a design engineer working on a part of a jet engine is directly involved in creating an artifact. An aerodynamics engineer who is developing a new numerical method for solving supersonic combustion is working on a tool for developing an artifact. Direct and indirect engineering activities have in common that they are directed towards a practical goal. This distinguishes engineering from basic science, where creating new knowledge is a goal in itself, although there is no clear demarcation line between basic science and engineering but rather a continuum. When it comes to technology-related knowledge and engineering knowledge, few publications actually propose frameworks for categorizing them.

Vincenti (1992, 1990) is considered one of the first authors to deal with engineering knowledge as a distinct form of knowledge, compared to scientific knowledge. This distinction has not been clearly acknowledged before, as engineering knowledge was just seen as applied scientific knowledge. Vincenti (1990) presents a typology of engineering knowledge and explores how engineers use these types of knowledge in their work. The aspects that distinguish engineering knowledge from scientific knowledge are omitted in the following, although Vincenti goes to great length with this respect. The knowledge categories and respective activities for generating them are shown in Table 2-5. The crosses in the table should be read as "knowledge in category B can be generated by activity A". For example, "Theoretical tools can be generated by transfer from science".

Table 2-5: Knowledge categories and activities generating them according to Vincenti (1990, p.235)

Categories / Activities	**Fundamental design concepts**	**Criteria and specifications**	**Theoretical tools**	**Quantitative data**	**Practical considerations**	**Design instrumentalities**
Transfer from science			X	X		
Invention	X					
Theoretical engineering research	X	X	X	X		X
Experimental engineering research	X	X	X	X		X
Design practice		X			X	X
Production				X	X	X
Direct trial (including operation)	X	X	X	X	X	X

Vincenti distinguishes six types of engineering knowledge:

- *Fundamental design concepts*: Consist of the operational principle and normal configuration.
  - *Operational principle:* An operational principle is how the parts of a system behave in order to fulfil one or more functions. Vincenti borrows this notion from Polanyi (1964, pp.174-184, 328-332). Vincenti gives Cayley's invention of the airplane as an example. Before Cayley, airplane concepts were propelled by flapping wings that would also generate lift and control the aircraft. Cayley proposed to separate the function of lift generation, propulsion, and control and to assign them to different components of an airplane (Cayley, n.d.). With this concept, lift would be generated by a fixed wing instead of a flapping wing. Hence, Cayley's innovation in Vincenti's terms was an innovation of the operational principle of an airplance. What Vincenti means by "operational principle" is quite similar to the "working structure" of a system from Pahl et al. (2007).
  - *Normal configuration:* The "normal configuration" is "the general shape and arrangement that are commonly agreed to best embody the operational principle." (Vincenti, 1990, p.209) The notion of "normal configuration" resembles the notion of "dominant design" in the management literature (Utterback and Abernathy, 1975; Utterback and Suarez, 1993). A "radical technology" involves "a change in normal configuration and possibly also in operational principle." (Vincenti, 1990, p.210)
- *Criteria and specifications:* Criteria and specifications are basically requirements and constraints.
- *Theoretical tools:* "Theoretical tools" can range from mathematical methods and theories to more practical intellectual concepts of thinking about design. Mathematical methods and theories can be for example geometry and differential equations. Theories with more physical content can be fluid mechanics or structural mechanics. However, engineers also use "phenomenological theories" that are based on "ad hoc assumptions about phenomena crucial to the problem." (Vincenti, 1990, p.214) Examples for such theories are the calculation of the durability of screws and mass and cost estimates for aerospace systems at an early design stage. The formulas used cannot be traced back to physical first principles but are based on experiments and rule-of-thumb estimates.
- *Quantitative data:* "Quantitative data" can consist of physical properties and results from tests, which are used to conduct engineering activities.
- *Practical considerations:* An engineer's experience and tacit knowledge. Examples include the design of parts with taking manufacturing methods into consideration. The application of heuristics also falls into this category.
- *Design instrumentalities:* Formal and informal ways of how engineers proceed in design. Furthermore, it includes judgmental skills in making design decisions.

An interesting observation is that Vincenti puts a lot of importance to "direct trial" or using a modern expression verification, validation, testing, and operation.

In the context of this thesis, Vincenti's work is of interest, as using his taxonomy allows for identifying embodiments of these knowledge categories in technologies. For example, fundamental design concepts, criteria and specifications, theoretical tools, and quantitative data are mostly stored in documents, handbooks, and data bases. For using this knowledge in engineering, it has to be learnt and applied by engineers and other technical personnel. "Pracitical considerations" and informal "design instrumentalities" can only be embodied in people. This leads to the conclusion that at its core, engineering knowledge can be captured either by knowledge storage devices such as documents, handbooks, data bases, and people. People (or agents in general) are both able to store knowledge but also to use knowledge to perform an action.

2.4.3 Technology Transfer Knowledge

Gorman (2002) presents examples for the transfer of tacit knowledge and a taxonomy of knowledge. Four types of knowledge are distinguished: information, skills, judgment and wisdom, as shown in Table 2-6. Examples for these knowledge types are both shown in their declarative (explicit) and tacit (implicit) form. Gorman uses examples to illustrate that for most of human history tacit knowledge was transferred by moving people. One example is steel making, where France and England were rivals during the 18th century. Repeated attempts of espionage by the French were not successful in replicating English steel-making know-how. Only by importing steel-making workers did the French succeed in replicating the more advanced technology from England. A similar case is the transfer of English textile expertise to the US by importing knowledgeable workers. Gorman uses other examples such as the Transversely

Excited Atmospheric (TEA) laser and nuclear weapons to illustrate the vital role tacit knowledge plays in technology transfer.

Table 2-6: Four knowledge types and their explicit and implicit forms, according to Gorman (2002, p.228)

	Declarative (explicit)	Tacit (implicit)
Information (what)	Accretion, memorization, external memory aids	Restructuring
Skills (how)	Algorithms	Heuristics, tuning, hands-on, kinesthetic
Judgment (when)	Rules	Case-based experience, mental models, transactive memory, technological frames
Wisdom (why)	Codes	Moral imagination

There is a clear gap between the fine-grained typologies of engineering knowledge and the coarse-grained treatment of knowledge in the management literature. For the purpose of this thesis, an approach has to be found that is able to bridge the high-level understanding of organizational capabilities and fine-grained forms of engineering knowledge.

2.5 Measurement and Decision Theory

Determining the degree of heritage of a technology is essentially a measurement problem. The theoretical underpinnings of a measurement problem are provided by measurement theory. Measurement theory deals with "the process by which numbers or symbols are assigned to attributes of entities in the real world in such a way as to describe them according to clearly defined rules." (Fenton, 1994, p.199) Decision theory can be understood as "the formalization of common sense for decision problems which are too complex for informal use of common sense." (Keeney, 1982, p.806) The literature on measurement theory is relevant, as it provides the theoretical basis for how far heritage can be measured. Decision theory is relevant in making heritage-related decisions.

In the following, an introduction to relevant aspects of measurement and decision theory is given. The focus is on identifying the criteria for a meaningful measure and the construction of value functions that are used for measuring preferences between alternatives.

2.5.1 Introduction to Measurement Theory

In this section, some basics of measurement theory are introduced, to allow for the construction of proper heritage measures. More specifically, I focus on the representational theory of measurement (Fenton, 1994; Finkelstein and Leaning, 1984; Krantz et al., 1971). According to Fenton (1994), "Measurement is defined as the process by which numbers or symbols are assigned to attributes of entities in the real world in such a way as to describe them according to clearly defined rules." According to this definition, measurement is fundamentally an assignment process. Numbers or symbols are assigned to attributes of entities. A simple example for an entity in the real world would be a room. An attribute of the room is its temperature. The temperature can be measured by a thermometer. The thermometer measures, for example, 20 C° on a Celsius scale. The thermometer therefore assigns a number ("20") to the temperature. Fenton (1994, p.199) further explains that the description of attributes must adhere to intuition and empirical observation. Taking the temperature example, a higher temperature can be intuitively understood as "hotter as". An empirical observation can be, for example, that heated materials have the tendency to expand. A larger number would be assigned to hotter objects than to colder objects. To give another example: If the height of people is measured, taller people should have larger numbers assigned to them than smaller people. A common problem is that intuition can differ from person to person. Therefore, measurements are often based on a consensus of how to assign the numbers or symbols to attributes.

In order to compare measurements, some form of standardization is necessary. To support standardization, a model is usually defined that captures the assumptions and conditions of measurement. The model for measuring height could include whether or not a person can wear shoes, whether or not hairs are included. The model depends on its purpose. If the model is used for a study of human height, then shoes and hair should be excluded. However, measuring height for admitting children to a roller coaster is based on their height with shoes, as the objective is to ensure that the protective belt prevents a person to fall out during the ride. In engineering, lines of code (LOC) are used for measuring the productivity of a software coder. A good model for LOC should, for example, only count unique code, as copy-and-pasted code does not reflect productivity. Therefore, depending on the purpose, the model can be different.

At this point, some formal notions of measurement theory are introduced. The intuitive or empirical understanding of an attribute is represented by an "empirical relation system". An empirical relation system is defined as the tuple

$$(C, R) \tag{1}$$

where C is the *set of entities* and R the *set of empirical relations*. In the case of height, C would be the set of people whose height is measured. R consists of relations for the attribute to be measured. Such a relation could be "is tall", "taller than". Let's assume two people a and b are part of the set C. Let's further assume that a is taller than b. At this point, no numbers nor symbols have been assigned to the attributes. For assigning numbers or symbols, another tuple is required, which is called "numerical relation system". It is defined as

$$(N, P) \tag{2}$$

where N is a set of numbers and P a set of numerical relations. For making a measurement, the empirical relation system and the numerical relation system have to be related. This is done by a mapping M, which maps the entities from C to the numbers in N and the relations from R to the numerical relations in P. More formally:

$$M: (C, R) \rightarrow (N, P) \tag{3}$$

The mapping M is called "representation" and adheres to the "representation condition" if and only if all empirical relations are preserved. The representation condition can be formulated as (Fenton, 1992, p.358):

$$(x, y) \in R \Leftrightarrow \big(M(x), M(y)\big) \in P \quad \text{for all } x, y \in C \tag{4}$$

For example, the binary relation $\prec$ is mapped to the numerical relation $<$. The respective empirical relation system is defined as

$$(C, \prec) \tag{5}$$

whereas the numerical relation system is defined as

$$(N, <) \tag{6}$$

Applying the mapping M results in Cantor's representation condition (Fenton, 1994; Narukawa, 2007, p.23):

$$x \prec y \Leftrightarrow M(x) < M(y) \quad \text{for all } x, y \tag{7}$$

In ordinary language: For all x and y, if y is taller than x, then the value of the height of y must be larger than the value of the height of x. Taking the example of two people a and b and a taller than b, the condition $M(b) < M(a)$ must hold. For example for $M(a) = 175$ and $M(b) = 160$ the condition holds.

Although the representation condition seems to be obvious, there are metrics in software engineering and in systems engineering that violate the condition (Fenton, 1994). Examples are the original Systems Readiness Level (SRL) metric as well as diverse complexity metrics in software engineering (Fenton, 1994; Kujawski, 2013; London, 2015).

An important question is how far "heritage" can be measured. Intuitively, measuring physical entities such as length, weight, temperature seem to be different from measuring subjective judgements such as comfort, quality, and satisfaction. According to Fenton (1994), there is no principle difference between these two categories, as long as the measurement condition is satisfied. In case of subjective judgements, it depends on the existence of a consensus what the underlying concept to be measured is. As Larson & Wertz (1999, pp.798-799) remark, the main difficulty of measuring heritage is that there is no consensus on what heritage actually is. This is reflected by the different definitions for heritage presented in Section 1.2. Without a consensus, it is not possible to satisfy the representation condition in the general sense. This can be demonstrated analogous to the proof given by Fenton (1994) that no general measure for software complexity exists.

For an informal demonstration, a hypothetical example of heritage measurement is shown in Table 2-7. Sample heritage attribute values are given. A general heritage measure exists if for any combination of heritage factor values, a clear judgement of “has more heritage than” can be made. For simplicity, I omit the case of indifference “has similar heritage as”. If such an intuitive judgement can be made in general, a general heritage measure exists.

Table 2-7: Example for aternatives with different heritage factor values

Technology	**Successful operational history**	**Design modifications**	**Suppliers for components**	**System integrator**
Commercial aircraft A	10 years	No	Same	Same
Commercial aircraft B	none	New design	No previous experience	No previous experience
Commercial aircraft C	10 years	No	Some new suppliers	Same
Commercial aircraft D	10 years	Major modifications	Same	Same

For aircraft A and B, it is intuitively clear that aircraft A has more heritage than B. Comparing B and C, it is also clear that C has more heritage than B. The same holds for D and B: D has more heritage than B. However, things are not straightforward when comparing C and D. The two technologies only differ in the degree of design modification and changes in component suppliers. It depends on what importance one assigns to changes in the design versus changes in suppliers. As there is no general consensus for how to weight the two factors, there is no unique order with respect to heritage for the technologies under consideration. Hence, even if a specific weighting is assigned:

$$M(H(C)) > M(H(D)) \tag{8}$$

where $H(x)$ is the heritage of x, the representation condition is not satisfied, as

$$H(C) \succ H(D) \Leftrightarrow M(H(C)) > M(H(D)) \tag{9}$$

could be true but at the same time

$$H(C) \prec H(D) \not\Leftrightarrow M(H(C)) > M(H(D)) \tag{10}$$

in case D is considered to have more heritage. In such a case, the representation condition is violated. Analogous to Fenton's (1994) remarks on complexity measures, this is only proof for the non-existence of a *general* measure for heritage. It does not preclude that there are measures for *specific* interpretations of heritage. Thus, it is vital to clearly state the underlying assumptions of the heritage metric and consider alternative interpretations where possible.

Having provided a general introduction to measurement theory, different measurement scales are presented next. In the height measurement example, a specific type of scale was used, which allows for making statements such as “a is 15cm taller than b”. Such statements cannot be made with all types of scales. In the next section I introduce different types of scales and which mathematical operations can be performed on them.

2.5.2 Fundamentals of Scales

In measurement theory scales play an important role. Different types of scales allow for conveying different types of information. According to Stevens (1946), there are five types of scales:

- *Nominal:* A nominal scale simply puts an entity into a certain category according to its attributes. For example, balls with different colors can be put into categories such as black balls, white balls, red balls etc.
- *Ordinal:* An ordinal scale provides an ordering of entities with respect to their attributes. An example is to order a group of people with respect to their height. The order would be defined according to "taller than". Such an order is called a "strong order". A "weak order" on the other hand would be "taller than or equal height". An important aspect of ordinal scales is that they do not convey any information about the difference between the attribute of two entities. If one person is taller than the other, this may result from a height difference of 1cm or 30cm.
- *Interval:* The interval scale captures the difference between attribute values. A typical interval scale is the Celsius scale. The statement "It is 20°C colder in this room than in another." makes sense.
- *Ratio:* In addition to the attributes of the interval scale, a ratio scale possesses a unique and non-arbitrary zero value. The zero value allows for statements such as "Length a is twice length b." Mass, length, energy are example for ratio scales.

Each of these scales fulfills the representation condition if they are subject to certain admissible transformations, shown in Table 2-8 in the column "mathematical group structure". The values of a scale x can be transformed into the values of a scale x' via a function f. This can be shown by a well-known case of the Celsius and Fahrenheit scale. Celsius can be converted into Fahrenheit via a linear transformation $x' = ax + b$. The parameters a and b in this case are 1.8 and 32 respectively. For an ordinal scale, any monotonically increasing function can be used. For example, the values 1, 2, 3 etc. can be used for ranking alternatives. A function $f(x) = x^2$ can be defined which would result in the values 1, 4, 9. Such an ordinal scale would be equally suited. It can be easily seen that such a function would not satisfy the conditions for an interval or ratio scale as it is not linear. Regarding the permissible statistics, the permissible statistics of the nominal scale apply to all other scales, the permissible statistics for the ordinal scale to the interval and ratio scale and so on.

Table 2-8: Scale types and their empirical, mathematical, and statistical properties according to Stevens (1946)

Scale	**Basic empirical operations**	**Mathematical group structure**	**Permissible statistics (invariantive)**
Nominal	Determination of equality	Permutation group $x' = f(x)$ $f(x)$ means any one-to-one substitution	• Number of cases • Mode • Contingency correlation
Ordinal	Determination of greater or less	Isotonic group $x' = f(x)$ $f(x)$ means any monotonic increasing function	• Median • Percentiles
Interval	Determination of equality of intervals or differences	General linear group $x' = ax + b$	• Mean • Standard deviation • Rank-order correlation • Product-momentum correlation
Ratio	Determination of equality of ratios	Similarity group $x' = ax$	• Coefficient of variation

A common misconception is, for example, to treat TRL as it were an interval scale. However, as TRL is clearly an ordinal scale, operations such as taking the mean, multiplications, etc. may lead to results that are not meaningful. By taking the TRL levels 1, 2, 3, etc. as levels of an interval scale, it is assumed that the difference between each TRL is 1. However, various sources report that the difference in maturity between TRL is not equally distributed. For example, to get from TRL 5 to 6 requires much more effort than getting from TRL 2 to 3 (ESA, 2008; Szajnfarber, 2011). Hence, using an ordinal scale if it were an interval scale may lead to considerable errors.

There has been a continuous debate about the validity of the properties Stevens assigns to scales and their strictness has been disputed (Gaito, 1980; Norman, 2010).

To summarize, according to Stevens' scale typology, different scale types permit different mathematical and statistical operations.

Up to this point, I did not distinguish between notions that are widespread in the scientific literature: metric, measure, and indicator. The next section will introduce distinctions between these three concepts.

2.5.3 Metrics, Measures, and Indicators

The notions metric, measure, and indicator are often used interchangeably in the literature. In the following, I draw a few distinctions between these notions. As Fenton (1994) remarks, the notion of "metric" is often used for any number extracted from an entity. However, whereas any measure is a metric, not all metrics are measures in the sense of the representational condition (4). Hence, assigning a subjective number to an object for its quality would be a metric. However, this metric does not necessarily satisfy the representation condition. The situation would change, if a measurement model is defined that describes when the quality of an object is higher or lower than the quality of another.

Further, metrics and measures are not to be confused with indicators. An indicator indicates something. For example, a barking dog may indicate a gas leak. A measure can be an indicator for something. For example, the size of a table in centimeters may indicate how many people can sit at the table. The number of patents filed in a country may indicate how innovative a country is. The underlying entity for which the indicator provides an indication for is called "concept" or "construct" (Jarvis et al., 2003; Nardo et al., 2008). Indicators are particularly important for constructs that cannot be directly observed. For example, the innovation potential of a country cannot be directly observed (Nardo et al., 2008). "Technological progress" or "human intelligence" cannot be directly observed, contrary to the length of an object. Such constructs that are not directly observable are also called "latent variables". One or more indicators are used as "observable variables" for a latent variable. For example, an IQ test consists of a verbal, visio-spatial, and other parts in which one expects intelligence manifests itself. In practice, finding proper indicators for such constructs is not easy, as finding them depends on specific interpretations of the construct. For example, there is an ongoing debate about what human intelligence is and how it manifests itself (Hampshire et al., 2012).

The notion of indicator is relevant for measuring heritage, as heritage is not directly observable. Heritage is therefore considered a latent variable for which observable variables need to be found. Hence, the main task defining a proper measure for heritage consists of a proper decomposition of heritage and finding indicators for each of the components of heritage. Such an aggregated indicator is called "composite indicator".

The applicability of composite indicators is a matter of ongoing debate. According to Saisana et al. (2005), stakeholders and decision-makers are inclined to use composite indicators, as they aggregate complex information into a single number. On the other hand, statisticians and mathematicians criticize the loss of information by aggregation and the meaningfulness of certain composite indicators.

2.5.4 Value Functions

In the following, a very brief introduction to value functions is given. Value functions are of crucial importance in engineering decision making, as they enable the comparison of different design options with respect to a set of criteria. The reader is referred to the seminal book by Keeney and Raiffa (1993) for an exhaustive introduction to the topic. The concepts and notations are taken from the respective volume.

A value function is a function that maps a set of criteria to a scale for preferability or value (Keeney & Raiffa, 1993, p.68). "Preferability" can be understood as a preference statement with respect to an attribute such as "the cheaper the better", "the lighter the better" etc. More formally, a value function is a scalar-valued function with the property:

$$v(x_1, x_2, \dots, x_n) \geq v(x'_1, x'_2, \dots, x'_n) \Leftrightarrow (x_1, x_2, \dots, x_n) \gtrsim (x'_1, x'_2, \dots, x'_n) \quad (11)$$

v is the value function of a vector of consequences $(x_1, x_2, \dots, x_n)$ and $(x'_1, x'_2, \dots, x'_n)$ respectively. The value of $v(x_1, x_2, \dots, x_n)$ is larger or equal to $v(x'_1, x'_2, \dots, x'_n)$ if and only if the consequence vector $(x_1, x_2, \dots, x_n)$ is preferred over $(x'_1, x'_2, \dots, x'_n)$ or is considered indifferent. Note the similarity between this property and the representation condition in Chapter 2.5.1, (4).

A simple value function would be comparing two systems with respect to a single performance parameter, for example maximum speed. A higher speed is preferred over a lower speed. Let's assume that the respective speeds for a set of two alternatives are 200 and 100 km/h. Then, the following preference relation holds:

$$200km/h \succ 100km/h \quad (12)$$

Let's choose a value function v. Such a function needs to be strictly monotonically increasing, as larger values for speed are always preferred and indifference means that the speeds compared are equal. Let's assume a linear value function v. Any monotonically increasing linear function satisfies the property.

$$v(x) \geq v(x') \Leftrightarrow x \gtrsim x' \quad (13)$$

Note that this is the form of expression (11) with one single attribute.

As v is a linear function:

$$ax + b \geq ax' + b \Leftrightarrow x \gtrsim x' \text{ with } a, b \in \mathbb{R} \quad (14)$$

It can be easily shown that $x \geq x' \Leftrightarrow x \gtrsim x'$ holds for all values of $a \in \mathbb{R}^+ \backslash \{0\}$. This means that all linear functions with this property can be used as a value function for the case at hand.

The multidimensional case is usually formulated in an additive form.

$$v(x_1, x_2, \dots, x_n) = \sum_{i=1}^{n} \lambda_i x_i \text{ with } \lambda_i \in [0, 1] \quad (15)$$

An additive value function with continuous variables allows for "compensation". Compensation allows for a low x_i to be compensated by another x_j where $i \neq j$. Extending the example from before by number of passengers, a low maximum speed could be compensated by a large number of passengers and vice versa. Compensation is sometimes a desirable property. However, it often leads to results that are not desirable. For example, a system which has a speed of 0 could be compensated by a very large number of passengers. This obviously does not make sense, as a system that cannot move cannot provide any value. The choice of scales and weights for an additive value function for yielding meaningful results is not trivial.

Another approach to modeling the behavior of decision makers is to include the "diminishing marginal rate of substitution" (Cameron et al., 2011). In other words, substituting or compensating for one attribute gets more and more difficult. A multiplicative value function exhibits this behavior. A multiplicative value function can be defined as:

$$v(x_1, x_2, \dots, x_n) = \prod_{i=1}^{n} {x_i}^{\beta_i} \quad (16)$$

Note that the multiplicative value function can be transformed into the additive form by applying the logarithmic function to both sides (Keeney and Raiffa, 1993; Roberts, 1985). For example, a value function of the following form:

$$v(x, y) = (x - \alpha_1)^{\alpha_2} (y - \beta_1)^{\beta_2} \quad (17)$$

can be transformed into an additive value function:

$$log\, v(x, y) = \alpha_2 log(x - \alpha_1) + \beta_2 log(y - \beta_1) \quad (18)$$

A third form of a value function is:

$$v(x) = \sum_{i=1}^{n} c_i x_i + c_{n+1} \prod_{i=1}^{n} (x_i - b_i)^{\beta_i} \quad (19)$$

This is a combined additive and multiplicative value function which exhibits a weaker form of compensation. Depending on the value of the constants c_i and c_{n+1}, the additive or multiplicative behavior can be emphasized.

The weightings for value functions can be determined by asking the decision-maker a number of preference questions. A detailed introduction to preference elicitation can be found in Keeney and Raiffa (1993).

A recent approach that has gained popularity in the multi-criteria decision making community is the Choquet integral. The Choquet integral is an extension of the weighted sum that can be interpreted as a Lebeque integral. The Choquet integral is particularly suited for taking interactions between variables into account. Interactions occur when two or more variables are not independent. For example, the two variables horse power and fuel consumption for a car are not independent, as cars with more horse power tend to consume more fuel. The Choquet Integral can take those interactions into account by not only assigning weights to individual variables but also to sets of variables. In many practical applications, it is sufficient to assign weights to the sets consisting of pairs of variables that interact. The Choquet interval is of interest in the context of this thesis, as the variables used in the heritage metric are not independent. In the following, I will give a cursory introduction to the Choquet integral and how it can be used for constructing utility functions with interactions between variables. For a more detailed introduction, the reader is referred to Grabisch and Roubens (2000).

A Choquet integral for a set *N* of *n* criteria can be defined as:

$$C_\mu(x) := \sum_{i=1}^{n} (x_{\tau(i)} - x_{\tau(i-1)})\mu(\{\tau(i), \dots, \tau(n)\}) \tag{20}$$

where τ is a permutation on *N* such that $x_{\tau(1)} \leq x_{\tau(2)} \leq \cdots \leq x_{\tau(n-1)} \leq x_{\tau(n)}$ and $x_{\tau(0)} := 0$. μ is a capacity on *N*, defined as:

$$\mu: 2^N \to [0,1]$$

satisfying the properties

$$\mu(\emptyset) = 0 \tag{21}$$

$$\mu(N) = 1 \tag{22}$$

$$\forall A, B \in 2^N, [A \subseteq B \Longrightarrow \mu(A) \leq \mu(B)] \text{ (monotonicity)} \tag{23}$$

The interaction between variables is defined as:

$$\forall A \subseteq N, I(A) := \sum_{K \subseteq N \setminus A} \frac{(n-k-|A|)!k!}{(n-|A|+1)!} \sum_{L \subseteq A} (-1)^{|A|-|L|} \mu(K \cup L) \tag{24}$$

For any pair of criteria i and j, the interaction index is given as:

$$I_{ij} := \sum_{K \subseteq N\{i,j\}} \frac{(n-k-2)!\,k!}{(n-1)!} [\mu(K \cup \{i,j\}) - \mu(K \cup \{i\}) - \mu(K \cup \{j\}) + \mu(K)] \tag{25}$$

Furthermore, the importance index for a criterion i is defined as:

$$v_i := \sum_{K \subseteq N \setminus i} \frac{(n-k-2)!\,k!}{n!} (\mu(K \cup i) - \mu(K)) \tag{26}$$

Using the interaction index and importance index, the Choquet integral with respect to a 2-additive capacity, representing pairs of interacting variables can be defined as:

$$C_\mu = \sum_{i=1}^{n} v_i x_i - \frac{1}{2} \sum_{i=1}^{n} I_{ij} |x_i - x_j| \tag{27}$$

The first term of the Choquet integral can be interpreted as the weighted sum of the criteria x_i. In case I_{ij} is positive, the second term can be understood as a penalty for $x_i \neq x_j$. In case I_{ij} is negative, the term can be understood as a bonus for $x_i \neq x_j$. This formulation of the Choquet integral either penalizes or provides a bonus for consistency in the criteria values.

To summarize, a value function can be used for translating attributes into a preference scale. Three common value functions are the additive, multiplicative, and mixed value function. The additive value function allows for a linear compensation of one variable by another. The multiplicative value function allows for a diminishing marginal rate of compensation. The mixed additive and multiplicative value function allows for different degrees of compensation. As a more recent example for a value function, the Choquet integral was presented that allows for taking interactions between dependent variables into account.

2.5.5 Uncertainty and Sensitivity Analysis

According to Nardo et al. (2008) and Saisana et al. (2005) it is important to assess the robustness of a composite indicator with respect to variations in input data, input data errors, and weighting factors. Robustness assessment is performed via uncertainty and sensitivity analysis. According to Saisana et al. (2005) uncertainty analysis is concerned with how the uncertainties in the input values propagate to the value of the composite indicator. Sensitivity analysis by contrast "studies how much each individual source of uncertainty contributes to the output variance." (Saisana et al., 2005, p.308)

Uncertainties are associated with each of the development steps for a composite indicator:

(a) selection of subindicators,

(b) data selection,

(c) data editing,

(d) data normalization,

(e) weighting scheme,

(f) weights' values and

(g) composite indicator formula.

Monte Carlo simulation is commonly used for uncertainty and sensitivity analysis (Saisana et al., 2005). In this thesis, uncertainty and sensitivity analyses are performed by varying input parameters of the heritage metric and by observing the resulting effect.

2.6 Contributions to Thesis Objectives

The literature covered in Chapter 2 is a starting point for addressing the thesis objectives. Table 2-9 provides an overview of the literature covered in Chapter 2 and how it addresses the thesis objectives.

The system engineering literature provides framworks and methodologies for developing the technology framework, notably the reuse and commonality literature. The reuse literature presents different forms of reuse and challenges of reuse. Notably, reuse is difficult due to differences in context between the original and the new application. The commonality literature introduces different forms of commonality such as functional, technological, and operational commonality. Furthermore, the notion of "divergence" helps to explain why initially optimistic degrees of commonality seldom materialize. Divergence is important in making estimates about the degree of heritage in technologies in the initial stages of systems development. The initial estimate needs to be discounted, in order to take divergence into account. Both, the technology infusion and change propagation literature address how technologies and systems change and develop models that can anticipate the potential impact of these changes. It provides a basis for modeling technological change and how it impacts design heritage.

The verification, validation, and testing literature introduces different forms of verification, validation, and testing. Moreover, the way how these activities are conducted throughout the system life cycle are presented. These different forms are useful for developing the VVTO framework by providing key definitions.

The strategic management and technology management literature introduces the resource-based view and capabilities and competencies. This literature provides the conceptual underpinnings for modeling technological capabilities. However, the strategic management and technology management literature stays at a high level of abstraction. Hence, the technology history literature is consulted to identify concrete forms of technological knowledge and how they contribute to technological capabilities. In particular, the literature on engineering knowledge and technology transfer knowledge provides insights into what knowledge is required for developing a technological capability.

Finally, the literature on measurement and decision theory provides the theoretical underpinnings for the heritage assessment methodology, specifically for the development of a heritage metric that quantifies the degree of heritage.

Table 2-9: Contribution of existing literature to thesis objectives

Literature \ thesis objectives	**System architecting framework**	**Technology framework**	**VVTO framework**	**Statistical evidence**	**Heritage assessment methodology**	**Heritage measurement**
Systems engineering						
Reuse		Forms of reuse				
Commonality		Commonality taxonomy				Divergence
Technology infusion					Design change	
Change propagation					Design change	
Verification, validation, and testing			Forms of VVT			
Strategic management and technology management						
Resource-based view		Capabilities				
Capabilities and competencies		Capabilities				
Technology history						
Technology evolution		Technology change				
Engineering knowledge		Capabilities				
Technology transfer knowledge		Capabilities				
Measurement and decision theory						
Introduction to measurement theory					Heritage measurement	
Fundamentals of scales					Heritage measurement	
Metrics, measures, and indicators					Heritage measurement	
Value functions					Heritage measurement	
Uncertainty and sensitivity analysis					Heritage measurement	

3 Conceptual Framework

The conceptual framework presented in this chapter provides the theoretical underpinnings for the statistical analysis and heritage assessment methodology. The framework defines the concepts and the relationships between concepts. Developing a conceptual framework or also called "conceptual model" is a common approach in modeling (Sokolowski and Banks, 2010). The methodology uses the concepts and relationships to support decision-makers in assessing heritage technologies. The conceptual framework attempts to be generic, in order to be applicable to diverse engineering domains such as space systems engineering, aeronautics, and automotive engineering.

Fig. 3-1 shows the components of the conceptual framework. The components each address a relevant aspect of heritage technology. The systems architecture framework defines the relationships between a system and its context, such as stakeholders and external systems. The technology framework provides a model for "technology", based on the definitions in Section 2.1.4. Finally, the verification, validation, testing, and operations framework defines under which conditions a technology is considered proven.

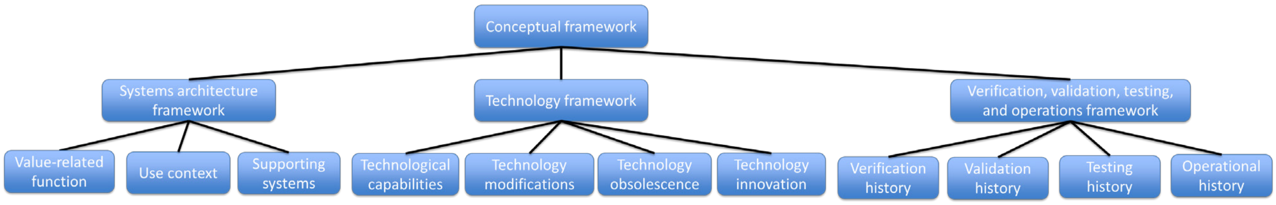


Fig. 3-1: Components of the conceptual framework

The scope of the individual frameworks is larger than what is needed for the heritage assessment methodology and can be, in principle, applied to technologies in other domains.

3.1 Systems Architecture Framework

3.1.1 Selection of Systems Architecture Framework

A systems architecting framework defines elements of a systems architecture and its context. Its main purpose in the context of this thesis is to represent the system / technology under consideration and its context. The focus is in particular on the early stages of systems development. In this section, relevant existing systems architecture frameworks are presented. First, objectives the systems architecture framework needs to fulfill are defined. Then, the most appropriate framework is selected. Instead of developing a new framework, an existing framework is used. The framework is then extended to heritage technology-specific aspects.

The following objectives for the systems architecting framework were defined:

a) _Applicable to general technical systems:_ The framework needs to be applicable to general technical systems, as the goal for the conceptual framework is its applicability to general technical systems. Examples for general technical systems are airplanes, cars, consumer goods, software, and spacecraft. There should not be unnecessary constraints to the usability of the framework.

b) _Takes system context into account:_ The framework needs to provide representations for the system context. The system context consists of the relevant elements that are outside of the system boundary. This aspect is particularly important for heritage systems, as their applicability strongly depends on the context. For example, the organization(s) developing and manufacturing a system is outside the heritage system's boundary. So are regulations, standards, norms, and competing systems. In addition, contextual issues played an important role in failures of using heritage technologies, such as the operational environment.

c) _Distinguishes between functional and physical architecture:_ A clear distinction between the functional and physical architecture is considered important, as it is part of most systems engineering and system design approaches (Haskins et al., 2007; Kapurch, 2010; Pahl et al., 2007). Concepts such as "functional decomposition" provide an additional layer of abstraction that helps to search for a broad range of solutions. The distinction between the functional and physical also allows for assessing a solution-neutral functional architecture before a solution-specific physical architecture is defined. Note that in software engineering, some approaches only implicitly deal with functions. One example is object-oriented software engineering. In object-oriented software engineering, a system's function is implicitly represented by use cases and scenarios (Bruegge and Dutoit, 2004).

d) <u>Provides sufficient semantics to be used in practical applications:</u> The systems architecture framework furthermore needs to provide sufficient content in order to be applicable in practice. For a practical application, the framework needs to be at the right level of abstraction. It should not provide too much detail and thereby losing applicability to a broad range of domains. However, it shall not be too abstract for modeling concrete cases. In other words, someone can take the framework and can use the model elements in it to model a system. It is not necessary to add domain-specific modeling elements in order to model a specific system.

Table 3-1 provides an overview of the frameworks which were taken into consideration for this thesis.

Table 3-1: Overview of considered systems architecting frameworks

Framework	Main area of application	Main difference to other frameworks
DoDAF v2.0 (DoD, 2009)	Defense acquisition	Applicable to system of systems, command & control, interoperability
ISO/IEC/IEEE 42010:2011 (ISO/IEC/IEEE, 2011)	General systems	Very generic: applicable to software, hardware
MIT System Architecture Lab framework (Crawley and Cameron, 2012)	General systems	Focus on value creation and delivery
Systematic engineering design approach (Pahl et al., 2007)	Mechanical systems	Working structure as a level of abstraction
SCAF (Peukert, 2008)	Space systems	Use of SysML diagrams for architecture views
MBSE Cookbook (Karban et al., 2011)	General systems	Focus on using SysML for systems architecting

The result of the assessment of some existing architecture frameworks is depicted in Table 3-2. In the following, it is explained how far each of the frameworks satisfies the selection criteria.

Table 3-2: Assessment of systems architecting frameworks with respect to selectrion criteria

Framework	a)	b)	c)	d)
DoDAF v2.0		X	X	X
ISO/IEC/IEEE 42010:2011	X			
MIT System Architecture Lab framework	X	X	X	X
Systematic engineering design approach			X	X
SCAF			X	X
MBSE Cookbook	X	X	X	X

The DoDAF framework's main areas of application are defense acquisition and systems of systems. Nevertheless, it can be tailored to alternative applications. It provides an extensive set of diagrams that can be used for modeling the system's context. Examples are the command chain and capability in which the system will be integrated. Functional and physical architectures can be modeled by different sets of diagrams: DoDAF distinguishes between the "operational", "systems/services", and "technological standards" view. The operational view is concerned with the functional architecture, whereas the "systems/services" view is concerned with the physical architecture of the system.

For the defense acquisition and systems of systems context, DoDAF provides an exhaustive set of diagrams and modeling elements. Thus, it provides sufficient semantics for practical applications in these contexts.

The ISO/IEC/IEEE 42010:2011 standard can be applied to a wide range of systems, software and hardware. However, it only takes few contextual elements into consideration, such as stakeholders and concerns. Furthermore, there is no explicit distinction between functional and physical architecture, which is probably due to the generic nature of the standard. It does not provide sufficient semantics for a practical application. The standard is therefore rather a framework for creating a framework.

The framework developed by the System Architecture Lab at MIT can be used for general systems, as demonstrated by examples from different engineering domains such as a centrifugal pump (mechanical engineering) and a computer algorithm (software engineering) (Crawley and Cameron, 2012). Furthermore, it provides an extensive set of elements for contextual modeling such as supporting systems and use context. Functional and physical architectures are distinguished. This distinction originates from the use of the Object-Process Methodology (OPM) as the modeling language. OPM is based on objects (structural element) and process (functional element). Furthermore, the framework is applicable to practical settings, as is demonstrated by its use in a course offered at MIT, where students use the framework for solving case studies of practical problems.

Pahl et al. (2007) provide a systems architecture framework for mechanical engineering. Although the framework might be applicable to other domains, it is clear from the examples in the book that the focus is on mechanical design. It also does not provide an extensive model of the system context. However, it distinguishes between functional and physical architecture and provides an additional intermediate layer between the functional and physical architecture. This layer is called "working structure". The framework can be used for practical applications as is demonstrated by its use in university courses, for example at the Technische Universität München (Lindemann, 2012).

The Spacecraft Architecting Framework (SCAF) was developed in alignment with the ISO/IEC/IEEE 42010:2011 standard. It provides various systems views for defining a spacecraft architecture. In its current form it is intended to be used for spacecraft systems engineering. Nevertheless it is sufficiently generic to be applicable to other domains. Furthermore, contextual elements are explicitly left out and only the spacecraft system is addressed (Peukert, 2008). The views in the framework are based on SysML structural and behavioral views. Hence, the physical and functional architecture are distinguished. In its current form, it does not provides sufficient semantics for modeling spacecraft. No spacecraft-specific SysML profile or stereotype is defined for this purpose.

Finally, the Model-Based Systems Engineering (MBSE) Cookbook provides guidelines for how SysML can be used concretely to model a complex system, in this case the Active Phasing Experiment (APE) of the European Southern Observatory (ESO) (Karban et al., 2011). Furthermore, it provides an explicit description of how to model contextual elements such as stakeholders and enabling systems. Functional and physical architecture are distinguished, based on the distinction made by SysML diagrams. Its practical application was demonstrated by the APE case study itself.

As a result of the assessment, two frameworks satisfy all requirements: the MIT System Architecture Lab framework and the MBSE Cookbook framework. In the following, the MIT System Architecture Lab framework provides the main concepts for the systems architecture framework and the MBSE Cookbook the way how to use SysML for this purpose. However, the use of SysML is restricted to cases where simpler representations are not sufficient.

3.1.2 Elements of the Systems Architecture Framework

The MIT System Architecture Lab framework provides a systems architecting framework, which covers aspects of the early stages of system and product development (Crawley and Cameron, 2012). At the core of the framework is the notion of "value". Value is understood as a form of benefit for someone. "Benefit" is "synonymous with the worth, importance, or utility created by a system." (Crawley et al., 2015, p.105) The framework provides the concepts to architect systems and products that generate and deliver value.

Currently, the framework is based on a lecture (Crawley and Cameron, 2012) and a book (Crawley et al., 2015). A formal specification or guideline is currently not available. In the following, only the most essential elements of the framework are presented.

Representing system architecture

In the following, the basic concepts for describing an architecture in the framework are introduced.

As defined before, a system architecture is understood as "the embodiment of concept, and the allocation of physical / informational function to elements of form, and definition of relationships among the elements and with the surrounding context." (Crawley and Simmons, 2006) A central element of this definition is the allocation of function to form. "Form" is understood as an object. At the top level, the allocation of function to form is realized by the "system concept". A system concept is the mapping between a function and an object able to perform this function as illustrated in Fig. 3-2. Note that the function, the form, and the mapping have to be present. The necessary existence of these three elements can be intuitively understood in the case of simple natural objects such as a stone. The stone as such does not have a function with respect to a human need, goal etc. However, a stone can be assigned a function such as serving as a paperweight, a projectile, or decoration. In each of these cases, the stone remains the same but the function it performs is different. The concepts in these cases could be "stone paperweight", "stone projectile" etc.

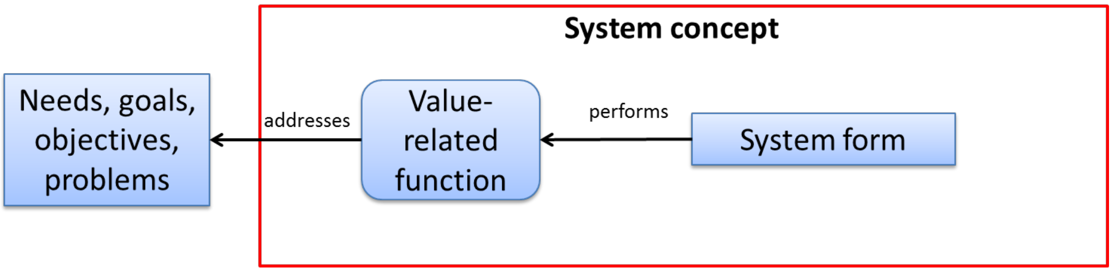


Fig. 3-2: System concept as the mapping between the value-related function and system form

A function at the top level is called "value-related function", as the function creates value for a beneficiary, for example a customer or stakeholder. The value-related function is often introduced as the "main function" in the product development literature (Erden and Komoto, 2008). Examples for system concepts are "train", "car", "rocket", and "mobile phone". To understand artifacts as a mapping between function and form is prevalent in the philosophy of technology and engineering literature. Kroes and Meijers (2006) and Kroes (2010, 2002) call this function – form interpretation of artifacts the "dual nature of artifacts". The highly influential book "The Sciences of the Artificial" by Herbert Simon precedes this understanding by defining artificial objects as:

"Let us look a little more closely at the functional or purposeful aspect of artificial things. Fulfilment of purpose or adaptation to a goal involves a relation among three terms: the purpose or goal, the character of the artifact, and the environment in which the artifact performs." (Simon, 1996, p.5)

Defining artifacts by their function – form mapping is therefore well-grounded in the existing literature. Note that system concepts are often defined functionally (air-conditioner, voice recorder, etc.) and sometimes additional attributes pertaining to its form are added (rubber projectile, chemical rocket, etc.).

A function consists of a process and an operand. For example, the function "transport passengers" consists of the process "to transport" and the operand "passengers". The operand is the object whose attribute or state is changed by the process. In the case of the passengers, their location is changed. This distinction between process and operand is consistent with common function definitions, for example in Otto and Wood (2000) and Pahl et al. (2007). Only the way functions are modeled is different. In OPM, "process" and "object" are modeled as independent entities whereas Pahl et al. (2007) and Otto and Wood (2000) represent functions as a single model element, as shown in Fig. 3-3.

Fig. 3-3: OPM definition of function versus a function from Pahl et al. (2007) and Otto & Wood (2001)

Here, a function is modeled as in Pahl et al. (2007) and Otto and Wood (2000). Their combined representation of process and object was considered to be an adequate level of abstraction. Fig. 3-4 shows an example of a function.

<<Function>> is the UML / SysML stereotype. It indicates that “transport passengers” is modeled as a modeling element “Function”.[16]

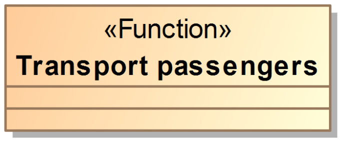


Fig. 3-4: Example function “transport passengers”

Modeling functions in this way is consistent with existing approaches to model functional architectures in SysML (Korff et al., 2011; Lamm and Weilkiens, 2010).

The operand is called value-related operand, if the change of the operand’s attributes or states creates value. For “transport passengers”, “passengers” are the value-related operand, as changing the passengers’ location is what creates value. The function that changes the state of a value-related operand is called a “value-related function”, as shown in Fig. 3-5.

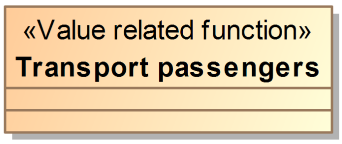


Fig. 3-5: The function “transport passengers” as a value-related function

A system architecture is a refinement of the system concept. To take the expression from the definition, it “embodies” the concept. In the following, these refinements that comprise a system architecture are introduced. To start with an example, the function “transport passengers” can be allocated to a variety of system concepts such as an airplane, a car, a train, a bus etc. Fist, each of these system concepts has different components. An airplane has wings and a fuselage, a car has a chassis, an engine, and wheels. Hence, a first element of a system architecture is the set of components. Second, the way the components interact with each other is different. For example, a car transforms torque from its engine into traction force which propels the car on a road. An airplane by contrast uses a combination of lift and thrust for moving through the air. The components and the relationships between these are called the “physical architecture”. Next, these components are based on different physical effects. For example, a wing generates lift, a gasoline engine transforms chemical energy into rotational energy via the physical effect of combustion. The way how these underlying effects and principles are harnessed in a system is called “working principle” as introduced by Pahl et al. (2007). Working principles are not only based on physical effects but a whole range of effects, principles, and patterns, as listed in Table 3-3.

Table 3-3: Effects, principles, and patterns underlying working principles

Effects, principles, and patterns of working principles	**Source**
Physical effect	(Pahl et al., 2007)
TRIZ solution principles for contradictions	(Ponn and Lindemann, 2011)
Biological phenomena	(Ponn and Lindemann, 2011)
Instructions (algorithms, methods, processes)	
Logic gate patterns	(Mead and Conway, 1979)
Software patterns	(Gamma et al., 1994)

The notion of “working principle” from Pahl et al. (2007) is similar to the notion of “core design concept” from the management literature such as Clark (1985), “operational principle” from the technology history and engineering

[16] A function in UML/SysML is represented by an “activity” modeling element and the stereotype “Function”.

philosophy literature (Vincenti, 1990). With Pahl et al. (2007) the way how working principles interact with each other is called “working structure”. Note that within a system hierarchy, a working structure can be called a working principle from a higher hierarchical level. The lower-level working structure is often reduced to the most important working principle. It is hence an abstraction. For example, the working principle of a gasoline engine described above is an abstraction of a real gasoline engine which consists of a working structure with numerous working principles. Finally, the working principles are mapped to functions.

In the following, I distinguish between the value-related function and functions that perform the value-related function. I call the latter “sub-function”. The sub-functions together with the relationships between them are called “functional architecture”. To summarize, the system architecture is a refinement of the system concept comprising components and their relationships (physical architecture), working principles and their relationships (working structure), and sub-functions and their relationships (functional architecture). Furthermore, the system architecture includes the mappings between these architectures. Fig. 3-6 illustrates the different elements of a system architecture.

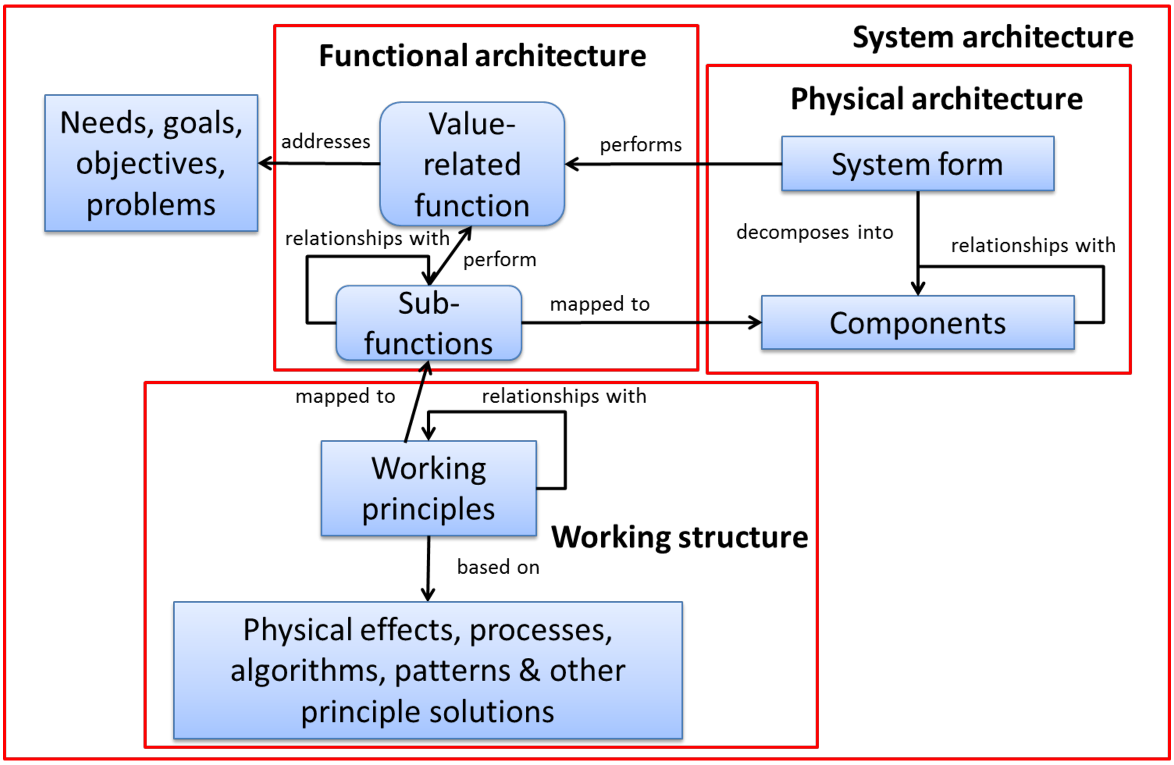


Fig. 3-6: System architecture consisting of functional and physical architecture, and the working structure along with mappings between them.

The system architecture alone is insufficient for implementing the system. For implementing the system, the design needs to be constrained by specific parameter values. Parameter values are for example the length of a metal rod, its material specification, and tolerances. The assignment of parameters to a system architecture is called “parametric design”, in order to avoid confusion between the general term “design” which refers to a plan for implementing an artifact. In practice, engineers define system concept, system architecture, and design recursively with frequent jumps between steps. However, usually the system concept freezes first, then the system architecture, and finally the parametric design. Later changes to the system architecture or even system concept are costly. This is the reason why conceptual and architectural decisions are considered to have a huge impact on the system development process (Schulz et al., 1999).

Representing the system context

A system operates in one or more contexts. A system usually needs other systems or actors to deliver value. These systems or actors are considered to be outside of the boundary of the system of interest. For example, mobile phones depend on a mobile network. In a mobile network a number of geographically distributed transceiver stations transmit and receive signals from mobile phones. This network is necessary as the transmitting power of mobile phones is too weak for communicating over long distances. Such an external system that is necessary for the system to deliver value is called a "supporting system". In the literature, supporting systems are also called "enabling system" (Haskins et al., 2007, p.5). Another example for a supporting system is a charging station network for electric vehicles. Without these charging stations, the vehicles cannot be operated.

An actor who operates the system of interest is called an operator. An operator is for example the pilot of an airplane or a bus driver. An operator can also be the user of a software, computer, or mobile phone. An operator can be the primary benefactor of a system but does not need to be. The pilot of a commercial airplane is not the primary benefactor of the airplane. The passengers are. In the case of a car, this might be different. The driver may drive the car in order to displace herself.

I call the set of elements that enables the system to deliver value "operational capability". The product / system, supporting systems, operator, and operands altogether form the whole product system, as shown in Fig. 3-7.

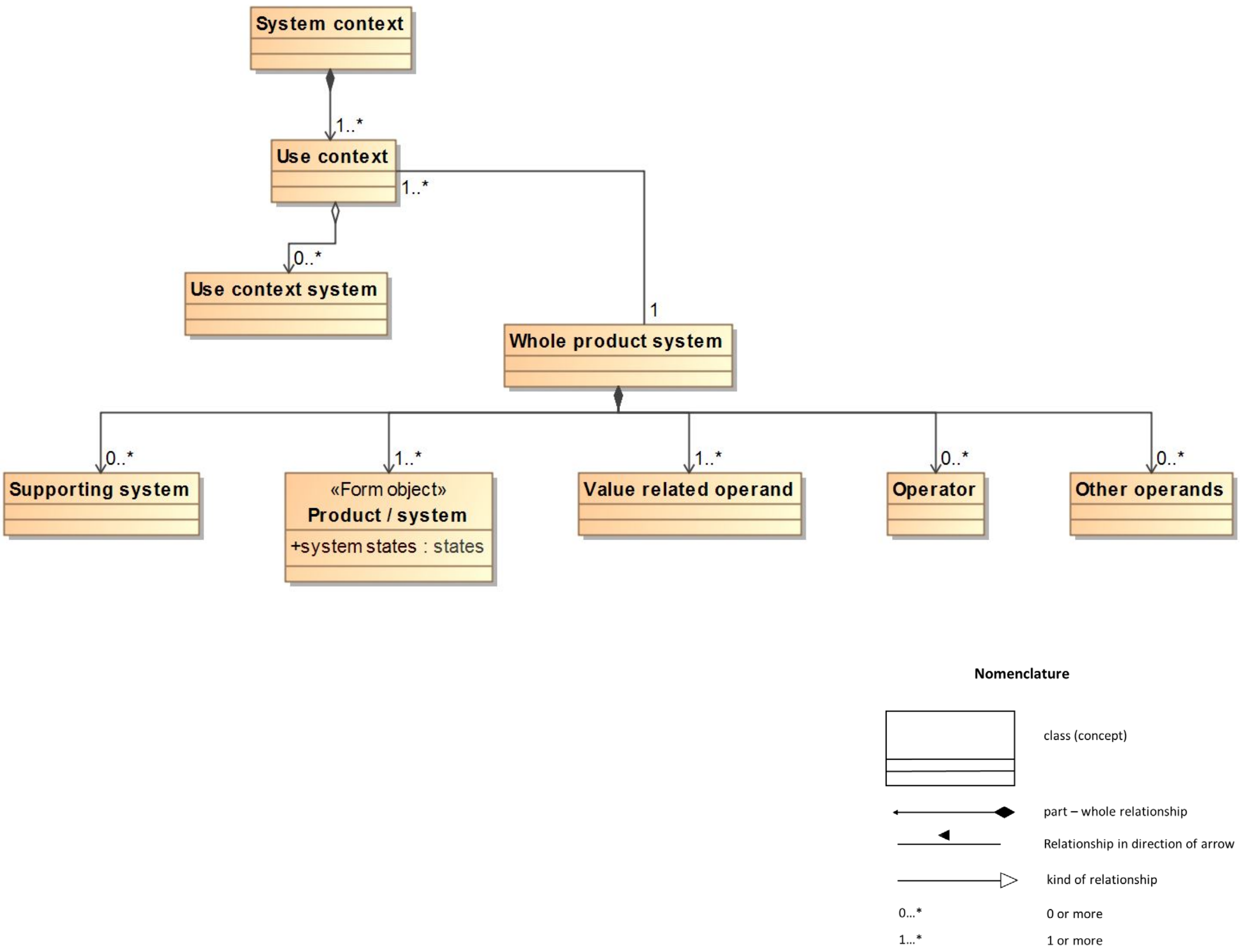


Fig. 3-7: A conceptual model for the system architecture framework, adapted from Crawley et al. (2015) and Crawley and Cameron (2012) using Systems Modeling Language (SysML) notation

The whole product system is embedded in one or more contexts. One context for an electric vehicle would be to transport a passenger within a city from one point to another. Such a use context is populated by a variety of use context systems: other vehicles, pedestrians, bicyclists, traffic signs, etc. These context systems directly interact with the electric vehicle. Context systems are not required for the system to deliver value. An electric vehicle does not receive any input from other vehicles, pedestrians, etc. for it to drive. Other contextual systems do not directly interact with the system but govern or constrain its operation. These are conventions such as regulations, standards, and laws along with stakeholders.

Use contexts change in space or time. Car drivers at the beginning of the 20th century had to pay attention to horse carriages. At the beginning of the 21st century, horse carriages do no longer dominate road traffic. Regulations for street vehicles differ from country to country. Safety regulations also significantly changed over the last 30 years.

3.1.3 Application Example for the Systems Architecture Framework

For demonstrating the practical usability of the framework an autonomous vehicle example is presented. The model is limited to the system and system context level but can be easily extended to more detailed levels by using the guidelines from the MBSE Cookbook (Karban et al., 2011).

Fig. 3-8 shows the elements of the self-driving car whole product system, namely, the self-driving car itself, the autonomous driving system, and the maintenance infrastructure. The self-driving car and the autonomous driving system are separated in this case, as it is assumed that an otherwise non-autonomous car is retrofitted with the autonomous driving system. The maintenance infrastructure is assumed to be an infrastructure that receives data from the vehicle and performs updates and other service activities if needed.

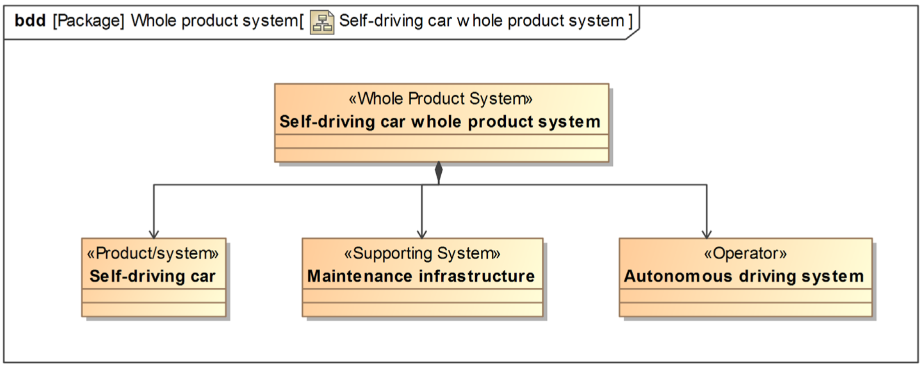


Fig. 3-8: Self-driving car whole product system

As shown in the SysML Internal Block Diagram in Fig. 3-9, the autonomous driving system receives sensor output from the vehicle and sends vehicle commands, for example for accelerating or breaking the car.

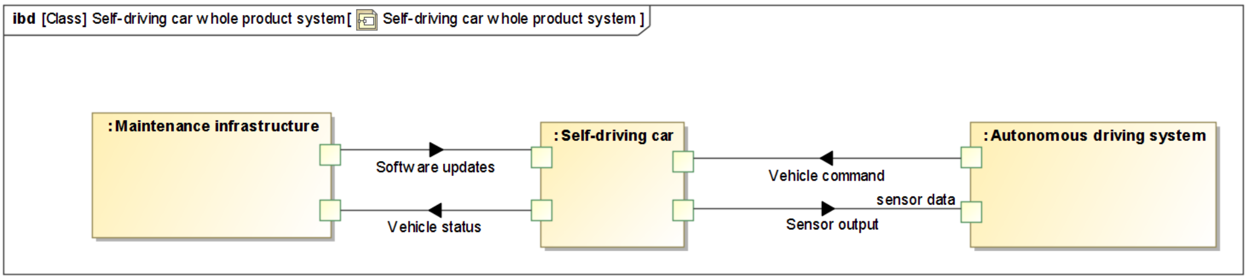


Fig. 3-9: The input-output relationships between the elements of the whole product system

Fig. 3-10 depicts the use context for a self-driving car in California. Critical elements are the infrastructure which includes roads, signposts, and signals, insurance companies which have agreed on insuring self-driving cars, and State regulations that impose certain rules on self-driving cars, such as a visual indicator if the autonomous mode is on or off.

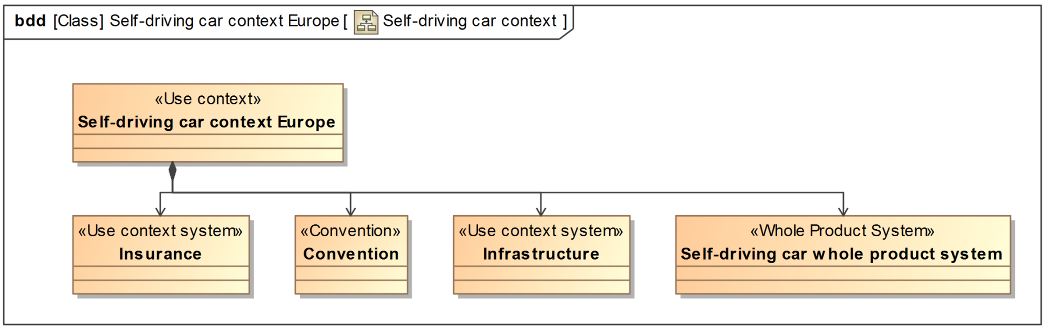


Fig. 3-10: Definition of a generic use context for self-driving cars

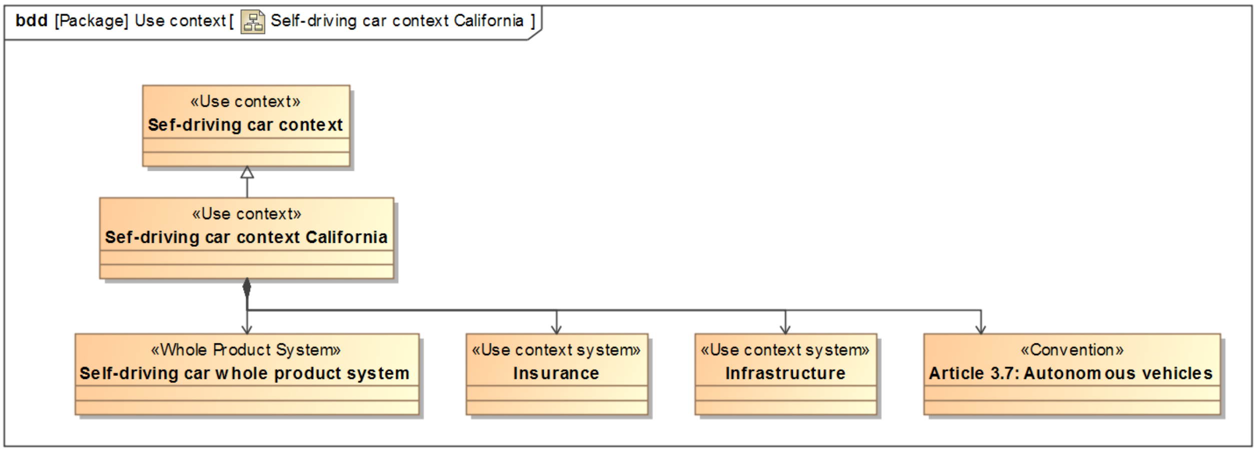


Fig. 3-11: Self-driving car context for California, derived from the generic use context

The use context can be used for deriving requirements and constraints, as it is demonstrated in the verification & validation framework introduced later.
The use context for self-driving cars is different in continental Europe (status 2014). For a continental European context, the 1968 Convention on Road Traffic requires the driver to be in control of the vehicle at all times (Taylor and Wissenbach, 2014).

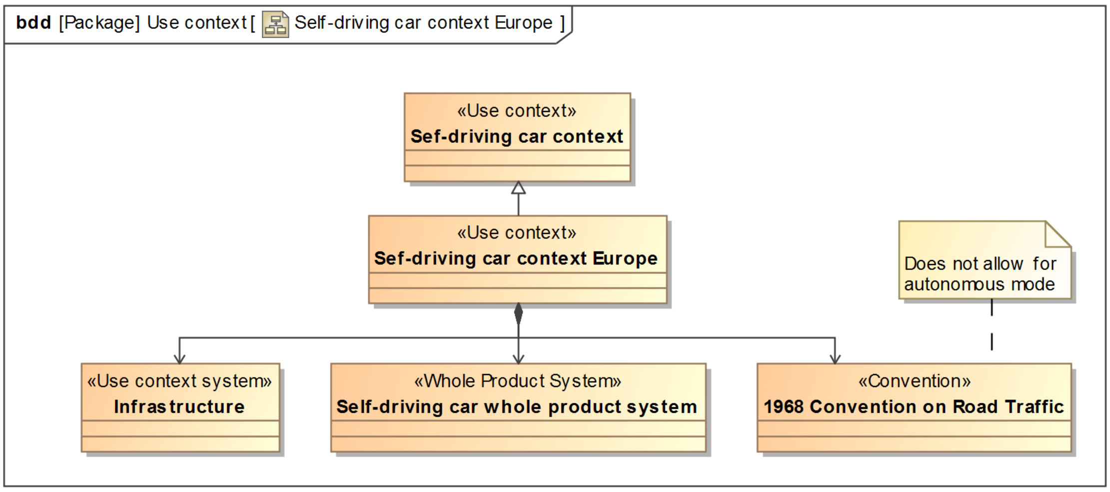


Fig. 3-12: Self-driving car context for continental Europe, derived from the generic use context

This example demonstrates how the systems architecting framework can be used to model different system contexts.

3.2 Technology Framework

3.2.1 Elements of the Technology Framework

The objective of the technology framework is to add more detail to the technology model presented in Section 1.3. It combines the technology model with the systems architecture framework presented in Section 3.1.

To briefly recapitulate, technologies in general are defined according to Section 2.1.4 as knowledge, method, system, or process or a combination of these. A technology is used to perform a task, to solve a problem, or to realize a function. Furthermore, a technology uses resources. A more specific technology definition in the context of heritage technologies was introduced in Section 1.3, where a technology consists of a set of technological capabilities, the design of an artifact, and optionally a set of artifacts based on the design. The notion of technology in this thesis is used in this limited sense of a set of technological capabilities pertaining to an artifact and the design of an artifact. The existence of an artifact is not a necessary condition for a technology to exist.

Looking at the MIT Systems Architecture Lab framework from the perspective of technology, its contextual model pertains to the artifact or system. The artifact is operated and generates value. In order to adapt the framework to technologies, further elements need to be added.

The systems architecture framework already distinguishes between a system, elements that the system needs in order to create value (whole product / system), and the system's context in which it operates. However, for properly representing heritage technologies, a few aspects are still missing:

- Technological capabilities;
- Verification, validation, testing, and operational history;
- Representations of the technology needed for its creation, modification, and operation, e.g. the system's design.

Hence, the systems architecture framework needs to be complemented by these elements. Fig. 3-13 depicts the elements of the technology framework. Within the framework, elements of the previous technology definition can be identified, such as technological capabilities, the design, and the artifact. The large rectangle with rounded corners delimits the elements that directly belong to a technology. Note that the arrows "consist of" between "technology" and the technological capabilities have been omitted to facilitate readability.

The relationships between the capabilities and various technology elements are represented. The research and development (R&D) capability along with the systems engineering capability develops the design of the artifact. These capabilities are grouped under development capabilities. Development usually ends when the first unit is produced and preparations for eventual mass production starts (Kossiakoff et al., 2011, p.107). The manufacturing capability allows for implementing the artifact(s). The operational capabilities enable to operate the artifact. Other capabilities that are not depicted are deployment and disposal capabilities. Each of the capabilities is enabled by a set of resources that are largely adapted from Bilbro (2008). The resources consist of skilled personnel, processes, models, methods, tools and other elements.

The technology has a life cycle phase and a VVTO history. These two elements belong to the history of a technology. "History" is important as a technology and its perception are shaped by its history, i.e. the decisions that were made that lead to the current state of the technology, the confidence in it, and why or why not it should be used. Furthermore, "history" is important, as it also determines in which life cycle phase the technology is in terms of its maturity. In the technology management literature, the notion of "history matters" can be found in the context of "path dependence" (Liebowitz and Margolis, 1995).

All elements from the systems architecture framework apply to the artifact and are partly omitted. The purpose of a technology is located outside of a technology, as the technology addresses needs, goals, and problems that are not part of the technology itself. The purpose of a technology is embedded in its context. The context includes context systems, conventions in the form of norms, standards, and regulations. The context usually directly constrains the technology and defines it is allowed to do. What the technology should do is usually formulated via the needs, goals, and problems the technology addresses.

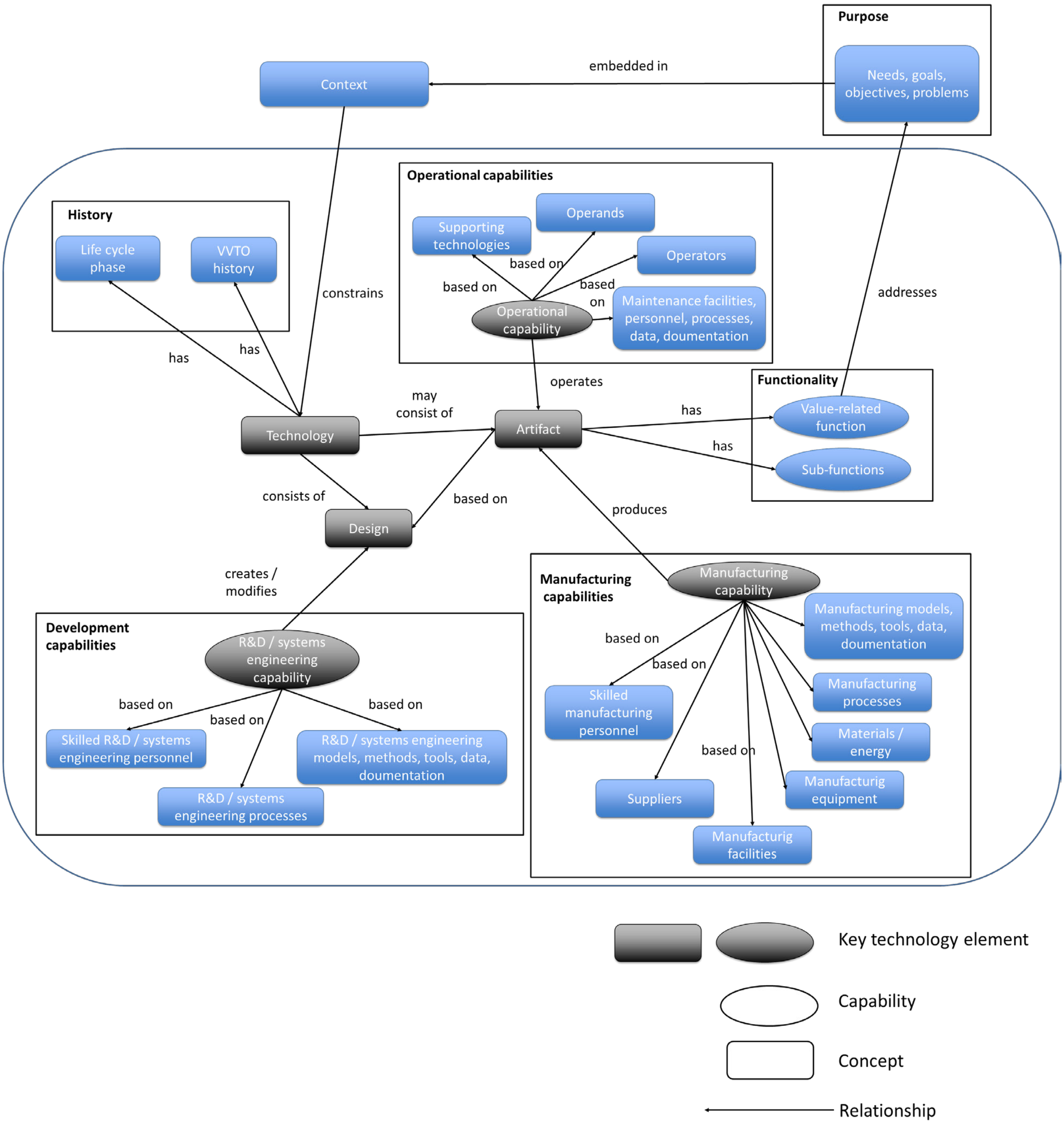


Fig. 3-13: Technology framework elements

One question is of course, which elements in this framework should be considered a necessary part of a technology and which ones are not. This question was briefly considered in Section 1.3 but a more elaborate answer will be provided here. I will go through each element of the framework and ask if this element should be considered a necessary element of a technology or not.

To start with, a technology has by its definition a purpose. Hence, the purpose is a necessary element pertaining to a technology. That purpose may change over its lifetime or even never be realized as intended, which would be the case for a technology that has never left the laboratory. Nevertheless, there is at least an intended purpose. Next, to address the purpose, a technology has a function. In order to perform the function, an actual artifact is needed or another form in which the general technology is embodied. For methods, processes, and knowledge the actual embodiment are the agents that perform the method, process, or the medium in which the knowledge is stored. For example, the knowledge of knowing how to open a bottle is embodied in a person capable of opening a bottle. An assembly line process is embodied in an actual assembly line that can execute the assembly line process. However, are instances really needed for a technology to exist? Let's consider the example of a space instrument that has been built once for a mission. The instrument was flown and the satellite on which it was flown was destroyed during atmospheric reentry. Would this technology be considered lost? Intuitively, this technology would not be considered lost, even if no artifact exists. The question would be if another similar instrument could be built. If yes, the technology is not lost. Usually a technology would be considered lost, when no organization or person can execute a certain process, method, or use the know-how. For a device, the technology would be considered lost if nobody knows how to create it, use it or even understands it as is the case for the mechanism of Antikythera, an ancient computing device (Freeth et al., 2006; Messler, 2013).

Fig. 3-14: Mechanism of Antikythera (Wikipedia, 2016b)

Following this intuition, I conclude that the existence of artifacts is not necessary for a technology to exist but capabilities associated with a technology are.

A technology exists if another artifact *could* be manufactured and operated. To test this hypothesis, it is assumed that for a certain technology an instance exists but no capabilities associated with it. Indeed, there are several examples from archeology that satisfy this condition. One example is Damascus steel, a special type of steel that is considered particularly tough and resistant. Attempts to reproduce Damascus steel have not been successful due to different raw materials and manufacturing processes. Another, more recent example is the Stradivari violin. It is claimed that instruments manufactured by the Stradivarius family are unique in their quality of sound, although this claim is disputed (Fritz et al., 2012). Assuming the claim is true and the Stradivari has a unique sound, it would be a case where artifacts of the technology exist but it is no longer reproducible. For the mechanism of Antikythera, the situation is different, as reproducing the mechanism was possible but its purpose is still disputed (Freeth et al., 2006). A recent example is the Saturn V rocket. Several instances of the Saturn V rocket exist but it is disputed if it could be reproduced today due to no longer existing metal alloys, craftsmanship, and suppliers. These examples often appear in discussions on "lost" technology. In each of these cases artifacts exist. It is therefore concluded that if an artifact of the technology exists, it does not necessarily mean that a technology exist.

If, in principle, the artifact can be recreated, the technology would be deemed to exist. For example, the Saturn V tanks could be recreated as developing large cryogenic tanks is a capability that is still prevalent today. It also depends on how wide or narrow a technology is defined. Is the objective to exactly replicate the Saturn V tank? This is certainty very difficult. Or is the objective to replicate the tank in a different context of suppliers, customers, etc. This is likely possible. To conclude, the existence of an artifact *may* imply the existence of a technology. By contrast, if the capabilities associated with a technology exist, the technology exists. Note that this reasoning implicitly assumes that knowledge is the basis for technology. If certain knowledge is lost, a technology is lost.

Next, which types of knowledge, i.e. capabilities are necessary for a technology to exist? First, it is obvious that the manufacturing capability needs to exist as it enables the creation of artifacts. For development capabilities this is less clear. There are many cases where the original design engineers of certain technologies have long retired but the artifacts are still being produced, in particular systems with long life cycles such as airplanes and space launchers. However, the existence of occasional upgrading and modification programs for retaining development capabilities is a hint that these capabilities are considered as important for keeping a technology "alive". It is therefore concluded that if development and manufacturing capabilities can be reactivated if necessary, the technology still exists.

Finally, operational capabilities can be considered less important, compared to the first two capabilities. However, a technology whose purpose is no longer known and can therefore not be operated is not able to deliver value. For example, it is unknown for which purpose the Antikythera mechanism was used. It is known how the mechanism functions but the context in which it was used is unknown. Therefore, it is not known how the mechanism delivered value and therefore it is not known how it could deliver value today if it were to be used. Again, appealing to intuition, the operational capability is intimately linked to value delivery. If the operational capability does not exist, the technology would be considered existent but would be unable to deliver value. In other words, the technology is not useful.

To conclude, necessary elements of a technology are its function, the purpose it addresses, R&D and systems engineering capabilities, and manufacturing capabilities. Instances of a technology and operational capabilities are important for the technology to deliver value but they are not essential in the sense of if they do not exist, the technology does not exist. The same is valid for technology representations. While they are needed for creating instances, from their non-existence does not necessarily follow that the technology does not exist.

Table 3-4 provides a summary of the essential and non-essential elements of a technology that have been elaborated in this section.

Table 3-4: Essential and non-essential elements of a technology

Technology framework element	Essential / non-essential for a technology to exist
Purpose	Essential, although not part of a technology as external to technology
Functionality	Essential for addressing a purpose
Artifact (or another instance of a general technology)	Not essential but needed for delivering value
History	Essential and part of technology
R&D / systems engineering capability	Essential and part of technology
Manufacturing capability	Essential and part of technology
Design (type)	Not essential but needed for creating artifacts
Operational capability	Not essential but needed for delivering value

3.2.2 Forms of Technology Change

Understanding technology change is key to understanding the evolution of technology (Arthur, 2009; Baldwin and Clark, 2000; Henderson and Clark, 1990; Nolte, 2008). A technology framework needs to be able to represent different forms of technology change. An overview of forms of technology change is shown in Fig. 3-15. To start on the left side, technology modification improves an existing technology. If the design is improved, it is called "design modification". If it improves an existing technology instance, it is called "retrofitting". If a capability is modified, it is called "capability modification". Innovation is an important mechanism that can be based on extending an existing technology by introducing a new feature, function, or component. Innovation can also be based on combining existing technologies in a new way, by extending an existing technology, and absorbing another technology. The main difference between modification and innovation is that an innovation is necessarily based on something new, such as an invention or new application of a technology. By contrast, a modification is not necessarily based on something new. Another important mechanism is technology loss. Technologies can be lost due to obsolescence or uninvention. Obsolescence means that the technology is no longer needed or available. Uninvention by contrast is the loss of a technology due to the loss of a vital capability (MacKenzie and Spinardi, 1995). Technology transfer and diffusion are mechanisms for spreading a technology.

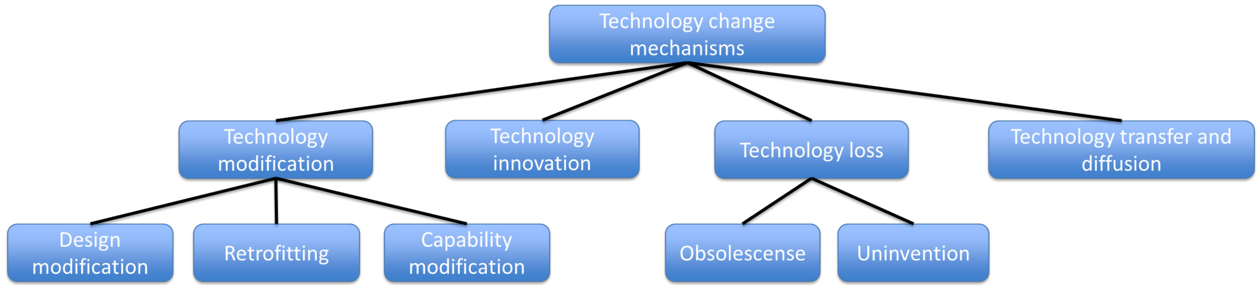


Fig. 3-15: Forms of technology change

In the following, different sources of changes are identified and how they impact different technology elements Fig. 3-16.

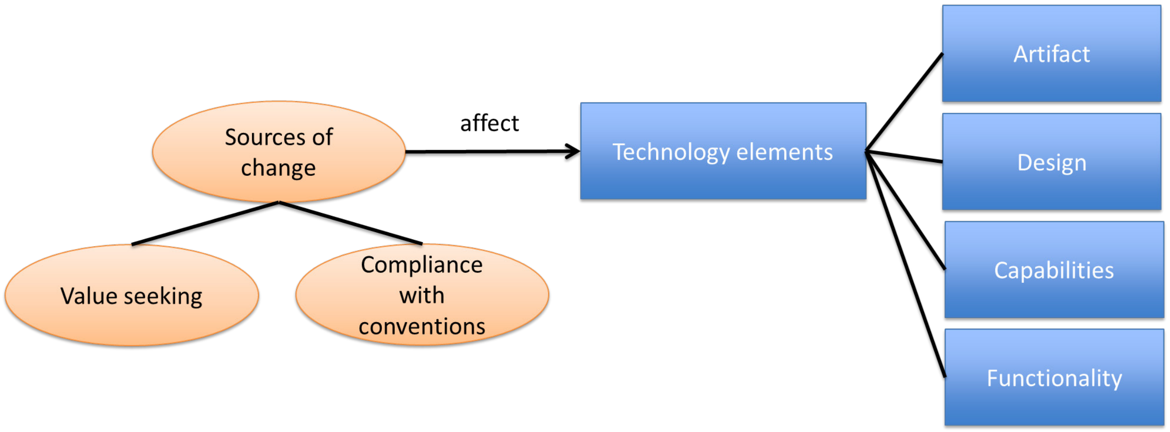


Fig. 3-16: Sources of changes that affect technology elements

At the most basic level, the motivation for changing a technology can be interpreted as a "value-seeking process" (Baldwin, C. Y., Clark, 2000, p.246). "Value" is interpreted as any form of benefit that a technology may provide. Baldwin & Clark assert that technologies are changed for creating and capturing value (Baldwin, C. Y., Clark, 2000, p.245). The creation of value depends on markets where a need for the technology exists. The term "market" is used here in the widest possible sense as a place where parties can exchange goods and services. This encompasses exchange for money but also other forms of exchange such as bartering. Technologies must be adopted by markets in order to create economic value (Katz and Shapiro, 1986). In other words, there are parties that are willing to exchange a technology for money or other objects. A rich set of literature deals with technology change and market adoption (Christensen, 1992a, 1992b; Katz and Shapiro, 1986; Parente and Prescott, 1994).

Other sources of technology change are changing regulations, norms, standards, values, and procedures. In the following, these sources are called "conventions". Some of them are mandatory to fulfill such as regulations. Their non-satisfaction leads to penalties. Others are not mandatory but expected to be adhered to such as norms, standards, values, and procedures. Non-satisfaction leads to sanctions. Note that "value" in this context is not a form of benefit but value in the sense of a moral principle. Satisfying conventions is not directly related to value delivery through a market but indirectly by representing interests of the public, professional organizations, and the organization owning the technology. As public interest and interests of organizations change, so do conventions. Technologies therefore have to adapt to conventions. One example is the environmental performance of automobiles. The permissible values for emissions have been continuously reduced in Western countries and car manufacturers are struggling to comply with ever demanding regulations. Complying with conventions is therefore a prerequisite for staying or entering the market. In other words, compliance is the entry ticket to the market but does not provide value by itself.

If seeking value is the primary driver of technological change, how does seeking value affect the different elements of a technology shown in Fig. 3-13? The following changes to the elements of a technology are logically possible. Note that "anticipated" is added to many change categories, as changes can be made in preparing for such a future event that necessitates a change.

- *(Anticipated) changes in value-related function and sub-functions:* The technology needs to perform a different value-related function or some of its sub-functions may be changed. The value-related function may be changed if the technology is expected to address a different market segment. A sub-function may be changed for increasing performance, mitigating negative effects of the technology, or improve value creation.
- *(Anticipated) changes in needs, objectives, and requirements:* Customer or stakeholder needs and preferences change. For example, new functionalities or a better performance are requested. Some product functions may evolve into commodities and are expected to be present without increasing customer satisfaction (Kano et al., 1984). The relationship between changing needs, objectives, requirements and technology changes has been extensively considered in the product development and systems engineering literature. Prominent examples are the use of product platforms to cost-effectively deliver product variants for addressing different needs (Jiao et al., 2007). Systems based on a common platform share components or manufacturing infrastructure, thus, profiting from economy of scale effects and shared development costs (Hofstetter, 2009). Product platforms are extensively used in the automotive industry (Cameron, 2011).
- *(Anticipated) changes in context:* Changes in the context can be changes in conventions. Conventions are regulatory changes, changing standards, norms, and values. For example, nuclear thermal propulsion was developed in the USA during the 60s and early 70s (Dewar, 2004). However, public acceptance of nuclear power for space applications has significantly changed since then, leading to protests against launching spacecraft with nuclear batteries (Launius, 2014).
- *(Anticipated) changes in resources the technology uses or consumes:* Inputs to the processes a technology performs may also be an important source of technology modifications. For example, the use of different power supply voltages induce additional requirements to a system, such as the use of an adapter.
- *(Anticipated) changes in manufacturing capabilities:* A capability changes and entails changes of other elements of the technology. Examples are new manufacturing processes that are introduced to decrease manufacturing cost or in order to comply with new regulations. For example, the obligation to use lead-free sold in space hardware in Europe has forced suppliers to change their soldering processes. The use of lead-free sold has induced design changes as lead-free sold is prone to developing whiskers that might lead to short circuits, if circuit paths are too close to each other.
- *(Anticipated) changes in operational capabilities:* These changes affect elements that are necessary for the technology under consideration to deliver value, for example, supporting systems. For example, the phasing out of analog television emissions forces TV set manufacturers to develop TV sets capable of receiving digital emissions. The supporting system in this case are the various TV stations. Without the TV stations, the TV set cannot provide value.
- *Design changes:* Design changes may occur, for example, when a designer has found a better solution to a design problem. Furthermore, changes in the architecture may occur, when a higher or lower degree of modularity is desirable. Component changes may occur due to changes in suppliers, component obsolescence, etc. Suppliers may change the specification of a component due to available materials, regulations, etc. New, more competitive components may enter the market or a component may no longer be manufactured. For example, during the development of the OCO-2 spacecraft, the obsolescence of on-board data handling board components lead to a considerable cost increase (GAO, 2009). The design changes in this case did not contribute to a higher value return to customers by e.g. returning higher-quality data. Nevertheless, obsolescence can be used to opportunistically upgrade a technology. For example, the replacement components usually have a higher performance than their predecessors and thus could increase the data processing rate on-board of the spacecraft. A further source of component change is the correction of errors. Customer complaints are often related to teething problems, which are typically minor errors detected after initial deployment and operation. In some cases these errors could be major, as in the case of the Boeing 787 Dreamliner, where battery problems lead to a grounding of all 787s.
- *Changes due to life cycle transition:* These are changes that are induced by changing technology life cycle contexts. For example, a technology may have reached its peak in market adoption and enters a phase of steady decline. In such a case, a company may slowly phase out production (Sandborn et al., 2007). The decision to phase out is often based on anticipated or already declining market shares.

3.2.3 Technology Modifications

According to the US Air Force (2001), modifications are "permanent changes to correct material deficiencies, improve reliability and maintainability, improve performance, or add or remove capability." In other words, modifications have the goal of correcting and improving a technology or to up- or downgrade it. To make a distinction between modifying the design of an artifact or the artifact itself, I furthermore distinguish between design modification and retrofitting. Design modifications are modifications made to a design of a system whereas retrofitting is the modification of existing artifacts. For example, design variants of a car that are based on an existing design are design modifications. By contrast, upgrading an existing B-52 airplane by mounting a new sensor is a case of retrofitting. Fig. 3-17 shows graphically how design modification affects the design of a technology, retrofitting affects an artifact, and how capability modification affects capabilities.

In general, there is no sharp demarcation line between technology modification and technology innovation. Some modifications are based on innovations and vice versa. However, modifications are often corrective and are not necessarily based on an invention as is the case for innovation. In other words, a modification does not necessarily imply something new. Consequently, modifications are a subset of technology changes in general.

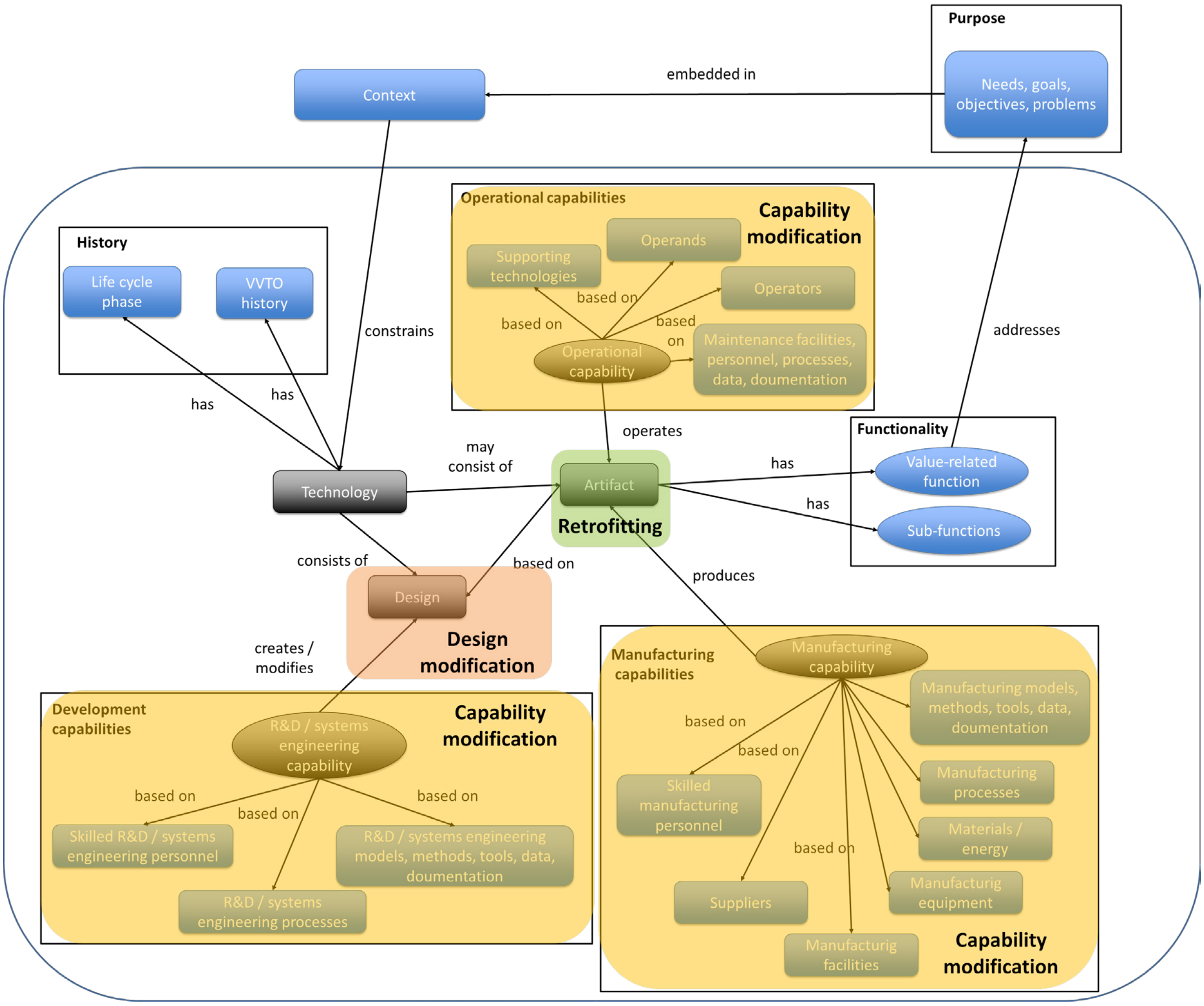


Fig. 3-17: Types of technology modification affecting technology elements

3.2.4 Technology Innovation

According to OECD (1991), innovation is “an iterative process initiated by the perception of a new market and/or new service opportunity for a technology-based invention which leads to development, production, and marketing tasks striving for the commercial success of the invention.” They thereby distinguish between the invention of a new technology and its commercial success. Innovation is considered one of the main drivers of modern economies by seeking and capturing value (Klein, 1984; Solow, 1957). Due to the large number of different types of innovation I am particularly interested in innovation typologies. I am furthermore interested in what aspects of technology certain innovation types affect. Chandy and Prabhu (2010), Garcia and Calantone (2002), Garcia (2010), and Kotsemir (2013) provide concise innovation classifications.

Due to the large number of innovation classifications I limit my survey to some of the most frequently cited types of innovation in the literature, most notably:

- Radical vs. incremental innovation (Henderson and Clark, 1990);
- Modular vs. architectural innovation (Henderson and Clark, 1990);
- Competency enhancing vs. destroying innovation (Tushman and Anderson, 1986);
- Disruptive vs. sustaining innovation (Christensen, 2013).

Finally, an alternative interpretation of radical innovation from Garcia and Calantone (2002) is considered, in order to demonstrate how it affects different technology elements than the one from Henderson and Clark (1990).

Henderson and Clark (1990) introduce four innovation categories: incremental, modular, architectural, and radical. The incremental – radical innovation distinction has been already established in the literature before. Incremental innovation introduces “relatively minor changes to the existing product, exploits the potential of the established design, and often reinforces the dominance of established firms.” (Henderson & Clark, 1990, p.9) Modular innovation is innovation “that changes only the core design concepts of a technology and innovation that changes only the relationships between them.” (Henderson and Clark, 1990, p.12). Radical innovation “is based on a different set of engineering and scientific principles and often opens up whole new markets and potential applications.” (Henderson and Clark, 1990, p.9) Architectural innovation “is the reconfiguration of an established system to link together existing components in a new way.” (Henderson and Clark, 1990, p.12) Henderson and Clark (1990) claim that architectural innovation can be a significant challenge to companies, as it requires a change in the existing mode of operation. These four innovation categories primarily pertain to the design, as shown in Fig. 3-18.

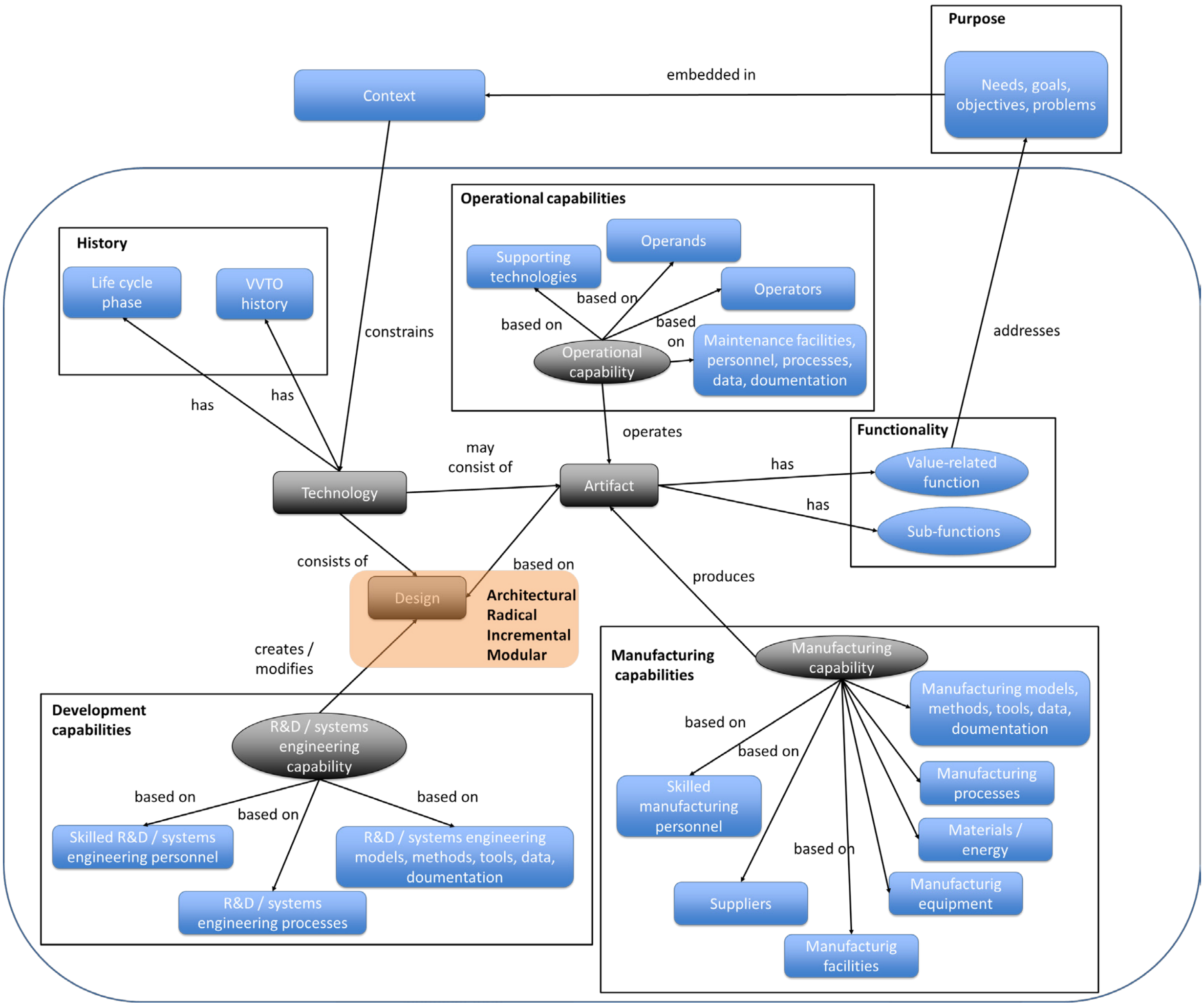


Fig. 3-18: Architectural, radical, incremental, and modular innovation affecting the design of a technology

Besides falling into one of the above categories, according to Tushman and Anderson (1986) an innovation can be competency enhancing or destroying. "Destroying" can be interpreted as "making obsolete". For example, pocket calculators and computers made human calculators obsolete. Table 3-5 shows the effect of competency destroying and enhancing innovation on technological capabilities and provides an example for each.

Table 3-5: Competency enhancing and destroying innovation

	Technological capability	**Example**
Competency destroying innovation	Made obsolete	Digital watches made the capability to design and manufacture mechanical watches obsolete.
Competency enhancing innovation	Enhanced, extended	Designing more efficient jet engines leads to building up experience and knowledge in jet engine design.

As I use the term "competency" synonymous to "capability", competency destroying and enhancing innovation affect technological capabilities as shown in Fig. 3-19.

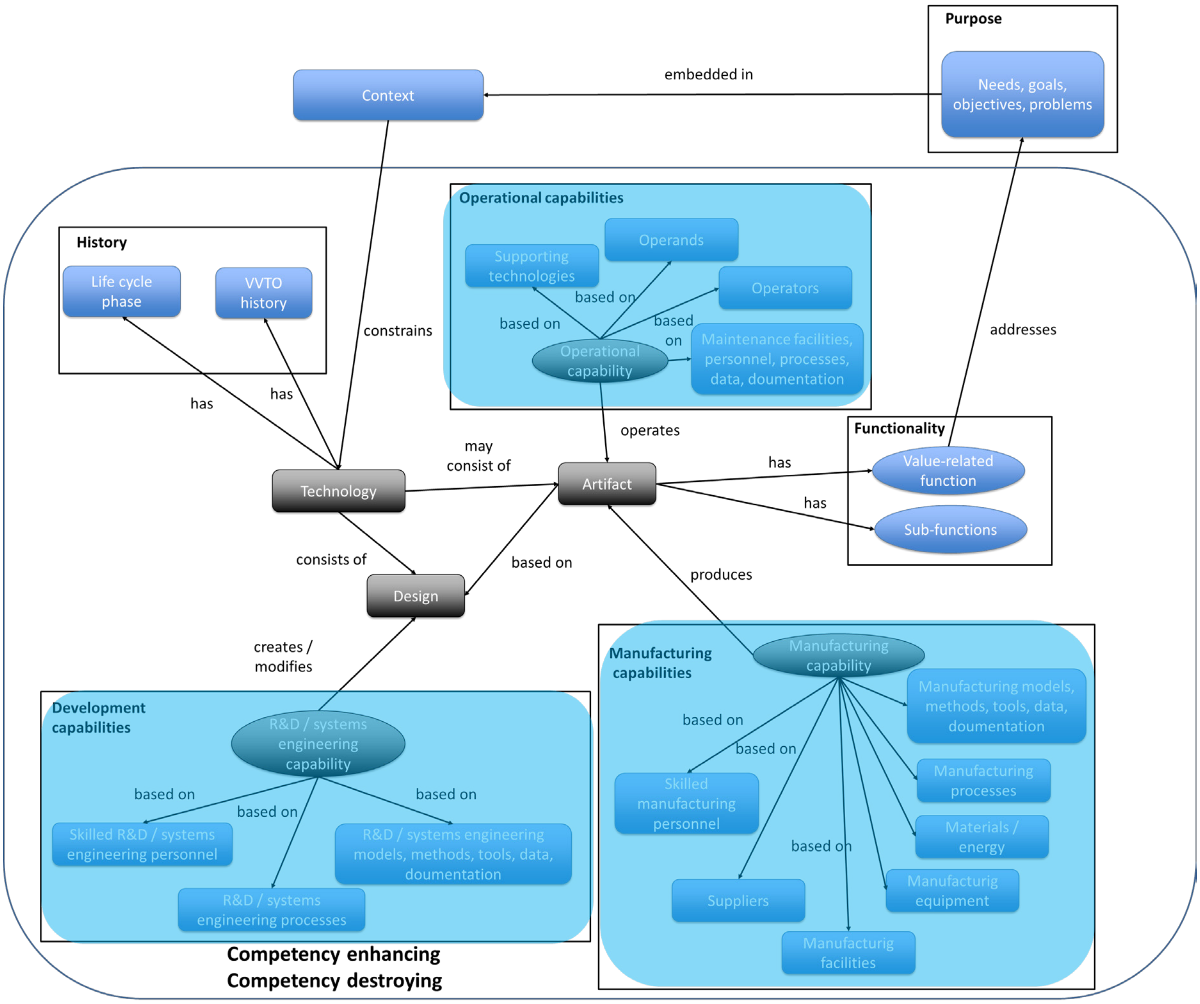


Fig. 3-19: Competency enhancing and destroying innovation affecting technological capabilities

Another well-known type of innovation is "disruptive innovation". The term has been coined in Clayton Christensen's book "The Innovator's Dilemma" (Christensen, 2013). In essence, disruptive innovation is the entrance of a technology into a new market that has been previously matured in a different market. Within the new market, it gradually makes incumbent technologies obsolete. Examples are the replacement of desktop personal computers (PCs) by laptops. Originally, laptops were intended for mobile use and had a considerably lower computing power and memory than PCs. However, both increased to a level where the computing power and memory of a laptop were sufficient for most customers, which lead to shrinking PC sales. Disruptive innovations are usually based on existing technologies. However, the context, i.e. the market, in which the technology enters is changed, as illustrated in Fig. 3-20.

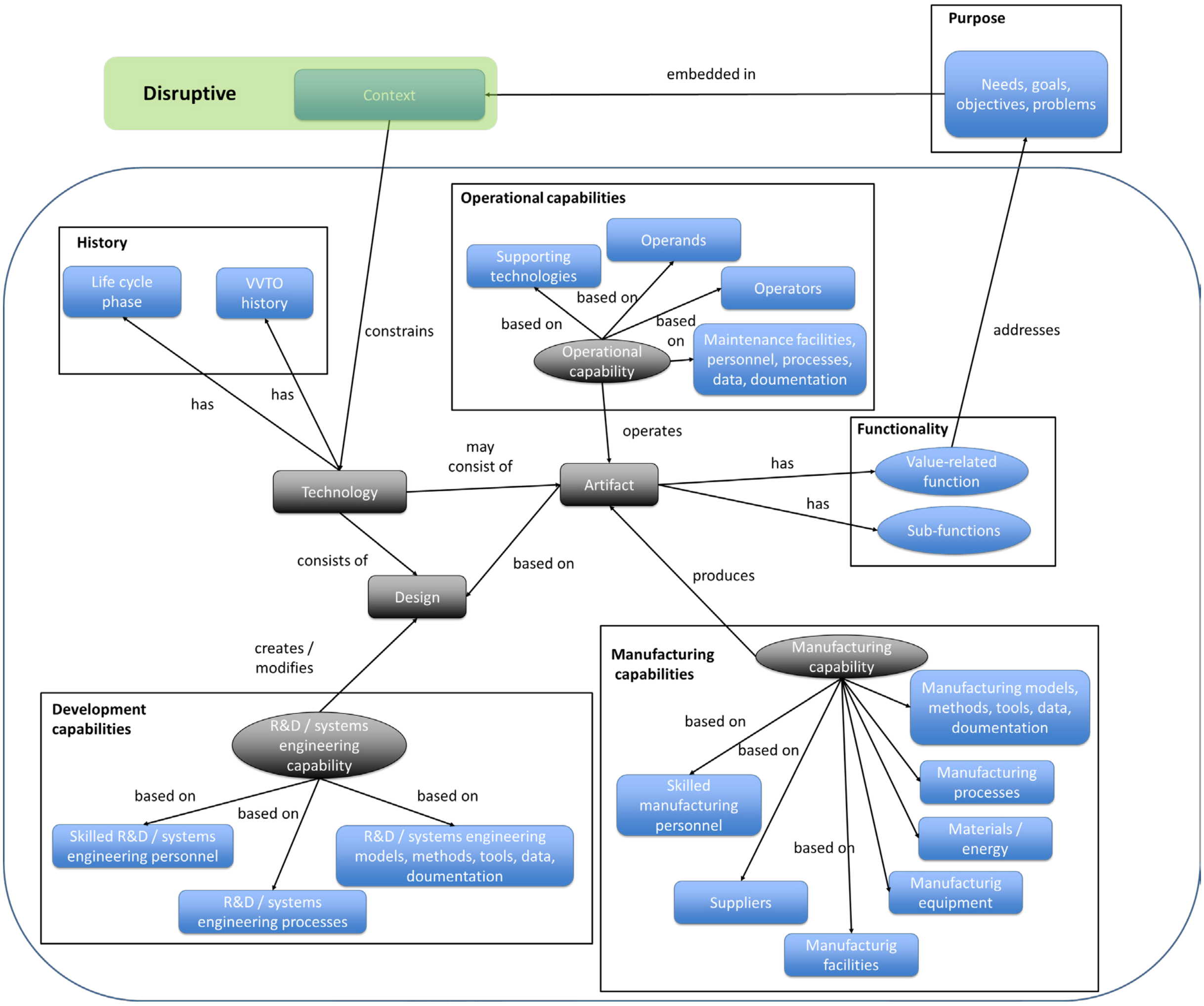


Fig. 3-20: Disruptive innovation originates in a change in context of a technology

The four innovation categories from Henderson and Clark (1990) were introduced before. The category of radical innovation is interpreted as a drastic change in the components and their relationships. However, Garcia and Calantone (2002) propose a different interpretation of radical innovation. A radical innovation in the sense of Garcia and Calantone (2002) is an innovation that creates a new market, is based on a new technology, drastically changes or creates a new organization, and changes society. One example of a radical innovation is the world-wide web. It lead to creating whole new markets such as e-commerce, is based on new technology such as the Transmission Control Protocol / Internet Protocol (TCP/IP), which is a set of protocols that allow computer networks to exchange data. Numerous new companies emerged due to the internet, and finally, it drastically altered the way how people communicate, most notably the use of emails instead of letters. Fig. 3-21 depicts these effects on the technology elements. A new design of a technology is created, therefore, the design is affected. Next, a whole range of new capabilities have to be developed. These capabilities are embedded in new or drastically altered organizations that belong to the technology context. Furthermore, the context also includes new markets that were previously not addressed. The operational capability is related to the changes in user behavior and supporting systems such as computer terminals that have internet access.

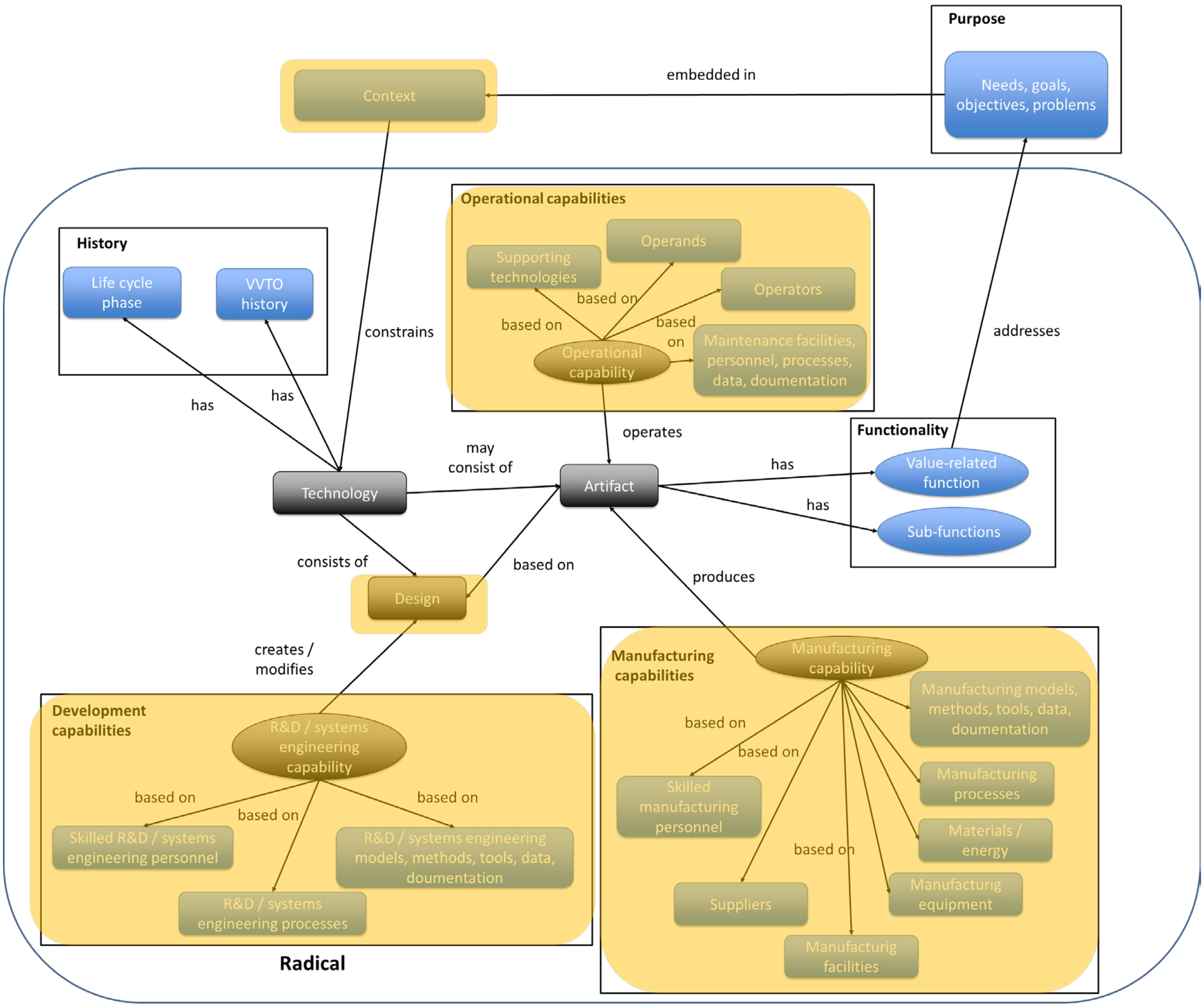


Fig. 3-21: Radical innovation according to Garcia and Calantone (2002) affecting capabilities, design, and context

In this section, I demonstrated how certain types of innovation are affecting elements of technology.

3.2.5 Technology Loss

One consequence of innovation is obsolescence. Obsolescence can be defined as “the state of being which occurs when an object, service or practice is no longer wanted even though it may still be in good working order.” (Fowler and Fowler, 1995) Bartels et al. (2012) define obsolescence as “the status given to a part when it is no longer available from its original manufacturer.” They list a number of reasons for no longer producing a part (Bartels, Ermel, Sandborn, & Pecht, 2012b, p.1):

- Nonavailability of materials needed to manufacture the part;
- Decreased demand for the part;
- Duplication of product lines when companies merge;
- Liability concerns.

Hence, obsolescence as the replacement of an existing technology by a better technology is only one cause of obsolescence.

In the context of heritage technologies I am more interested in technologies that are no longer available. The lack of a need is only one of several possibilities why a technology is no longer available. Hence, the following definition of “obsolescence” was adapted from the one from Bartels et al. (2012).

Definition: Obsolescence

The status given to a technology that is no longer available from its original manufacturer.

I furthermore consider the case in which a technology is no longer available *in general*. More specifically, for getting access to the technology, it would need to be newly "invented" and developed. Such a technology is an "uninvented" technology, according to MacKenzie and Spinardi (1995).

Definition: Uninvention

The status given to a technology that is in general no longer available.

The main difference between "obsolescense" and "uninvention" is that obsolescence does not imply that the technology is completely lost. It might just be that the production line was shut down and would be too costly to reopen. All the equipment, personnel, and knowledge might still be there (Birkler et al., 1993). In the case of uninvention, substantial elements of a technological capability have been lost. Recreating the technology would basically lead to newly developing the technology. I admit that the difference between obsolescence and uninvention is gradual. A technology might get obsolescent in one company and subsequently in other companies. Finally, there are no longer suppliers that are able to supply the technology. The technology might still not be considered uninvented in case production could be easily relaunched. However, after loss of personnel, equipment, processes, and documentation, it is safe to claim that the technology would need to be newly created and hence it is uninvented. An extreme case where obsolescence and uninvention would coincide is the case of a person that possesses a unique skill that is vital for a technology to exist. When this person dies, the technology would also no longer exist. Unless the skill is newly learned by somebody else, the technology will remain lost. This is a case of obsolescence, as the technology is no longer available from the supplier. It is at the same time uninvention, as the technology is no longer available in general. Therefore, uninvention implies obsolescence but obsolescence does not automatically imply uninvention.

In the context of heritage technologies, obsolescence and unvinvention are both relevant. Obsolescence occurs frequently for electronic components. Uninvention has occured for special materials such as the Apollo heatshield material and alloys for rocket engines such as the F-1 engine.

Various types of obsolescence can be derived from the technology framework, as shown in Fig. 3-22. Seven sources of obsolescence are described in more in detail in the following, as they frequently appear in the literature:

- Value-function related obsolescence: Obsolescence may occur, when a product is replaced by a product which provides more value to a customer. "Value" is understood here as benefit per cost. Hence, an increase in benefit, decrease in cost or both can lead to an increase in value. For example, a microprocessor with a higher performance than a previous version makes the previous processor obsolete. Cell phone generations have been repeatedly made obsolete by smaller and lighter phones which in addition provide more functionality. A more controversial case is planned obsolescence, where a product is made obsolete, although the new product might not provide increased value. Planned obsolescence is often related to products that wear out after a certain period of time in order to push customers to buy a replacement.
- Business context-related obsolescence: Another type of obsolescence occurs when a product is no longer profitable and a company decides to cease its production. In such a case, the product still delivers value and is not substituted. Reasons for a lack of profitability might be a diminishing market share, low profit margins, and changing priorities of a company. A changing business context can induce obsolescence indirectly via absent operational capabilities such as product support.
- Operational capability-induced obsolescence: Obsolescence can also be induced by the lack of supporting systems. For example, printers get obsolete when ink cartridges are no longer produced. Computer operating systems get obsolete when support is no longer provided, as in the case of Windows XP. Obsolescence can also be induced when properly trained operators are no longer available. For example, the operation of the Voyager probes, which have been launched in the 70s, depends today on a hand full of operators that have the knowledge to operate the probes. Once these operators are no longer available, the probes will be lost, i.e. can no longer deliver value via scientific data. Another possibility is the loss of the value related operand. Without the value related operand, the system can no longer provide value. For example, workshops specializing in repairing horse-drawn wagons got obsolete once horse-drawn wagons were made obsolescent by automobiles.

This source of obsolescence is called "functional obsolescence" in the literature (Bradley and Dawson, 1998; Sandborn, 2007; Weerasuriya and Wijayanayake, 2014).

- *Manufacturing capability-induced obsolescence:* Obsolescence can also be induced by lacking manufacturing capability. Within the space domain scientific instruments are often developed by research institutes such as universities or small and medium companies. There are reported cases where an instrument went obsolescent when a component supplier was closing down the production line for the component. Other sources of obsolescence were induced by a change of staff, e.g. PhD students and post-doctoral researchers that left the laboratory. Even in small and medium companies changing staff can severely impede the capability to manufacture an artifact.
- *R&D, systems engineering capability-induced obsolescence*: Obsolescence is not only induced by a lacking operational or manufacturing capabilities but also by a lack of a development capability. The design of a technology seldom remains the same for years due to changes in the context. Space instrument designs are often modified for the next mission due to pressure to increase performance (Interview I2, I3). Such a redesign requires staff with a good knowledge of the original design, design documentation, including the verification, validation, testing documentation, and sometimes highly specialized software tools. Another well-known case of design obsolescence is the case of the European ATV vehicle for supplying the International Space Station (ISS). The original design and systems engineering team has been disbanded and the technology is considered lost, i.e. needs to be newly developed if another ATV vehicle is commissioned.
- *Artifact-related obsolescence:* A less relevant form of obsolescence is the case when artifacts no longer exist. Such a case would only be called "obsolescence" if other forms of obsolescence are present. If all capabilities are still present, an artifact could be manufactured. If capabilities lack and there is no artifact, then the technology can be definitely considered no longer available such is the case for war planes from the First World War.
- *Design-related obsolescence:* A lack of technology representations such as a lack of design documentation can lead to technology obsolescence. This is not limited to design documentation but extends to documentations related to all technology life cycle phases such as verification, validation, and testing documentation. A lack of technology representations then leads to a lack of design, manufacturing, and operational capabilities.

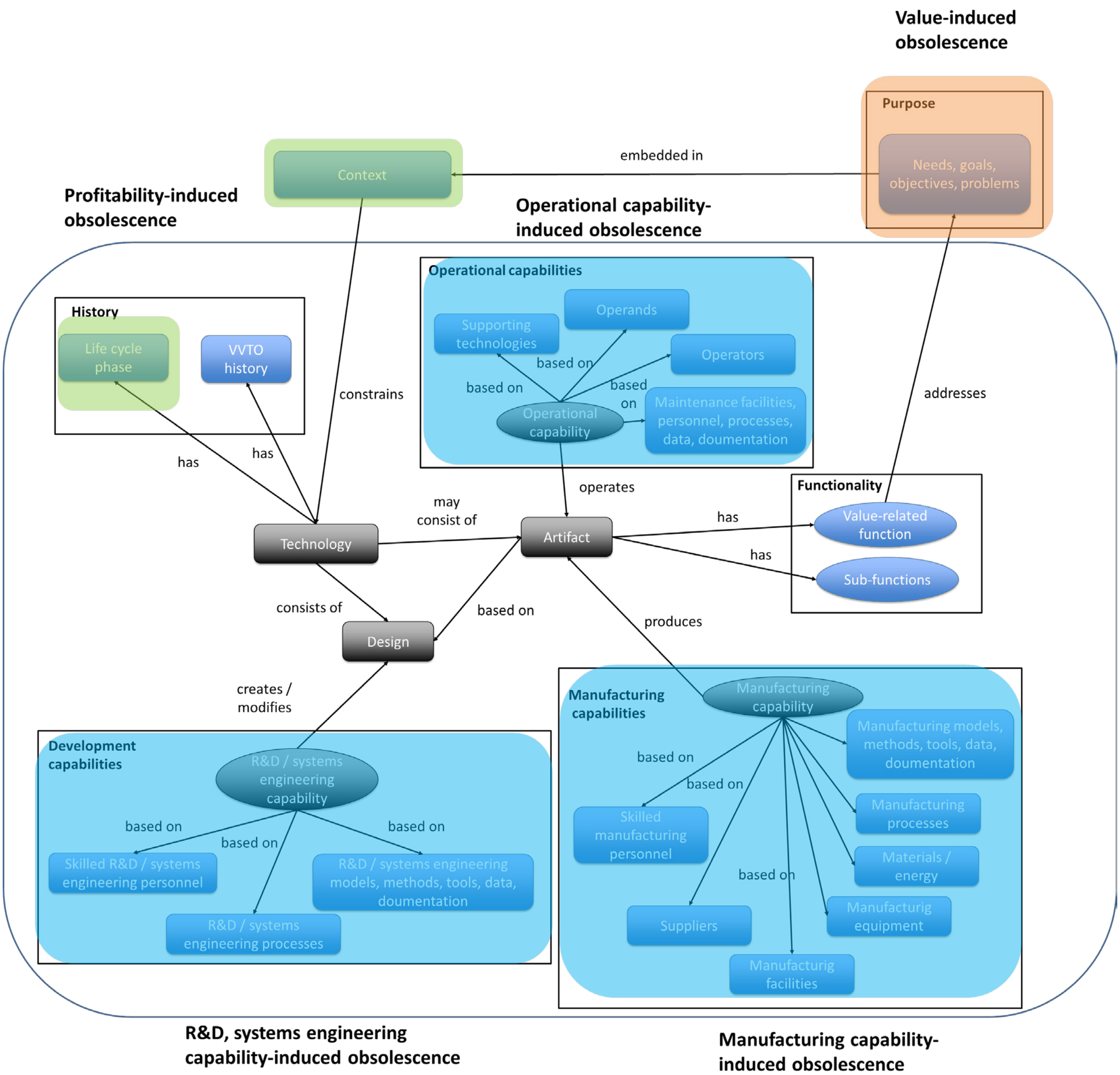


Fig. 3-22: Sources of technology obsolescence

To conclude, almost all technology elements can induce technology obsolescence. Some elements can induce obsolescence indirectly such as design-related obsolescence which leads to a lack of one of the capabilities. Other obsolescence types lead to obsolescence when other types of obsolescence are present, such as artifact-related obsolescence and capability loss. One of the most significant sources of obsolescence is, however, a changing context such as the business context of a technology.

For uninvention, obsolescence has gotten to a point where the technology can no longer be reconstituted without significant redevelopment. This is in particular the case when design and manufacturing capabilities are permanently lost. Furthermore, a loss of technology representations such as design documentation impedes the reconstitution of a technology. Instance-related obsolescence might be a source of uninvention if the instance is a source of information that allows for reconstituting a technology. Reverse engineering may allow for creating documentation from an artifact. However, reverse engineering requires that some capabilities related to the technology are already present. Otherwise, understanding the technology would not be possible. For example, for reverse engineering an electronic device, knowledge about electronics needs to be already preexisting.

To summarize, two subtypes for technology loss were introduced: obsolescence and uninvention. Obsolescence implies that a technology is no longer available from a supplier. Uninvention is a more permanent state of a technology where the technology is no longer available in general and needs to be newly developed. Obsolescence can be caused by external sources, such as a lack of profitability or regulatory changes. Internal sources of obsolescence are capability loss, loss of representations such as documentation, and loss of artifacts.

3.2.6 Technology Transfer and Diffusion

Technology transfer is briefly covered in this section, in order to get a better understanding of technological capabilities. The term "technology transfer" is itself difficult to define (Wahab et al., 2012). Here, a transferred technology involves a transfer of technological capabilities. A transfer consists of at least the capability to use a technology. Moreover, development and manufacturing capabilities are often transferred as well. Looking into technology transfer cases may provide insights into the elements of technological capabilities, as it involves a "replication" of technological capabilities. According to Bozeman (2000), technology transfer involves not only the transfer of technological objects but also of knowledge embodied in these objects. Knowledge transfer is therefore a necessary condition for technology transfer.

Technologies and technological capabilities can diffuse (Attewell, 1992; Eaton and Kortum, 1999; Geroski, 2000; Keller, 2004). One diffusion definition is that a product is adopted by a market segment (Katz and Shapiro, 1986). In other words, it is used by more people. For example, a few decades ago mobile phones were only used by a few people. Today, mobile phones are ubiquitous.

Diffusion may also stand for more firms possessing the technological capabilities for a technology (Bozeman, 2000b, p.629; Kogut & Zander, 1992; Zander & Kogut, 1995). For example, the first operational airplanes were developed and manufactured by the Wright Corporation in the USA at the beginning of the 20th century. Just a decade later, several European firms were already capable of developing and manufacturing their own airplanes (Gibbs-Smith, 1987, 1975).

Note that diffusion, in the sense of more users, may happen without a diffusion of development and manufacturing capabilities. Monopolies often have unique access to a technological capability and dominate a market segment.

In the following, the notion of "technology diffusion" is used in the second sense, involving the diffusion of some form of development and manufacturing capability.

Technology diffusion has strategic implications for firms. With more and more firms possessing a certain technological capability, the capability's competitive role changes. According to Gerybadze (1998, p.17), a technological capability may at first provide a competitive advantage. Yet, due to technology diffusion, it may lose its competitive advantage, as more and more firms possess the technological capability. At some point, such a technology becomes a commodity.

Fig. 3-23 illustrates graphically which technology elements need to be transferred or created in a technology transfer case.

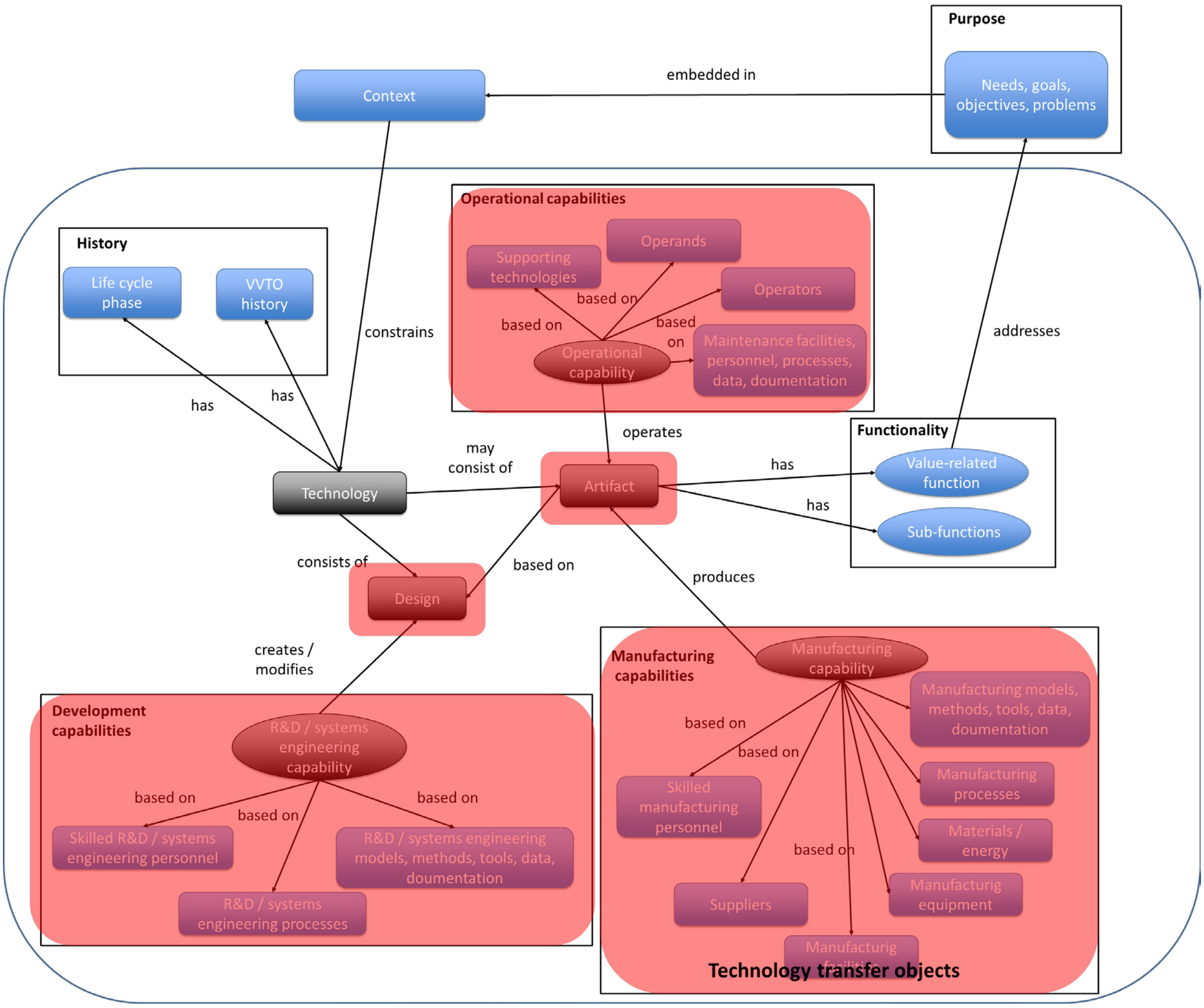


Fig. 3-23: Transfer objects for technology transfer

An exploratory analysis of historical technology transfer cases was conducted in order to identify important elements of a technology. The objective was to find out, which technology objects were transferred and if these transfer objects had any relevant impact on the transfer success or failure. As shown in Table 3-6, 30 technology transfer cases were assessed. Data was taken from publicly available sources, notably Collins (1974), Gordon and Rigmant (2002), Gorman (2002), MacKenzie and Spinardi (1995), and Uhl (2001). Some of the technologies are associated with multiple transfers such as the TEA laser, which was transferred 12 times. 19th century steel manufacturing transfer from England to France is also considered twice: Once before personnel was transferred and after personnel was transferred. The cases are biased towards technologies in the aerospace and defense sector.

Table 3-6: List of technology transfer cases assessed

Technology transfer case	Origin	Target	Technology type
Steel manufacturing (2 cases)	England	France	process
Textile manufacturing	England	USA	process
B-29 - Tu-4	USA	UdSSR	system
Atomic bomb (UK)	USA	UK	system
Atomic bomb (Soviet Union)	USA	UdSSR	system
V-2 - R-1	Germany	UdSSR	system
V2 - Redstone	Germany	USA	system

Sidewinder – K-13	USA	UdSSR	system
V-1-10Kh	Germany	UdSSR	system
Hs-293	Germany	UdSSR	system
Wasserfall - R-101	Germany	UdSSR	system
Schmetterling - R-102	Germany	UdSSR	system
Taifun - R-103	Germany	UdSSR	system
Apple II - Agat	USA	UdSSR	system
V-1 - Republic-Ford JB-2	Germany	USA	system
MG-42 - T24	Germany	USA	system
TEA laser (12 cases)	UK university	UK university	system

For assessing the individual technology transfer cases, a total of four technology success and failure categories were defined:

a) <u>*Success: reproducing operational system*</u>
An operational system results from the technology transfer. Operation is demonstrated by one or more system instances that were operationally tested. However, the technology may not enter service and not make it into serial production.

b) <u>*Success: operational system in service*</u>
The technology enters service and the organization has acquired development and manufacturing capabilities to evolve the technology. Such an adoption is in most cases serial production and nominal operation of the system but can also go so far as the technology serves as the basis of a whole family of systems, such as in the case of the R-1 missile and the Tu-4 bomber, where their heritage can be still identified in systems in operation today such as the R-7 launcher and the Tu-95 Bear (Kopp, 2012).

c) <u>*Failure to reproduce operational system*</u>
The organization fails to reproduce a technology that performs the function of the original technology. The performance characteristics do not need to be in the same range as the original technology. Hence, step a) could not be achieved.

d) <u>*Failure to put operational system into service*</u>
The technology does not enter service and does not serve as a basis for further technology evolution within the organization. The transition from a) to b) was not made.

Furthermore, five types of transfer objects were defined:

- <u>*Personnel:*</u> Was a transfer of personnel involved? Such a transfer may consist of personnel from the source organization working at the transfer target organization. A transfer may also consist of visits and written or oral communication.
- <u>*Development and manufacturing documentation:*</u> Documentation involves plans, instructions, descriptions, and explanations related to a technology. Not only design drawings are relevant but also descriptions of how the technology functions, performance parameters, tolerances, operational characteristics, rationales.
- <u>*System instances:*</u> System instances are concrete physical artifacts.
- <u>*Production facilities:*</u> Tooling, production lines etc. Production facilities are associated with the manufacturing capability of a technology.
- <u>*Preexisting technological capabilities:*</u> Has a system with similar functional and performance characteristics been developed by the organization before? These capabilities are mainly pertaining to development capabilities.

In three cases, the transfer of personnel or tight collaboration was a key factor in successful technology transfer (Collins, 1974; Harris, 1998, 1992). Until these transfer mechanisms were established, the respective technology could not be reproduced. Two of these cases are process technology transfer cases (textile and metal production) and one is a system (TEA laser).

Of the other 12 cases, two cases failed to create a working system. In one case, the original system was still at a prototypical stage and thus, the failure can be attributed to the immaturity of the original system. In the other case, the industrial and scientific basis of the receiving country did not have the technological capability to develop guidance systems. However, of the 12 cases, five cases (including the two failed cases mentioned before) failed to reach serial production. The main reason is that the systems were not able to satisfy the requirements set by stakeholders (in these cases the military) and development was terminated. Interestingly, for all five failure cases a transfer of personnel, design artifacts, and original system instances occurred. Thus, even if the technological capabilities have been successfully transferred, a technology might be rejected as it does not sufficiently satisfy stakeholder needs. Therefore, the transfer of technological capabilities is only a necessary but not a sufficient condition for successful technology transfer if "success" is defined as the technology being adopted by the new context.

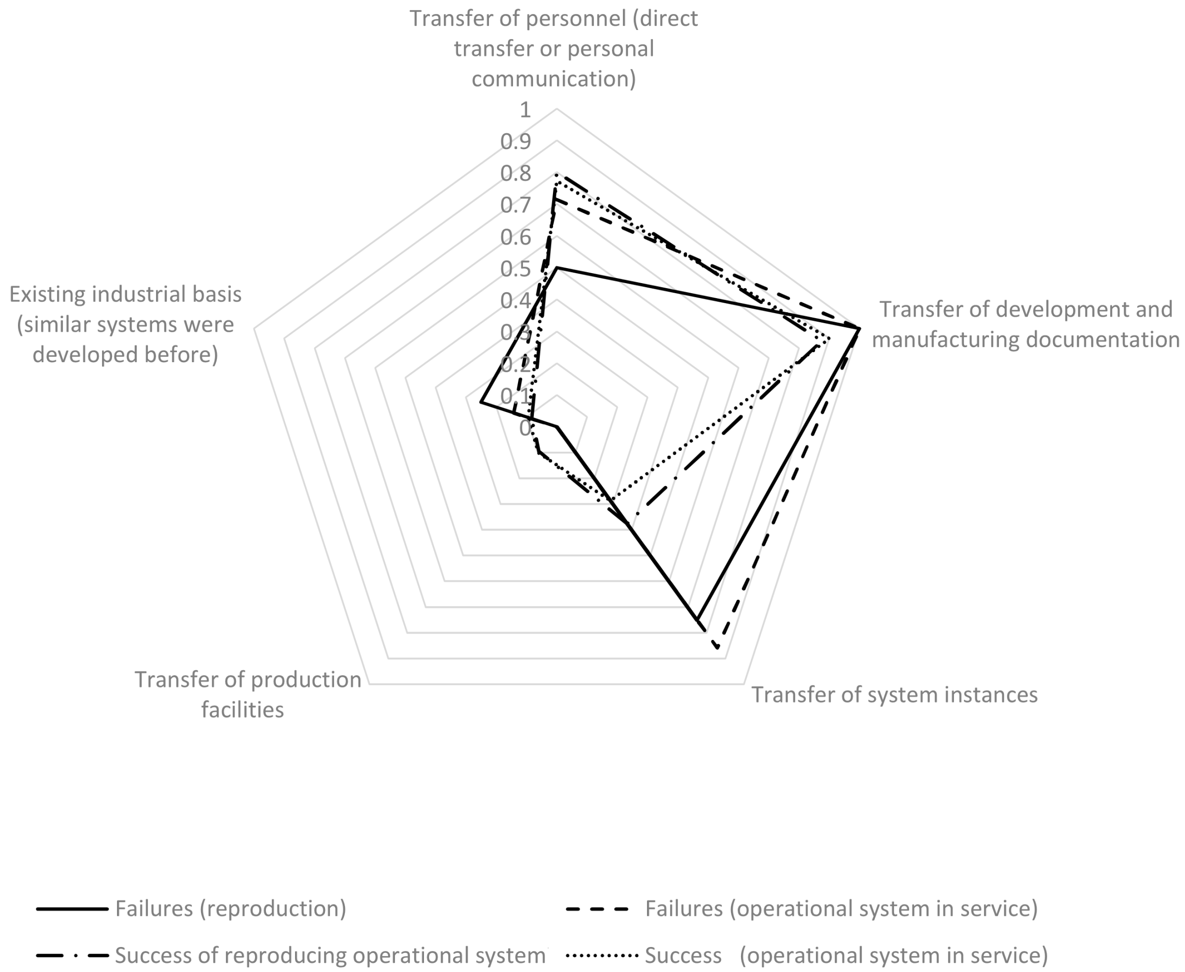


Fig. 3-24: Technology transfer categories for successful and failed cases

Results

Fig. 3-24 shows the results of the analysis. In general, the shape for the four technology transfer categories is quite similar. The transfer of production facilities seems to have played a minor role in the assessed transfer cases. Similarly, an existing industrial basis played a minor role for all categories. On the other hand, almost all cases involved a transfer of development and manufacturing documentation, independently of successful or failed transfers. A transfer of personnel took place in roughly 70% to 80% of the successful and operational service failure transfer cases. Only in the case of failures to reproduce an operational system, 50% of the cases involved a transfer of personnel. In the case where the technology failed to be put into active service, a transfer of personnel occurred in about 70% of the cases. For both failure categories, 70% to 90% involved a transfer of system instances. Whereas for the two success categories, only 30% to 40% involved a transfer of system instances.

Limitations

One limitation of this study is that it is based on easily accessible historical data. Hence, the sample might be subject to selection bias (Berk, 1983; Heckman, 1977). One observation is that for defense and aerospace cases, only successful instances of technology transfer are well documented and reported. One reason is certainly that prominent cases such as the transfer of German V-2 technology has formed the basis of the rocket industry in the USA and Soviet Union. The Tu-4 airplane formed the basis for Soviet long-range airplanes (Gordon and Rigmant, 2002). Thus, the number of publications is much larger for these cases. By contrast, only limited data was available for less successful cases. More specifically, the data for technology transfer failures might have a higher degree of uncertainty associated with it compared to the transfer successes.

Another limitation is that this analysis does not provide insights into how much development effort was actually saved by transferring a technology instead of developing it. The degree to which the transferred knowledge was actually used for the reproduced systems differs considerably.

This analysis was conducted with the objective to provide insights into technological capabilities. One limitation is that the transfer of a capability is rather a transfer of some key technology elements in order to grow a capability elsewhere. Hence, it only provides limited insights into what a capability is constituted of "in action". Nevertheless, the analysis at least shows typical preconditions for developing a capability.

Conclusions

At least for the cases analyzed, the transfer of production facilities and preexisting capabilities for similar systems did not seem to be necessary conditions. The lack of cases with preexisting capabilities might be due to selection bias. The cases chosen are mostly cases where the objective of technology transfer was building up a technological capability of strategic relevance. The lack of cases where production facilities were transferred can be explained by the technology transfer process. Often, preexisting production and manufacturing technologies were used and the transferred technology adapted to these preexisting technologies.

The role of transfer of personnel or communication seems to be vital. For the failures in reproducing the technology, transfer of personnel occurred significantly less frequently than for the successful cases. This is also the case with the transfer of system instances. However, their transfer seems to be correlated with failure rather than success. One explanation could be that adapting the technology to the new context is more difficult when system instances exist, as they might impose too many design constraints on the new context.

Due to the small number of cases studied, considerable uncertainty is associated with the results. Nevertheless, some of the conclusions provide hints for identifying important elements of technological capabilities:

- *Vital role of design artifacts:* Design and manufacturing documentation seems to be a vital source of knowledge.
- *Vital role of personal interaction:* Interaction with personnel involved in one or more of the life cycle phases of the original system seems to be vital. There are some cases such as the Tu-4 case where no knowledge was transferred via personal communication. However, these cases seem to be rather exceptions.

Looking at these two aspects from a knowledge transfer perspective, design artifacts transfer explicit knowledge, whereas personal interactions allow for a transfer of tacit knowledge.

3.2.7 Application Example for the Technology Framework

The technology framework can be used for representing various technology-related phenomena. In the following, I demonstrate how the framework can be used for representing concrete technology examples. Note that the technology framework is not a method or tool. However, it can be a starting point for developing methods and tools based on it, as is shown in later sections of this thesis with respect to heritage technologies.

Using the technology framework, notions such as "technology development" can be modeled, as shown in Fig. 3-25. Technology development may not only have the aim to develop a product / system or process but also to develop the technological capabilities that go along with it.

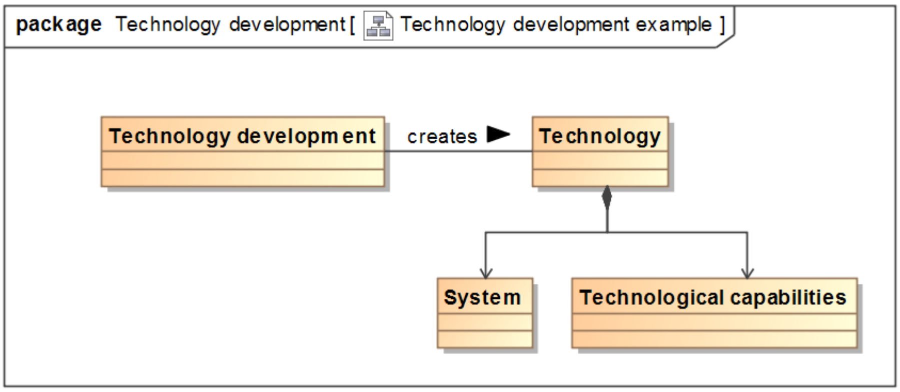


Fig. 3-25: Example of a technology development model

In the following, the example of the Wright Brothers' airplane is used to illustrate how the technology framework can be used for representing different aspects of this radical innovation. The Wright Brothers case is an interesting example of technology development, as it marks the origin of heavier-than-air flight. Furthermore, the technology is well-documented and the complexity of the technology is rather low, compared to more recent radical innovations such as the internet.

Technology development as the simultaneous development of a design, artifact, and technological capabilities is applied to the Wright Brothers' airplane development case, depicted in Fig. 3-26. The Wright Brothers developed the airplane technology, which includes the development of an airplane but also the capability to develop improved versions of their initial airplane and even different types of airplanes.

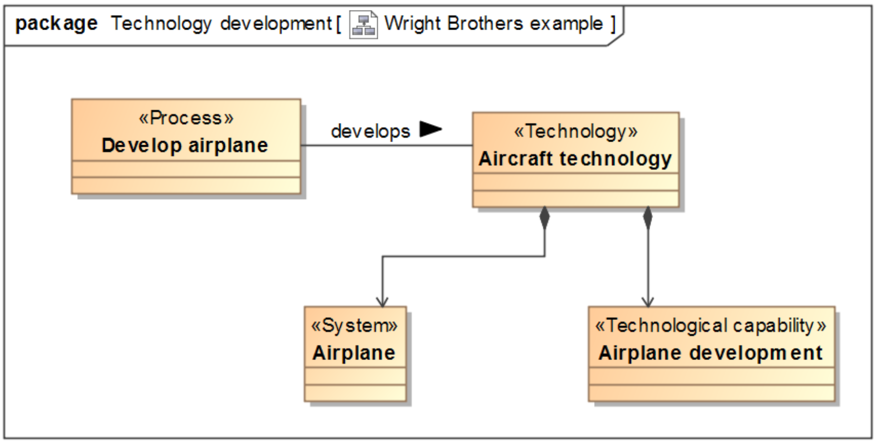


Fig. 3-26: Wright Brothers airplane development example

Note that the development process itself is usually performed once and is not repeated (Browning et al., 2006, p.105). There are exceptions such as technology transfer, reverse engineering, and innovation diffusion where development efforts are duplicated and repeated. Hence, the capability "airplane development" pertains to the capability to develop new airplanes. It is therefore a "potentiality", as the new airplane is of course not yet developed. Developing airplanes is not yet a "nominal" activity, which is a precondition for a capability. The Wright Brothers have developed the potentiality to develop ever new airplanes. Although the development process is usually not repeated, there are different degrees of "newness" to the process, according to Browning et al. (2006). This is consistent with the AD² levels introduced by Bilbro (2008) that define degrees of difficulty of development. Taking the Wright Brothers example, the development of the first motorized airplane had a high degree of newness, whereas the subsequent incremental improvement of the first airplane was a process with a lower degree of newness.

Between the years 1899 and 1909, the Wright Brothers developed, assembled, and operated a series of airplanes (Gibbs-Smith, 1987). Among these airplanes is the world's first operational airplane, the Wright Flyer, and the Wright Model

A, which is considered as the first practical airplane. The Wright Model A was produced in a small lot of nine planes. Fig. 3-27 shows three major capabilities that were developed with the Wright Flyer:

- Building up a capability for developing airplane control systems
- Building up a capability for airplane airfoil design
- Building up a capability for airplane gasoline engine design and manufacturing

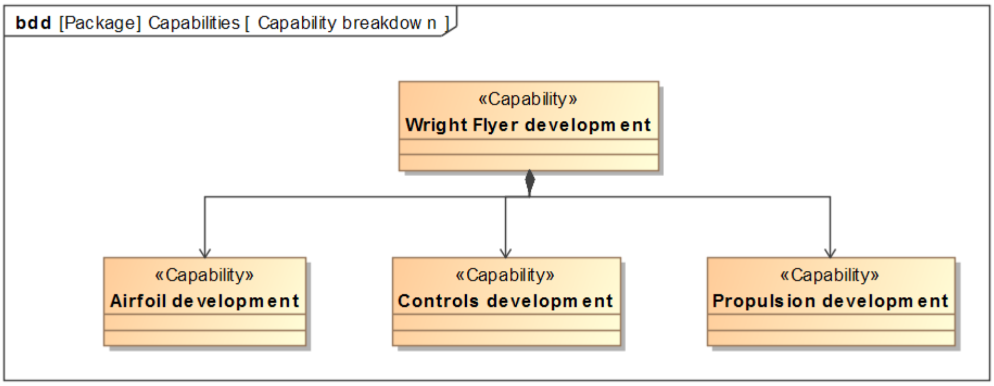


Fig. 3-27: Wright Flyer R&D capabilities

Once these capabilities were developed, later incremental innovations to the original design could be made without major problems. Fig. 3-28 shows a breakdown of the “airfoil development” capability. It shows process knowledge and resources (personnel, equipment, and facilities). First of all, a wind tunnel was of crucial importance for systematically testing different airfoil shapes and measuring their drag-to-lift ratio in a controlled environment. The wind tunnel is in itself a technology that needs to be operated properly. For example, the fan that generated wind was propelled by a leather belt powered by a gas engine. A series of line shafts and pulleys was used for transmitting the torque force from the engine to the fan. Another device for testing airfoils was a bike, retrofitted with a device that enabled testing airfoils and measuring drag and lift coefficients.

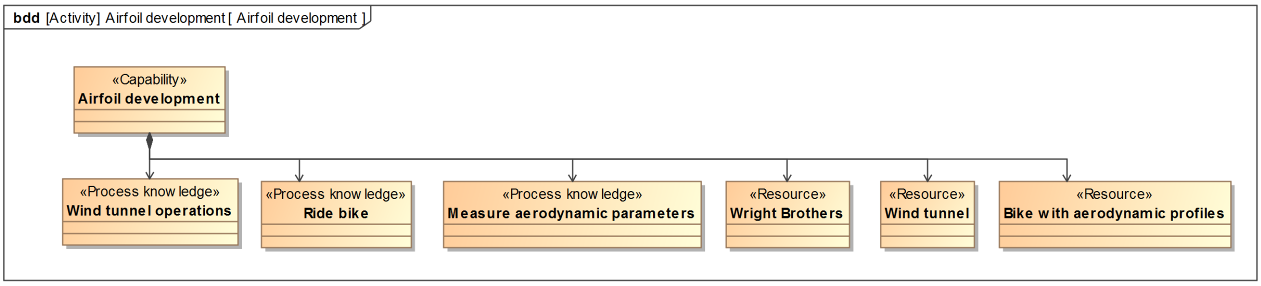


Fig. 3-28: Airfoil development capability breakdown

How were the capabilities created? The capabilities were created by executing processes that developed process knowledge, for example, the sequence of steps for determining which airfoil design is the best for a given application. Fig. 3-29 provides an overview of the technologies that were developed by developing the first Wright Flyer. At the beginning of the development process, the people and organizations involved in the development were the Wright Brothers, their mechanic Charlie Taylor, who was responsible for developing the gasoline engine for the plane, and a local foundry called Buckeye Iron & Brass Works. They were contracted for building the aluminum crank case for the engine. Developing an aircraft at this point was not a business-as-usual activity for all actors. Thus, they had the potentiality to develop an airplane but certainly not the capability at the beginning. Hence, the results of the development of the propulsion, airfoil, and controls was the design of an airplane, an instance of an airplane, and the capability to develop an airplane.

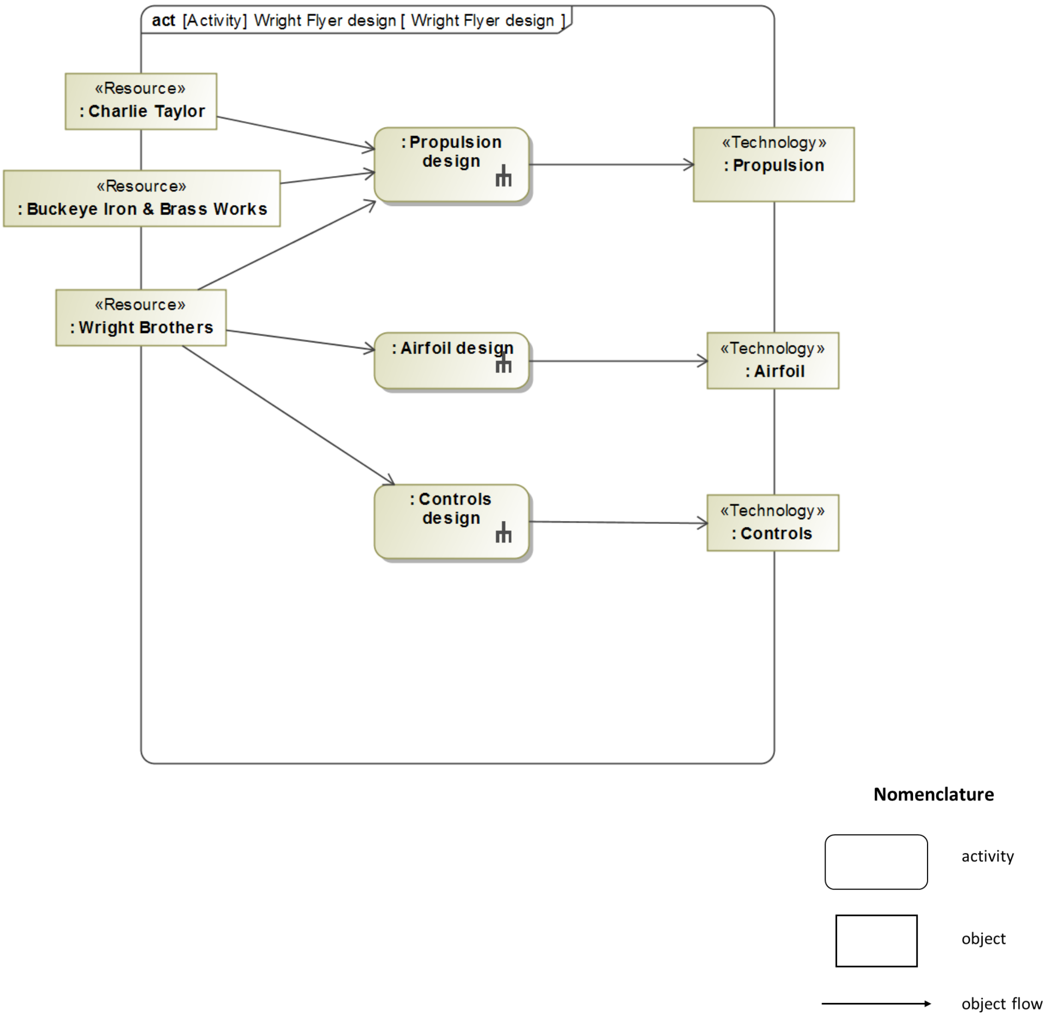


Fig. 3-29: Technology development by first Wright Flyer

Note that the capability of developing a Wright Flyer type airplane is intimately related to the architecture of the aircraft. The control concept of the airplane of warping the wings to change the plane's direction was possible, as the airplane was a biplane. If the Wright Brothers would have decided to develop a monoplane after the first Wright Flyer, they probably would have had to develop new capabilities. Fig. 3-30 shows the airplanes to which the Wright Flyer development capability was applied to, such as the Wright Flyer II and III and the Wright Model A, the first commercial airplane in history (Gibbs-Smith, 1987, p.13).

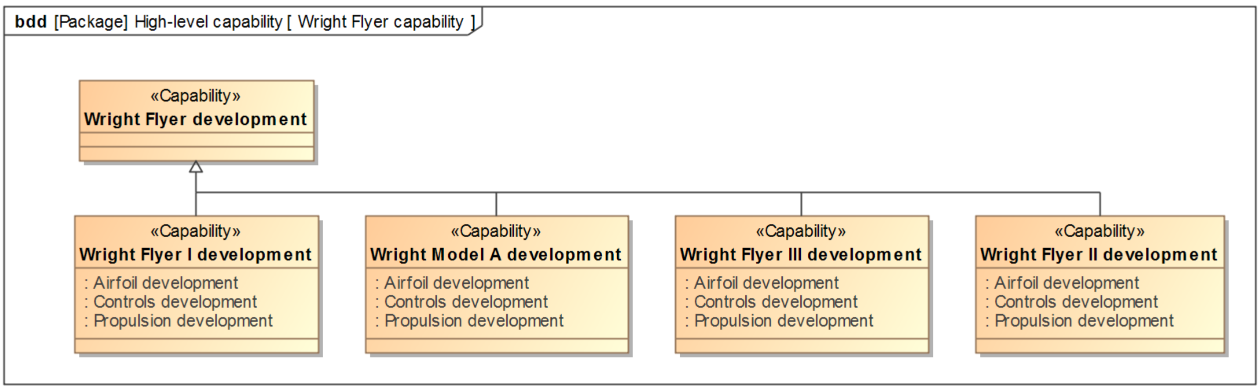


Fig. 3-30: the Wright Flyer development capability and its application to different airplanes

The Wright Flyer example illustrates how the technology framework can be used for describing how technologies evolve. It provides a "vocabulary" for describing the evolution of technologies.

3.3 Verification, Validation, Testing, and Operations Framework

How much a technology is proven depends on the extent of its successful verification, validation, testing, and operations history. A high-heritage technology has an extended successful history of verification, validation, testing, and operation with respect to certain contexts. This context-dependence is crucial in assessing heritage technologies. Hence, it is important to develop a VVTO framework for describing VVTO history with respect to a certain context. One of the key questions is how these terms can be properly applied to the early stages of systems development. Another question is how changes to VVTO history can be represented if the context changes. When does the VVTO history still make a technology proven and when does it no longer? This framework is based on the systems architecture and technology framework.

3.3.1 Verification and Validation in the Early Phases

One of the key challenges of verification and validation in the early phases is the lack of knowledge about the system's design. What is known about the system is usually its subsystem technologies and the relationships between them. Furthermore, the concept of operations (ConOps) and key system level requirements are usually defined such as the main system function and key performance requirements. I make the following claim with respect to verification and validation at an early stage of systems development:

During the early phases of systems development, the basic system architecture and subsystem technologies are verified against the ConOps and key system level requirements.

For example, according to the INCOSE Systems Engineering Handbook, the "stakeholder requirements definition process" consists of the following outputs (Haskins et al., 2007, p.57):

- Concept documents: concept of production, concept of deployment, concept of operations (ConOps), concept of support, concept of maintenance, concept of disposal
- Stakeholder requirements
- Measures of Effectiveness (MOE) needs
- MOE data
- Validation criteria
- Initial Requirements Verification and Traceability Matrix (RVTM)
- Stakeholder Requirements Traceability

Most of the process activities are related to the interactions between the system to be developed and its environment, e.g. stakeholders, regulations, standards, legacy interfaces. Key artifacts are the concept documents used, in particular the ConOps document which includes, among other elements, the operational scenarios for the system. The operational scenarios describe how and in which contexts the system will be operated.

Fig. 3-31 shows how the systems architecture framework is integrated with the context. Important extensions of the model are additions to the use context. The use context includes the notion of "conventions". "Conventions" subsume laws and regulations, industry standards, and organizational / enterprise policies, values, procedures, and standards. Laws and regulations are most important, as non-compliance may lead to legal persecution. There is no obligation to comply with industry standards. However, they have the status of "norms". This means that non-compliance may have socially detrimental consequences such as alienation from a community. The important point about laws, regulations, and industry standards is that they are external to a firm. By contrast, enterprise policies, procedures, and standards define "how things are done" within a firm. Often, constraints imposed on a system can be traced back to conventions. For example, the use of pulsed nuclear propulsion was no longer possible after the Partial Test Ban Treaty in 1963 forbade nuclear tests in space (Dyson, 2002). The treaty constrained interplanetary propulsion technology alternatives to the ones not based on nuclear devices. Further sources of constraints are supporting systems. Typical constraints are interface requirements such as for power supply or data transfer.

Environmental requirements can be traced to the operational environment in the use context. Note that the environmental requirements extend to transportation, deployment, installation, nominal operations, contingency situations, and disposal. Stakeholder requirements can be traced to needs of stakeholders. These requirements are usually functional or performance-oriented.

The system is now verified against requirements and constraints and validated against stakeholder needs.

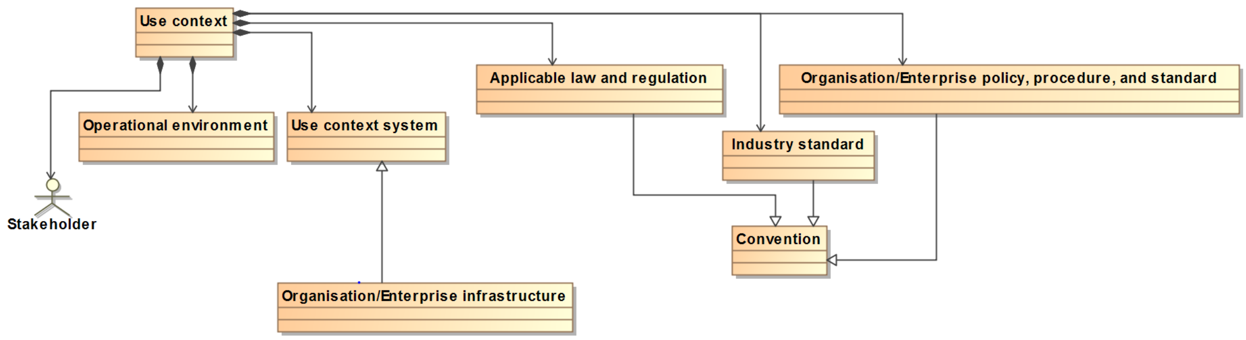


Fig. 3-31: Integrating the systems architecture conceptual model with the requirements and context conceptual model

The framework allows for a more detailed view on verification, validation, testing, and operational history, which is one of the key elements of heritage.

3.3.2 Elements of the Verification, Validation, Testing, and Operations Framework

In the following, the elements of the VVTO framework are introduced. I start with the operational history, as it is the easiest element to grasp. I continue with verification, validation, and testing. Finally, I map the VVTO framework elements to the TRL and the ESA heritage levels in order to link the framework to existing concepts for technology readiness and maturity.

Operational history

Operational history is the element of VVTO history that is easy to grasp. Operational history consists of a set of operational units, as shown in Fig. 3-32**.** An operational unit is a unit of measuring operational history such as total operating hours, number of missions, on- off cycles etc. For space missions, the relevant operational unit is usually the number of missions on which a system or component was used. For some technologies, there might be several operational units, such as for a battery used in a spacecraft power system. For the battery, the number of day-night cycles is relevant, as each time the battery is charged during day and discharged during night. However, the number of missions on which the battery instances have been flown successfully is also a relevant operational unit. An operational unit takes place in a certain use context. The battery instances may have been operated successfully on two LEO missions but not a single time on a GEO mission.

Furthermore, it is important to consider if the battery was switched off in orbit (state), it was charged and discharged (behavior), or it was heated up after being in hibernation mode (state transition). Thus, the state or mode in which the technology was operated is important, along with the behavior associated with the state. Furthermore, state transitions are important. For the stakeholders, it is furthermore relevant which function was performed that is relevant for them, such as the reliable provision of power for other on-board systems.

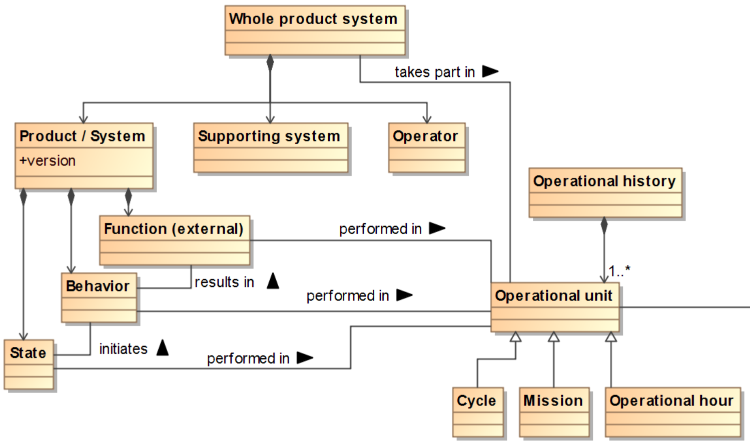


Fig. 3-32: Decomposition of operational history and contributing elements

The state "nominal operation" can further be decomposed into the behavior that takes place during this state such as "charge battery" and "discharge battery". Table 3-7 shows an example table for a battery. Such a table captures the environments in which the modes took place.

Table 3-7: Example for linking operational modes, operational environments, and missions in a battery state – operational environment matrix

	LEO	**GEO**
Nominal operation (charge- and discharge cycles)	Mission 1, Mission 2, Mission 3	Mission 4 on-orbit failure
Hibernation mode	no	no
Off-mode (during launch)	Mission 1, Mission 2, Mission 3	Mission 4

In the early phases of systems development, detailed data of states and behavior is often not available. In particular, this is the case when the technology was not developed by the organization that is doing the assessment. In such cases, at least the operational environment(s) should be identified, in order to avoid unjustified transfers of operational history. LEO operational history for example is likely not transferrable to GEO, as the thermal and radiation environment are different. Such data is usually available from proposals that potential contractors submit. Often the data is even in the public domain, as potential contractors have an interest in demonstrating that their technology is proven.

For estimating the VVTO history of a system in the early phases, listing the operational environment along with the number of operational units is often sufficient. In a more detailed assessment, the major modes of important technologies and their transitions should be identified as well. For example, the deployment of mechanical structures in space is a common failure mode. Hence, it is important to know when and in which environment deployment took place.

VVT history

VVT history is the history of a system's verification, validation, and testing. In most cases an operational history does not exist when the system is under development, or the system is going to be used in a new operational environment. VVT history is also relevant for new states or states that usually do not occur in operation such as emergency modes. The main difference between operational history, which is related to validation, and verification is that verification is done with respect to requirements and constraints and not necessarily the real operational context. For example, a spacecraft is usually not tested in space to pass the qualification test. Instead, the space environment is simulated in, for example, a thermal-vacuum chamber. Thus, a requirement such as "The spacecraft shall operate in the LEO space environment" is decomposed into sub-requirements such as "The spacecraft shall pass the thermal-vacuum chamber test" and "radiation test". Tests can be designed for verifying these requirements individually or in combination.

Fig. 3-33 illustrates the relationships between verification, validation, and testing. As listed in Table 2-3 verification can be conducted via tests, analysis, inspection, demonstration, experiments or certification. All verification activities are related to a system under development. There are four types of tests, namely development tests, acceptance tests, qualification tests, and operational tests (Haskins et al., 2007). A test is performed in a test environment. At a low technology readiness level (TRL), tests are usually conducted in a laboratory environment. From TRL 5 onwards, tests are conducted in a relevant environment. The relevant environment represents the operational environment for the technology. Each verification activity is related to a requirement or constraint. The verification activity tries to verify if a requirement or constraint has been satisfied by a system. On the other hand, validation activities are related to stakeholder needs and validate if these are satisfied by the system.

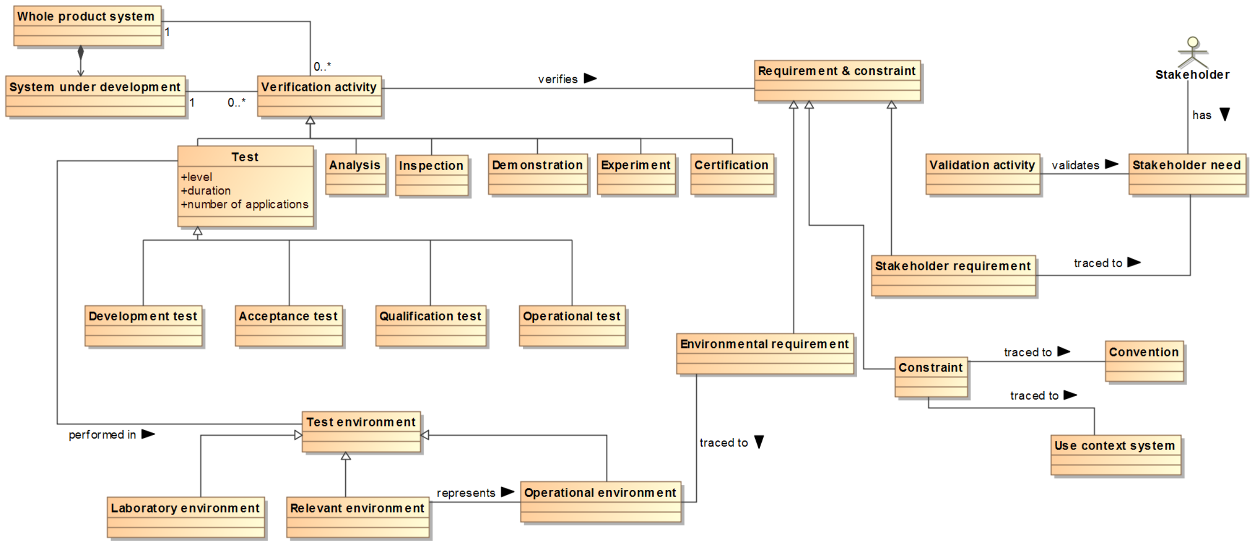


Fig. 3-33: VVTO conceptual model

3.3.3 Application Examples for the Verification, Validation, Testing, and Operations Framework

Table 3-8 shows the relationship between the VVTO framework and TRL. It can be seen that the framework covers all verification activities described in the ESA TRL Handbook (ESA, 2008). "Functional verification" indicates that the technology performs its intended function. How far performance parameters are verified is not specified in the TRL Handbook. What the table shows is that up to TRL 4 the technology is independent of the specific context in which it will operate. These aspects come in from TRL 5 onwards in the form of the environment and the system in which the technology is integrated.

Table 3-8: Relationship between VVTO framework and TRL (ESA, 2008)

TRL	Verification result	System status
1	Functional	Physical principle
2	Functional	Basic concept
3	Functional	Key technology characteristics
4	Functional	Full technology
5	Relevant environment	Full technology and interactions
6	Relevant environment	Integrated technology
7	Intended operational environment	Integrated technology
8	Qualification campaign	Integrated technology
9	Full lifecycle	Integrated technology

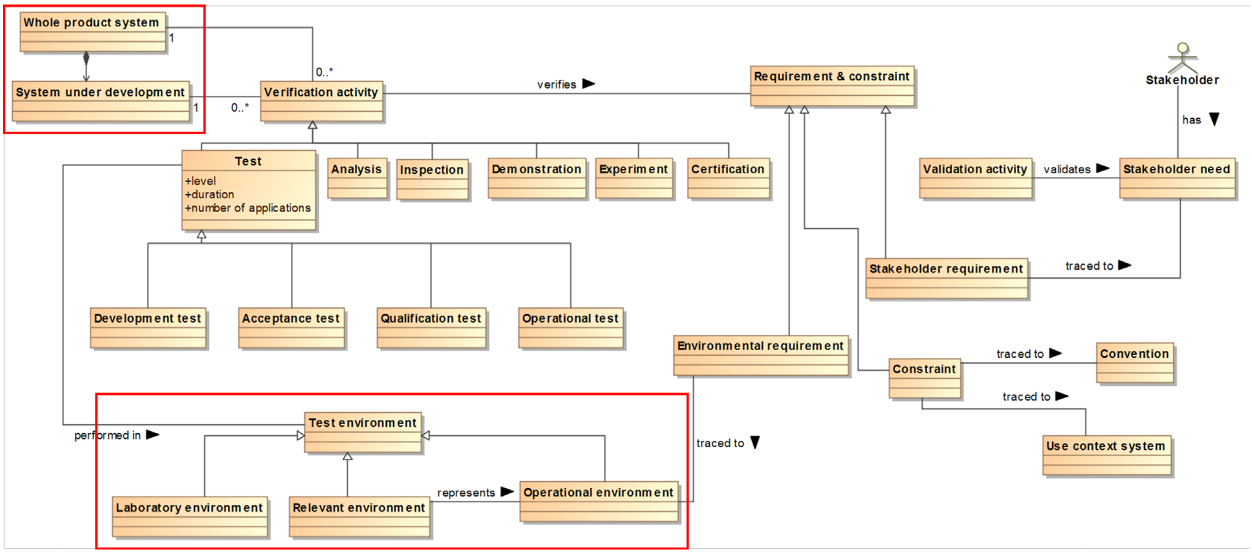


Fig. 3-34: Putting TRLs into the context of the VVTO framework

Table 3-9 shows how the VVTO framework can be used to put the TRLs into context. In the column on the left side, two hierarchical levels are shown. From TRL 1-4, the focus of verification activities is on the individual system or technology without taking the interactions with supporting systems and contextual systems seriously into account. The reason for neglecting the supporting systems is that at these TRLs the verification activities focus on whether or not the system / technology works at all. Thus, feasibility is the main issue. After feasibility has been demonstrated, at TRL 5 and 6, the technology with supporting and context systems is taken into consideration. Hence, the interactions between the system / technology and supporting systems as well as the environment. The later operational environment is represented in the form of the "relevant environment". The relevant environment represents key aspects of the operational environment and differs from technology to technology. The ESA TRL Handbook mentions the case of a new liquid droplet radiator for which microgravity and vacuum is a prerequisite for operation (ESA, 2008). The relevant environment in this case is the space environment. Other technologies may only require a simulated space environment such as in a thermal-vacuum chamber. Finally, at TRL 7-9, the system / technology has to be verified in its operational environment, together with its whole product system. For example, a battery is flown on a specific CubeSat type. The table also clarifies why among other reasons, the step from TRL 4 to TRL 5 is considered significant: both, the hierarchical level as well as the testing environment changes.

Table 3-9: Putting TRLs into the context of the VVTO framework

	Functional verification (analysis, experiments, tests) (does it work at all?)	**Tests in relevant environment**	**Tests in operational environment**
System in context and with operational capability		TRL5, 6	TRL7, 8, 9
System under consideration: individual system / technology	TRL1, 2, 3, 4		

Table 3-10 shows the relationship between the ESA heritage product categories, shown in Table 1-5 and the VVTO framework. Note that the heritage product categories are usually used after a technology has been put into operation, except for category D. Hence, category A, B, and C, are used for technologies that have reached TRL 9 at some point. Furthermore, the ESA heritage product categories implicitly take the system into which the product is integrated and the natural environment into consideration by using the term "project specifications".

- *Category A:* Qualification test program at least as severe as actual project specifications, including environmental specifications. This means that both, the requirements imposed by the system into which the technology is integrated and the environmental requirements are equally or less severe than the testing environment.
- *Category B:* The system into which the technology is integrated may differ. Alternatively, the environment may have changed.
- *Category C:* For a modified technology, the technology itself is changed. Hence, first, the function has to be verified. In a further step, the technology may advance from category C to B to A.
- *Category D:* A newly developed technology has to be first functionally verified on a technology level.

Table 3-10 can be used to track the trajectory of a technology throughout its lifecycle. For example, a technology which has originally been classified in category A moves to B, if it is used for a different application. Furthermore, if it is modified, it moves to C. Another example would be a newly developed technology, entering from category D and moving to B and A with respective testing.

Table 3-10: Relationship between VVTO framework and ESA heritage categories

	Functional verification (analysis, experiments, tests) (does it work at all?)	**Tests in relevant environment**	**Tests in operational environment**
System in context and with operating capability	B	B	A
System under consideration: individual system / technology	C, D		

A combination of TRL, ESA heritage product categories, and the VVTO framework can be used for localizing a technology's status with respect to VVTO. The VVTO framework provides the conceptual underpinnings for TRL and the ESA heritage product categories. As shown in Table 3-9 and Table 3-10**,** TRL and ESA heritage product categories can be described in terms of technology, its context, and various degrees of VVTO. Furthermore, specific technology VVTO trajectories can be tracked.

4 Statistical Analysis

In the following, a statistical analysis for heritage benefits is performed. The benefits as listed in Section 1.4 are:

- Potentially large savings in development cost and schedule;
- Reduction of programmatic risks, notably cost and schedule overruns;
- Higher confidence in the quality and reliability of a system.

My focus will be on the first two points pertaining to programmatic implications of using heritage technologies. The third point which is relevant for assessing mission risk is left as a topic for future work. The systems architecture, technology, and VVTO frameworks are used as a starting point for choosing the variables that may correlate with these benefits. Due to limitations of available data, a number of simplifications are made. The statistical analysis intends to inform the development of the assessment methodology, presented in Chapter 5. In the following, I will walk through each step of the statistical analysis.

4.1 Research Hypotheses

From the benefits identified in the literature, four hypotheses are defined, as shown in Table 4-1.

Table 4-1: Research hypotheses related to heritage benefits and corresponding 0-hypotheses

Hypotheses	**Corresponding 0-hypothesis**
H1: The more heritage technologies used, the lower the development cost.	H1-0: No relationship between the degree of heritage technologies used and development cost.
H2: The more heritage technologies used, the shorter the development duration.	H2-0: No relationship between the degree of heritage technologies used and development duration.
H3: The more heritage technologies used, the lower the development cost overrun.	H3-0: No relationship between the degree of heritage technologies used and development cost overrun.
H4: The more heritage technologies used, the smaller the development schedule overrun.	H4-0: No relationship between the degree of heritage technologies used and development schedule overrun.

As mentioned in Section 1.4, the benefits are limited by the inappropriate heritage technology use that has reportedly lead to cost overruns and delays (Affects H3 and H4). Therefore, alternative hypotheses could be defined in which there is no or even a detrimental effect of using heritage technologies. The hypothesis that there is no effect is called “0-hypothesis”. In this case, it is the hypothesis that there is no relationship between the amount of heritage technologies used and development cost, development duration, cost overruns, and delays, respectively. The corresponding 0-hypotheses for each of the hypotheses H1-H4 is listed in Table 4-1. A second alternative is that using heritage technologies leads to the opposite of the desired effect. For example, using more heritage technologies leads to higher cost overruns. Thus, if there is an effect of using heritage technologies, I also want to know if the effect is positive or negative. Furthermore, I would like to know the magnitude of the effect and how it compares to other factors that usually affect cost, schedule etc. This leads to the supplementary research questions in Table 4-2.

Table 4-2: Supplementary research questions related to the effects of using heritage technologies

Supplementary research questions:
Is the effect of using heritage technologies negatively or positively correlated with respect to the programmatic variables?
What is the magnitude of the effects of using heritage technologies?

In the next step, a research approach will be presented, in order to provide statistical evidence for these hypotheses.

4.2 Research Approach

To address the hypotheses, I use a statistical approach called "multiple regression". Multiple regression allows for analyzing the *effect* of multiple independent variables on a dependent variable. An independent variable is the variable whose effect on the dependent variable I want to investigate. More precisely, I want to answer questions of type "With an increase in x, does y decrease or increase?", where x is an independent variable and y is the dependent variable. An "effect", is not a causal relationship but rather the strength of the correlation between the independent and dependent variable. Taking the strength of the correlation into account enables answering questions of type "With an increase in x, *how much* does y decrease or increase?" With multiple independent variables, the independent variables with the largest effect on the dependent variable can be identified. Multiple regression is also the most popular approach to *control* for the effect of independent variables other than the independent variable of interest. "To control" means that other independent variables are kept constant while the effect of the independent variable of interest is observed. In other words, the effect of the independent variable of interest is isolated from the independent variables that are not of interest.

The objective is finally to illuminate the causal relationships between variables. A "causal relationship" is a relationship of type "x causes y". Correlation does not imply causation. This is why I did not use "cause" in the previous paragraph. One way to find causal relationships is by adding additional variables that are known or suspected to have a causal relationship with the dependent variable. By controlling for these variables, it is possible to identify causal relationships. In general, causal relationship are difficult to find, as there is always the possibility that a yet unknown variable is responsible for the behavior of the independent and dependent variable. Such a variable is called "common cause". An example is the correlation between an increase in ice cream sales and drowning deaths. The common cause for increased ice cream sales and drowning deaths is the increase in temperature during summer.

For an in-depth introduction to multiple regression, the reader is referred to introductory literature in statistics and econometrics such as Angrist and Pischke (2008, 2014), Levine and Stephan (2014), and Wooldridge (2015).

In the following sections, I will introduce the steps of the statistical analysis. First, the dependent variables of interest are defined. These are the following program management variables: specific development cost, development duration, cost overrun, and delay. In the next step, the independent variables are identified. There are two types of independent variables. The first type of independent variable is a variable that represents an aspect of heritage technology. The second type of independent variable is a variable that is known to have an effect on the four program management variables but does not represent an aspect of heritage technology. If I want to know how large the effect of heritage technologies on the program management variables is, I need to control for these variables.

After having selected the variables, I need to select scales for each variable, namely, ratio, interval, ordinal, or nominal scales.

Once the variables and their scales are defined, the population of interest is selected. Selecting the proper population is important for extending the results of the statistical analysis for the *sample* to the entire *population*. If this is possible, conclusions for the sample are valid for the population. A sample with this characteristic is called "representative". If the results are generalized beyond the population, one has to argue why this generalization is valid. For example, if I find out that the development cost of a sample of interplanetary spacecraft diminishes with the amount of heritage technologies used, I may claim that this result is *in general* true for interplanetary spacecraft. However, I would need to justify why this holds true for LEO spacecraft.

In the following step, the sampling method is selected. Ideally, I would apply random sampling, which mitigates the effect of selecting a sample that does not correctly represent the population. An example for such a sample which does not represent the population is selecting university students for a psychological experiment.

Finally, the method for statistical analysis is selected, where I mostly use multiple regression. However, I occasionally use the difference between group means for categorical data.

4.2.1 Selection of Variables: Heritage Technology

The independent variable of interest here is heritage technology. The dependent variables of interest are the programmatic variables specific development cost, development duration, development cost overrun, and schedule overrun. Heritage technology is decomposed into design heritage and technological capability. VVTO history is included as an exclusion criteria, as will be explained in Section 4.2.2. In the following, the variables design heritage and technological capability will be described in detail for the context of the statistical analysis:

- Design heritage: The part(s) of the design of the space system that has been inherited. Design heritage is inherited at the parts, equipment, subsystem, bus, and system level. In many spacecraft designs, inherited component designs are integrated, together with newly developed components. The design heritage can be more or less modified. An inherited space system design has less heritage if it is modified. Similarly, modified parts, subsystems, bus designs have less heritage if they are modified. In the following, I use the notion of "component" whenever I refer to an arbitrarily defined part of a system. For spacecraft, components will be defined at the bus, subsystem, equipment, or part level. For launchers, components are major subsystems such as engine and stage structure or even entire rocket stages. The architecture of the system is considered implicitly. By architecture, I mean the way how the components of the system are related to each other. For example, I want to distinguish between a subsystem that only consists of proven components but needs to be newly developed and a subsystem that is used "off-the-shelf". Such an off-the-shelf subsystem has a higher heritage, as not only its components but also the relationships between the components are proven, i.e. the way how the components are related to each other.

- Technological capability: Technological capabilities are represented by three indicators. The first indicator is *organizational capability*: If an organization has already developed a certain class of space system, it is considered to have a higher capability than an organization that has not developed this class of system. By "class of system" I mean in the following broad categories of systems such as "rocket launcher", "interplanetary spacecraft", "planetary rover", and "planetary lander". I use these broad categories, as I assume that the capabilities associated with these system categories are at least partially distinct. For example, the development of planetary rovers requires a distinct set of capabilities than an interplanetary spacecraft, e.g. the capability for developing a chassis with wheels. Furthermore, I focus on the organization that was the prime contractor for the space system for practical reasons. Data for all subcontractors is generally difficult to find. I expect that the capability to develop a certain class of system rests with the prime contractor, although I acknowledge that the prime contractor depends on suppliers. I assume that the prime contractor has at least capabilities in system-level design, R&D, and systems engineering. "Class of system" is not to be confused with "space program class" which is introduced as a control variable. The second indicator is *development team similarity*: If a team has participated in a similar space system development project before, it has experience in developing such a system. Again, I would expect that a team that has worked on a certain class of system can transfer its knowledge to the next project. Whereas a team that has already built a planetary rover is expected to transfer part of its knowledge to the next rover project, such a transfer is less certain for a different class of system such as a LEO spacecraft or a launcher. The third indicator is *program manager experience*: If the person managing the project has prior experience with a similar class of space system, he or she is expected to have knowledge that can be beneficial for the next development program. I do not directly use design and manufacturing capabilities as variables, as they are generally hard to measure. Instead, I assume that these capabilities are at least partly embodied in the organization, team, and program manager.

In addition to these heritage-related variables, a number of additional variables from the literature are introduced that have been found to have statistically significant correlations with one or more of the programmatic variables. These variables serve as "controls" for the heritage-related variables. These control variables are taken from Hamaker and Componation (2005), Coonce et al. (2009), and Emmons et al. (2007), who performed multiple regression analyses for the development cost of space systems. Note that they only performed analyses for the absolute development cost and not mass-specific development cost. At this point, I can only assume that some of these variables are likely to have a statistically significant relationship with the dependent variables I use. Fig. 4-1 provides an overview of the dependent and independent variables. The independent variables are represented by ellipses and the dependent variables by rectangles. References are added for the dependent variables from the literature.

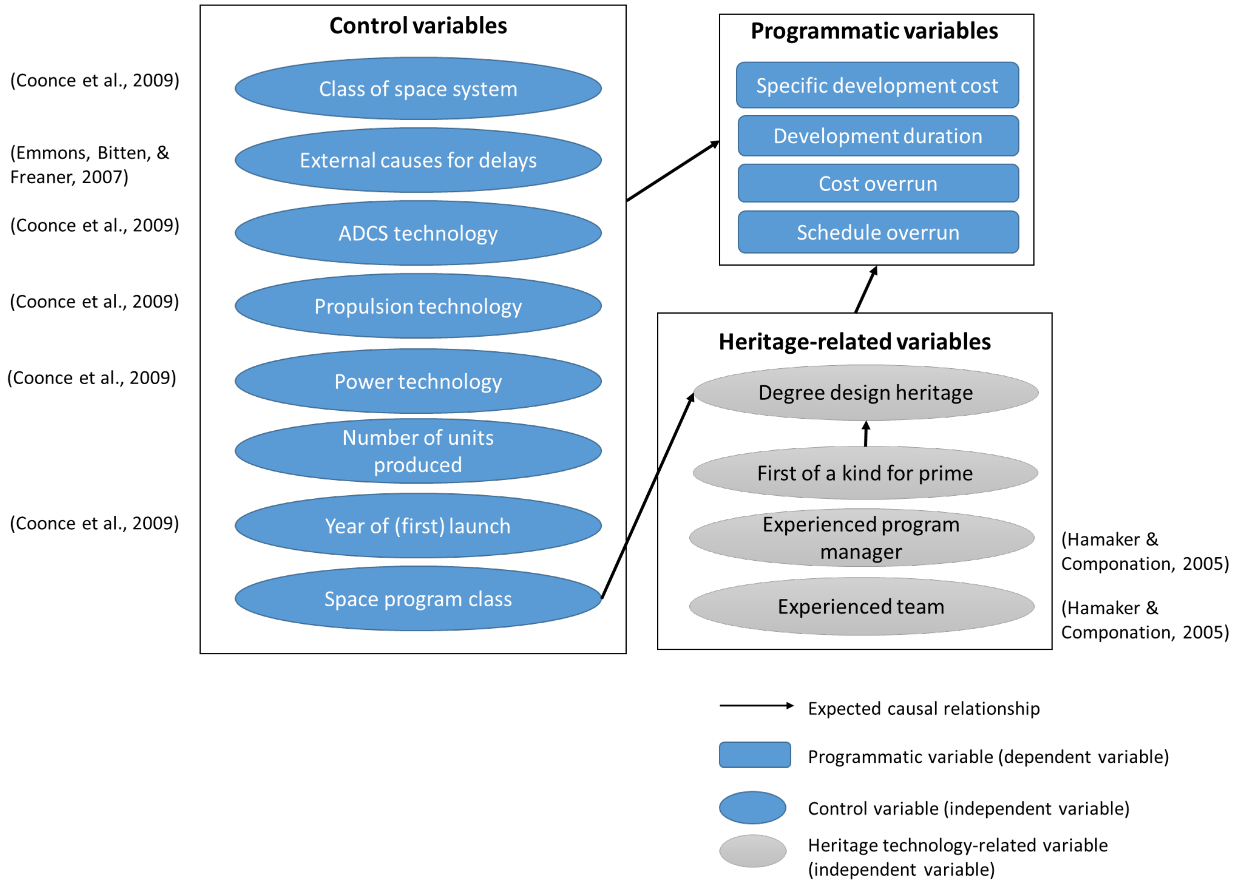


Fig. 4-1: Independent variables and dependent variables for multiple regression

The independent variables used as controls are introduced in the following. In most cases the control variables are nominal, i.e. they describe categories. Nominal variables are describe using so-called "dummy variables". Dummy variables can be either 0 or 1 for Boolean dummy variables (true or false) or 0 to n for a variable with n categories.

- *Class of space system:* Three categories are used that are known to have different cost ranges, according to Hamaker and Componation (2005), Koelle (2007), and Larson and Wertz (1999):
  - *Interplanetary spacecraft:* This category includes interplanetary orbiters, fly-by probes, planetary landers, and planetary landers.
  - *LEO / MEO / GEO spacecraft*: This category covers spacecraft that operate in LEO, MEO, and GEO.
  - *Launcher:* This category subsumes launchers that are capable of launching satellites into space. One exception is the Titan 1 that was used as an intercontinental ballistic missiles only. The missile was kept in the sample, in order to represent the totality of the Titan rocket family that originated from the Titan 1.

- *External causes of delays:* If external causes that lead to significant cost / schedule overruns were identified in the literature, the value of this variable is 1. "External" means that program management had no control over these factors. Typical external factors are budget cuts and launcher availability. "Significant" in this context means that external factors were responsible for a significant fraction of the cost and schedule overrun (>25%). This criteria is important, as I want to distinguish between cases where technological or program management issues were responsible for cost and schedule overruns and cases where the causes were beyond the control of program management.

- *ADCS technology:* (Coonce et al., 2009) Three ADCS technologies are distinguished. The list is not exhaustive, as ADCS technologies such as gravity gradient stabilization are missing. However, technologies that were not used by any of the spacecraft from the sample were excluded.
    - *No ADCS:* Planetary rovers have no ADCS system.
    - *Spin-stabilized:* Some older spacecraft such as Pioneer 10 are spin-stabilized.
    - *3-axis stabilized:* Most modern spacecraft are 3-axis stabilized.

- *Propulsion technology:* (Coonce et al., 2009)
    - No propulsion system
    - Mono-propellant
    - Bi-propellant
    - Combined mono and bi-propellant

- *Power generation technology:* (Coonce et al., 2009)
    - No power generation
    - Silicium solar cells
    - Gallium Arsenide solar cells
    - RTGs

- *Number of units produced:*

  The number of units produced is relevant, as producing two or more units may lead to a decrease in production cost for the subsequent unit. This effect is called economy-of-scale effect or learning curve effect (Koelle, 2007; Larson and Wertz, 1999). I distinguish between a single unit produced, two units produced, and serial production:

    - Single unit (applicable to interplanetary and LEO / MEO / GEO spacecraft)
    - Two units (applicable to interplanetary and LEO / MEO / GEO spacecraft)
    - Serial production (applicable to launchers)

  Two units are taken into consideration, as usually the manufacturing cost of the spacecraft is not explicitly indicated in space program cost reports. I expect that manufacturing two spacecraft for a single mission is more expensive than manufacturing a single spacecraft, even when economy-of-scale effects are taken into account.

- *Space program class:* Public space programs are often classified into small, medium, and flagship class programs. At NASA, the three categories are distinguished by their cost range: Small programs cost less than 250M$ (Mars Pathfinder); medium programs less than 1B$ (Voyager, MER, etc.); a program that costs more than 1B$ is considered a flagship class program (Cassini-Huygens, MSL, etc.). Similar categories exist at ESA. These categories are often associated with different degrees of heritage technology use and different extents of international collaboration. For example, small and medium class programs usually include a small amount of new technologies and use a high degree of heritage technologies. Flagship class programs are often conceived to include a large amount of new technologies in order to push the status-quo. Everything else equal that would not be an issue. However, as flagship missions rely on collaboration, they are more likely to have higher overhead costs and a higher risk of delays, as previously investigated by Dwyer et al. (2015). Hence, it is important to control for the space program class in order to capture program management factors that differ between program classes. The space program class is not to be confused with "class of system" that is used as an indicator for organizational capability.

- *Year of (first) launch:* Coonce et al. (2009) demonstrate that the development cost of NASA spacecraft decreases over time by approximately 3% per year after adjusting for inflation. This decrease is attributed to increasing organizational productivity, defined as output divided by input (Krugman, 1994). In other words, the organization can either do more with the same amount of resources or produce the same output with less resources. Productivity increase is attributed to factors such as new design and manufacturing processes.

At this point I also need to define the dependent variables more precisely:

- *Specific development cost:* The specific development cost is development cost divided by the dry mass of the space system. I use the development cost after adjusting for inflation. I use the US-dollar value in 2005 as the reference value. Whenever indicated, I use the development cost between Phase B and launch, excluding the launch and operations cost. From Phase A to Phase B the space program transitions from definition to development.

- *Development duration:* I use the development duration from Phase B to launch. In some cases there is a slack between the end of Phase B and Phase C. If this slack was indicated, I subtracted the duration of the slack from the duration. If there was a significant gap between flight readiness and launch, I also subtracted the duration of the gap from the development duration.
- *Development cost overrun:* I define cost overrun as the ratio between the initially projected development cost and the final development cost of the program, subtracted by 1. For example, a program with 110M$ final development cost and an initially projected development cost of 100M$ results in a ratio of 1.1. Subtracting 1 yields 0.1 which is equivalent to a 10% cost overrun.
- *Development schedule overrun:* I define the development schedule overrun as the ratio between the initially projected duration of the development program and the final development duration, subtracted by 1. For example, a program with a development duration of 48 months and an initially projected development duration of 40 months results in a ratio of 1.2. Subtracting 1 yields 0.2 which is equivalent to a 20% development schedule overrun.

One of the challenges of calculating overruns is what to define as the initial development cost and development duration estimate. When programs suffer from significant cost and schedule overruns, so-called "rebaselining" is a common approach for adapting the projected cost and schedule to the new circumstances. For example, MSL was rebaselined several times. In such a case, one cannot simply take the earliest estimate, as rebaselining can include the addition / removal of instruments or technologies. If a program was subject to rebaselining, the last baseline is used as a reference.

An important aspect is to distinguish between "treatment" and "effects", or in other words, the hypothesized causal relationships between the variables. The notions "treatment" and "effect" are often used in medical research. A "treatment" can be a drug and the "effect" how a patient's condition changes due to using the drug. One common mistake in multiple regression is to confuse treatment and effects (Angrist and Pischke, 2014). For example, it is a known phenomenon that key performance parameters of spacecraft usually increase during development such as mass, power, and data rate (Bitten and Freaner, 2010; Freaner et al., 2008). This increase might be dependent on the amount of heritage technologies used. In this case, the "treatment" is the amount of heritage technologies used and the effect the ratio between the initial and final mass, power, and data rate of a spacecraft. Hence, using mass, power, and data rate as treatment variables does not make much sense. Hence, for each of the dependent variables, I assess if the variable would be affected by any of the heritage-related variables. Furthermore, I checked if the variables are likely to change during the development of the space system.

4.2.2 Select Scale Levels for Heritage-related Variables

For measuring heritage, measurement levels are needed. For each of the four heritage indicators, scale levels are defined.

Design heritage: For component design heritage, values within the interval [0,1] are chosen. The four levels in Table 4-3 are used. Only component designs of which at least one instance has been operated in its intended environment are considered. This is an exclusion criteria that defines a minimum threshold for VVTO history. A heritage design that does not fulfill this criteria is considered newly developed. This criteria significantly facilitates data collection, as most of the reported heritage designs satisfy this criteria. Otherwise, I would need to assess the detailed VVTO history of heritage designs. In most cases such data is not publicly available.

Table 4-3: Fine-grained component design heritage levels

Value	Conditions
1	Component design is used off-the-shelf without modifications or minor modifications.
0.75	Component design is used with modifications or its subcomponent designs are proven component designs but haven't been used as a system before. Hence, its architecture is new. Implicitly, the architecture of the system (the way the components interact) has less weight than the components themselves.
0.5	The component design is partly based on new sub-component designs and has been newly developed. Alternatively, the component design has been subject to major modifications.
0.25	A majority of the component designs is newly developed and have not been operated in this architecture before.
0	Newly developed component designs, where most of its subcomponent designs are newly developed. "Newly developed" means that a component instance has not yet been operated in its intended environment before.

For aggregating component design heritage to design heritage on a system level, a weighted sum is used. In most cases aggregation takes place from the subsystem level to the system level. Whenever data for subsystems is lacking, they are excluded. Weightings are closely related to the relative development cost contribution of a subsystem to the overall system. These weighting factors are either taken from the literature, such as in the case of spacecraft from Larson and Wertz (1999) or they are based on subjective assessments such as in the case of launcher and rocket engine components. For example, the development cost of rocket engines is disproportionally higher than the development cost of a rocket stage structure. I use development cost as a weighting, as there are strong correlations between development cost and the complexity of space systems (Bearden, 2003; Bearden et al., 2012). If data on a subsystem level is completely lacking, estimates on the system level are made.

In order to protect against wrongly estimated values and aggregation errors in the fine-grained metric, an alternative coarse-grained metric is introduced. The levels for this metric are defined in Table 4-4. The idea behind this metric is to define broad categories for design heritage that should be less prone to estimation errors. If design heritage has an effect on the four dependent variables, both, the fine-grained and coarse-grained metric should yield similar results.

Table 4-4: Coarse-grained design heritage categories

Category	Conditions
0	Newly developed
1	<u>Heritage parts / equipment:</u> The space system consists of heritage parts and equipment, e.g. RTGs, antenna. However, the subsystems are newly composed, i.e. no heritage subsystems are used.
2	<u>Heritage subsystems:</u> One or more subsystem / stages of the space system are existing or an existing subsystem / stage has been modified
3	<u>Heritage bus:</u> The spacecraft bus is already existing but the payload can be newly developed. For launchers, all stages need to be based on existing designs. Modifications to the bus / stages are allowed.
4	<u>Carbon copy:</u> The spacecraft is identical to a predecessor, except small modifications. The bus and the payload are identical or almost identical. "Carbon copies" are usually associated with spacecraft and not with launchers, as launchers are usually produced in series.

In other words, the two metrics are based on the same concept "design heritage". If design heritage has an effect on the programmatic variables, the effect should be independent of the concrete metric used.

Technological capability:

Technological capabilities are represented by three indicators with ordinal scales: organizational capability, team transfer, and program manager experience.

- Organizational capabilities fall into two categories that are defined in Table 4-5.

Table 4-5: Ordinal scale for organizational capability variable

Category	Conditions
0	First time the organization (prime contractor) has developed a space system from a class (launcher, lander, orbiter, rover) for a class of mission (destination: LEO, GEO, Lunar, Mars, outer solar system). Furthermore, if more than 20 years have passed since the last time a space system from the class has been developed by the organization, then the new system is considered a "First". It is expected that after 20 years, most of the personnel with experience is no longer available.
1	At least one previously developed space system from a class as defined under category 0.

It is very important to note that the organizational capability is defined, not with respect to a specific system design, but with respect to broad categories of knowledge associated with certain types of space systems in order to avoid interactions with the design heritage variable. This definition is distinct to that of "learning curves" where the cost of manufacturing the next production unit is measured. Here, I am interested in the knowledge / experience that is embodied in the organization and enables it to develop certain types of systems.

- Team similarity (only for interplanetary spacecraft data) are measured on an ordinal scale, as shown in Table 4-6.

Table 4-6: Ordinal scale for team similarity variable

Category	Conditions
0	The spacecraft / launcher is developed without the involvement of the team that has worked on predecessors. In case data is not available, it is assumed that teams have changed, if the prime contractor or prime investigator has changed. For example, a spacecraft is developed by NASA Ames instead of JPL. It is assumed that teams change when the prime changes. This is a simplification, as the subcontractors may still remain the same.
1	The prime contractor / prime investigator remains the same and there is evidence that confirms that the teams have essentially stayed the same.

- Program manager (only for interplanetary spacecraft data):

The "program manager" is the manager that was responsible for the development of the spacecraft. At least for NASA programs the program manager responsible for the program after launch is different from the one involved in development. Furthermore, "experience" is limited here to already having been in the role of a program manager before. This is due to the difficulty of properly accounting for other forms of experience, for example, experience in mission operations, preliminary studies etc. Program managers usually have extensive previous experience in the space sector and it is difficult to compare their experience. Table 4-7 shows the three program manager categories. Program manager data was only collected for interplanetary missions. Hence, the categories are limited to program manager experience with interplanetary missions.

Table 4-7: Program manager experience categories

Category	Conditions
0	No previous experience with program management of interplanetary missions.
1	Experience with one mission and has served in the role of program manager during development before for an interplanetary mission.
2	More than one interplanetary mission managed in the role of program manager during development.

4.2.3 Selection of Population: Launchers, Spacecraft

For performing the statistical analysis, I need to define a population for which I want to draw conclusions. Hence, in this section I choose the population and describe the limitations of that choice. The population is the set of space systems for which I want to draw conclusions. However, I do not draw conclusions directly for the population but first for a sample, drawn from the population. In Section 4.4 I extend the conclusions derived from analyzing the sample to the population and discuss the validity of this step (Levine and Stephan, 2014). Space systems here include spacecraft and launchers. However, the population is further limited geographically and temporally. An overview of these limitations is given in Table 4-8.

For interplanetary spacecraft, only NASA, ESA, and JAXA space programs are considered. The main reason is availability of data, as will be shown in Section 4.2.4. For example, cost data for historical Soviet and Russian space missions is difficult to get access to. Even in cases where cost data exists, the cost data is difficult to interpret due to significantly lower wages. Furthermore, only spacecraft developed or commissioned by governmental agencies are considered. Again, the main reason is the availability and accuracy of data. Cost data and information about cost overruns and delays are well-documented for NASA missions, as the Government Accountability Office (GAO) provides independent assessments of major NASA space programs. In addition, budget requests and budget approval data from NASA is publicly accessible.

The availability of data in terms of the period in which the space systems were developed is also limited. For interplanetary spacecraft, data was available for the period stretching from the 1970s to 2015. For LEO to GEO spacecraft reliable data was only available for spacecraft from 1996 to 2015.

Table 4-8: Considered populations and their limitations

Population	Geographic limitations	Period
Interplanetary spacecraft	Developed by space agencies NASA, ESA, JAXA	From 70s to 2015
LEO to GEO spacecraft	Developed by NASA and commercial companies in the US	From 1996-2015
Launcher	Developed in Europe, USA	From 1959-2015

For launchers, European and U.S. launchers are selected as the population. Soviet, Russian, and Indian launchers are again excluded, due to difficulties in obtaining credible cost data. As the lifecycle of launchers stretches over several decades, the population of launchers dates back to 1959.

The question from which populations samples are collected is important for external validity, i.e. how far the results from analyzing the samples can be generalized for the population and beyond.

4.2.4 Sampling Method: Convenience Sampling

The selection of individuals out of a population is called “sampling” (Levine and Stephan, 2014). The sampled set of individuals is called “sample”. In the following, I select a sampling method which is a compromise between avoiding potential bias and data availability. One can distinguish between two categories of sampling methods: probability sampling and nonprobability sampling. In probability sampling, each individual out of a population has a certain well-defined probability to be selected into the sample. Probability sampling is considered the most rigorous sampling approach in the literature. It prevents selecting a non-representative sample out of a population (Angrist and Pischke, 2014). The statistical effect of selecting a non-representative sample is called “selection effect”. A sample subject to the selection effect may lead to false generalizations for the population. For example, many studies in psychology are based on a sample consisting of university students. However, university students may not be representative for the general population. The reason why university students are often used is that they are easily accessible. It is therefore convenient to use them as the sample. Sampling approaches based on convenience are called “convenience sampling” approaches.

Here, I choose convenience sampling. This decision is driven by the availability of data for space systems. I can justify this decision, as the number of launchers and governmentally funded space programs is low. It is in the order of dozens for launchers and in the hundreds for spacecraft. Hence, even a rather small sample may represent a significant fraction of the population. Table 4-9 shows the samples of interplanetary spacecraft, LEO to GEO spacecraft, and launchers, totaling 54 individuals.

Table 4-9: List of spacecraft, launchers, and propulsion systems along with sample size N

Spacecraft (Interplanetary)	**Spacecraft (LEO to GEO)**	**Launcher**
N=22	**N=15**	**N=17**
Viking Orbiter	TDRS K	L3S Europa
Viking Lander	LDCM	Ariane 1
Phoenix	MMS	Ariane 2
Mars Pathfinder	NPP	Ariane 3
Mars Climate Orbiter	SMAP	Ariane 4
Mars Global Surveyor	GLAST	Ariane 5
Mars Observer	Glory	Titan I
MAVEN	GPM	Titan II
Juno	WISE	Titan III
MSL	OCO-1	Titan IV
Cassini	OCO-2	Falcon 1
Dawn	HETE 1	Falcon 9
Kepler	HETE 2	Saturn I
MER	QuickBird 1	Saturn IB
Voyager	QuickBird 2	Saturn V
Pioneer 11		Space Shuttle
Magellan		
NEAR		
LRO		
GRAIL		
LADEE		
Messenger		

The data for the individual space systems can be found in Appendix B.1. The data has been compiled from various sources that are listed in Appendix B.2. Note that not all relevant data was available for all individuals from the sample. Hence, for some statistical analysis, the sample size is smaller than given in Table 4-9. The small sample size limits the use of specific statistical analyses. For example, controlling for selection bias effects is difficult. More specifically, some of the spacecraft and launcher development programs were subject to severe cost / schedule overruns due to external factors. For example, the Viking spacecraft's launch date was delayed by two years due to congressional budget restrictions (Ezell and Ezell, 2009). Cost / schedule overruns due to external factors are subtracted from the development cost whenever data was available or controlled for via the "external causes of delays" dummy variable.

To summarize, I use convenience sampling due to the limited availability of heritage-related data for space systems and the low number of space systems in general. The limitation of this sampling approach is that potential selection bias could be present in the sample. With the availability of a larger data set, probabilistic sampling could be performed in the future.

4.2.5 Statistical Methods: Multiple Regression, T-Test, F-Test

Depending on the data at hand, different statistical methods can be used for its analysis. I mainly use a statistical method called "regression analysis". Regression analysis is commonly used for assessing how a change in the independent variable changes the dependent variable (Angrist and Pischke, 2008, 2014; Levine and Stephan, 2014; Wooldridge, 2015). The result of the analysis is a linear function that fits the data points. If the slope of the graph of the function is positive, an increase in the independent variable is related to an increase in the dependent variable. If the slope is negative, an increase in the independent variable is related to a decrease of the dependent variable.

For the case at hand, I use regression analysis for assessing the relationship between the degree of heritage technology used and the programmatic variables. More specifically, regression analysis allows for determining if there is an increase, decrease, or no effect from using heritage technologies. Furthermore, it allows for determining the degree of increase and decrease. Regression analysis can be performed with more than a single independent and dependent variable.

The general linear regression equation for individual data points is:

$$y_i = \beta_0 + \beta_1 x_{1i} + \cdots + \beta_k x_{ki} + \varepsilon_i, i = 1, \ldots, n; k = 1, \ldots, m \tag{28}$$

i is the i-th data point, y_i is the value of the dependent variable and x_i the independent variable for the i-th data point. β_j are regression coefficients. ε_i is an error term. For a regression with a single independent variable x_i, the equation simplifies to:

$$y_i = \beta_0 + \beta_1 x_i + \varepsilon_i, i = 1, \ldots, n \tag{29}$$

Regression analysis is performed by choosing the β_j such that the sum of the square of the error term ε_i for all data points is minimized.

$$S(\beta_i) = \sum_{i=1}^{n} (y_i - \beta_0 - \beta_1 x_{1i} - \cdots - \beta_k x_{ki})^2 = \sum_{i=1}^{n} \varepsilon_i^2 = min!, i = 1, \ldots, n \tag{30}$$

The resulting general linear regression equation with the coefficients determined in the previous step is:

$$y = \beta_0 + \beta_1 x_1 + \cdots + \beta_k x_k, i = 1, \ldots, n \tag{31}$$

Often multiple regressions are run by successively adding independent variables x_k such as:

$$(1)\ \ y = \beta_{01} + \beta_{11} x_1 \tag{32}$$

$$(2)\ \ y = \beta_{02} + \beta_{12} x_1 + \beta_{22} x_2 \tag{33}$$

$$\ldots$$

$$(k)\ \ y = \beta_{0k} + \beta_{1k} x_1 + \cdots + \beta_{kk} x_k \tag{34}$$

Each time an independent variable is added, the regression coefficients are determined anew. The resulting coefficients for each regression equation is reported in the form of a coefficient matrix, shown in Table 4-10. Usually, the matrix entries do not only contain the value of the respective coefficient but also its standard error and the so-called p-value I will introduce in one of the following paragraphs.

Table 4-10: Regression coefficient matrix

Variable	Coefficient values for regression equation (1)	Coefficient values for regression equation (2)	…	Coefficient values for regression equation (k)
-	β_{01}	β_{02}	$\cdots$	β_{0k}
x_2	β_{11}	β_{12}	$\cdots$	β_{1k}
x_3	-	β_{22}	$\cdots$	β_{2k}
$\cdots$	$\cdots$	…	$\cdots$	$\cdots$
x_k	-	-	$\cdots$	β_{kk}

It is also common practice to fit other functions than linear functions to the data. One form of alternative regression function I use later is based on the natural logarithmic function and has the following form:

$$\ln(y) = \beta_0 + \beta_1 x_1 + \cdots + \beta_k x_k \quad (35)$$

For calculating the absolute values of the coefficients, the equation can be manipulated to yield the following form:

$$y = \exp(\beta_0) \exp(\beta_1 x_1) \dots \exp(\beta_k x_k) \quad (36)$$

Note that with the natural logarithm, small changes in the coefficients have an exponential effect on the dependent variable.

An important parameter in regression analysis is the coefficient of determination R^2. The coefficient of determination is a measure of how well the statistical model fits the data. It is defined as:

$$R^2 = 1 - \frac{S_{res}}{S_{tot}} \quad (37)$$

With the sum of square of residuals S_{res} defined as:

$$S_{res} = \sum_{i=1}^{n} (y_i - f_i)^2 \quad (38)$$

Where f_i is the value of the statistical model at the point x_i. The total sum of squares S_{tot} is defined as:

$$S_{tot} = \sum_{i=1}^{n} (y_i - \bar{y})^2 \quad (39)$$

Where $\bar{y}$ is the arithmetic mean of all y_i :

$$\bar{y} = \frac{1}{n} \sum_{i=1}^{n} y_i \quad (40)$$

The closer the statistical model is to the simple average of the data points, the lower is R^2. If the statistical model is equivalent to the average, R^2 is 0. It means that the independent variable has no effect on the dependent variable. If the independent variable has an effect on the dependent variable and the statistical model perfectly fits the data points, R^2 is 1.

One shortcoming of using R^2 is that it always increases with the number of variables that are added to the model. This effect is independent of how well the model fits the data. However, this contradicts what R^2 should represent, namely, how well the model fits the data. As a remedy, the *adjusted* R^2 is introduced that accounts for the number of independent variables in the model. If the addition of a variable reduces the fit of the model, the adjusted R^2 decreases. For the regression runs presented in this chapter I will therefore refer to the adjusted R^2 instead of R^2.

I call a regression a multiple regression, if there is more than one independent variable in the regression equation. The majority of statistical analyses that I perform later are based on multiple regression. Multiple regression allows for systematically adding independent variables and observing how the effect on the dependent variables changes. By doing so, the underlying causal mechanisms between the variables can be inferred, although I can never be sure that there are no other, hidden, variables. Note that the independent variables do not need to be continuous but can be binary or categorial such as technology options. Either a certain technology is used or it is not. Hence, multiple regression is a powerful method for analyzing the space system data by uncovering the effect of multiple independent variables on a dependent variable.

At this point, I still do not know when I should accept a hypothesis and reject the corresponding 0-hypothesis. In general, the likelihood of rejecting the 0-hypothesis when the 0-hypothesis is true is expressed by the p-value. For example, a p-value of 0.01 indicates that there is a 1% likelihood of rejecting the 0-hypothesis when in reality the 0-hypothesis is true. The smaller the p-value, the lower the likelihood that I draw a false conclusion from the statistics. A large p-value can be interpreted as a low confidence that there is any relationship between the dependent and independent variable. A helpful relationship between the p-value and standard error is that multiplying the standard error by 1.96 corresponds to a p-value of 0.05. The p-value is calculated by a variety of statistical tests (Levine and Stephan, 2014). For regressions with a single independent and dependent variable the *t-test* is commonly used for calculating the p-value. For multiple regression, the overall statistical significance of the model is evaluated via the *F-test* (Wooldridge, 2015). Still, the t-test is used in multiple regression for evaluating the statistical significance of individual independent variables.

In order to have a fixed criterion for when a p-value is low enough, the concept of "statistical significance" was introduced. A result from a statistical analysis is "statistically significant", if the 0-hypothesis can be rejected. The threshold value at which I consider a result statistically significant is α. α is also called the "level of significance". If p is smaller than α, the 0-hypothesis is rejected. Depending on the domain, there are different statistical significance levels that are commonly used. Common levels are 0.01 and 0.05. If the p-value is above the threshold, the statistical significance is insufficient for rejecting the 0-hypothesis. If it is below the threshold, the 0-hypothesis can be rejected. In the following, I use $\alpha = 0.05$, as it is a commonly used threshold value. In other words, I think that a likelihood of 5% of rejecting the 0-hypothesis when the 0-hypothesis is true is good enough for this analysis.

The 0-hypothesis for multiple regression is different from the one for a simple regression. For multiple regression, the 0-hypothesis is that *no* linear relationship exists between the dependent variable and all the independent variables. The 1-hypothesis is that a linear relationship between the dependent variable and at least one of the independent variables exists (Levine and Stephan, 2014).

Another statistical significance test is needed when groups are compared. Groups are compared by calculating the difference between group means. The 0-hypothesis in this case is that both groups have been drawn from the same population with an identical mean value. The 1-hypothesis is that the groups have been drawn from populations with distinct mean values. Hypothesis testing is performed by the 2-tailed t-test. The test can be interpreted as checking, to what degree the tails of the normal distribution of the groups overlap.

In general, a larger sample has a higher probability that the sample mean is close to the population mean. Hence, the standard error is smaller, which is a measure for the difference between sample mean and population mean. A smaller standard error means, again, that the p-value is smaller. There is no clear threshold for how many dependent variables can be added to a multiple regression analysis with a given sample size. Rule-of-thumb values of 10-15 per independent variable have been reported. With a sample size of about 50, this would result in about 5 independent variables or less. In some multiple regression runs I successively add control variables and reach a maximum of 7 independent variables. I am aware that I violate the rule-of-thumb for the regression runs with more than 5 variables and have to take the results with care.

Table 4-11 shows the variables that are assessed with its respective scale type and statistical assessment approach. Most scales can be considered nominal or ordinal. Nominal, as the data can be categorized and ordinal, as a preference relation can be established. However, there is no difference in the statistical treatment of nominal and ordinal data here, as I do not aggregate nominal or ordinal data. For testing the relationship between design heritage and the variables in the top row, the p-value is calculated in each case. If p is below a threshold of $\alpha = 0.05$, the 0-hypothesis can be rejected. A 95% confidence interval is calculated accordingly.

Table 4-11: How relationships between variables are tested for statistical significance

<table>
<tr><th></th><th>Scale type:</th><th>Specific development cost</th><th>Development duration</th><th>Cost overrun</th><th>Schedule overrun</th></tr>
<tr><td>Scale type:</td><td></td><td colspan="4">Ratio</td></tr>
<tr><td>Design heritage (fine-grained)</td><td>Interval</td><td colspan="4" rowspan="5">t-test (group means, regression with one variable),
F-test (multiple regression)</td></tr>
<tr><td>Design heritage (coarse-grained)</td><td>Nominal / ordinal</td></tr>
<tr><td>Organizational capability</td><td>Nominal / Ordinal</td></tr>
<tr><td>Team similarity</td><td>Nominal / Ordinal</td></tr>
<tr><td>Program manager experience</td><td>Nominal / Ordinal</td></tr>
</table>

To summarize, multiple regression analysis allows for eliciting if there is a correlation between the dependent and an independent variable. Controlling for other independent variables, I can even work towards uncovering causal relationships between the dependent and an independent variable. For validating this relationship, a multiple regression model is developed, which holds typical spacecraft development cost drivers constant. The objective of introducing other cost drivers is to isolate the effect of, e.g. design heritage on specific development cost (Angrist and Pischke, 2014). The controls "power generation", "ADCS", "reaction control", "launch year" are taken from Hamaker and Componation (2005). They were selected, as they were reported as statistically significant in the publication. Further controls were added: Single and dual spacecraft are distinguished, as some of the development programs result in two spacecraft used in one mission. The literature usually takes the cost of these spacecraft into consideration as the theoretical first unit (TFU) and subsequent units produced. As the cost for the TFU is unknown, this control has been introduced. Furthermore, the mission class has been introduced in order to categorize space programs. It was introduced, as the ground rules for space programs often significantly differ between, for example, small spacecraft that use a lot of heritage technologies, compared to the development of flagship spacecraft that are based on new technologies.

In the next step, I will present the results of the multiple regression runs.

4.3 Results

In the following sections, I present the results for the statistical analysis of the space systems, presented in Table 4-9. I call the sample consisting of LEO, MEO, GEO, and interplanetary spacecraft, together with launchers "mixed sample" in the following. The results were generated by using MATLAB® and algorithms from the MATLAB® Statistics and Machine Learning Toolbox. They are presented in the following sections, as shown in Table 4-12. Sections 4.3.1 to 4.3.3 will present the results for the relationship between design heritage and programmatic variables. Sections 4.3.4 to 4.3.6 will present the results for the relationship between technological capability and programmatic variables.

Table 4-12: Structure of sections reporting on results of statistical analysis

Programmatic variable \ heritage variable	**Design heritage**	**Technological capability**
Specific development cost	4.3.1	4.3.4
Development duration	4.3.2	4.3.5
Cost / schedule overrun	4.3.3	4.3.6

For design heritage, I report results for a fine-grained and coarse-grained metric in order to test the plausibility of the results. For technological capability, I use organizational "Firsts", team transfer between space programs, and program manager experience as metrics. Finally, section 4.4 summarizes the results and ends with a discussion.

4.3.1 Design Heritage: Specific Development Cost

Multiple regressions are run on the interplanetary, LEO to GEO spacecraft, and launcher sample with respect to specific development cost. The results are presented in Table 4-13 for the fine-grained design heritage metric and in Table 4-14 for the coarse-grained design heritage metric. The best fit to the data was obtained for a natural logarithmic function that was applied to specific development cost.

For the fine-grained metric, design heritage shows a statistically significant relationship with ln-specific development cost in all multiple regression models. The effect is a consistent decrease of specific development cost. Across the regression models (1)-(6), the coefficient for design heritage in the exponent varies between -1.9 and -1.4. At a design heritage value of 1, this corresponds to a reduction of specific development cost of 85% to 75%. The relatively small change of the coefficient indicates that adding and removing controls has a limited effect on the effect of design heritage. According to Angrist and Pischke (2014) this indicates that the causal relationship between the dependent and independent variable is "robust". In other words, it is likely that there is an underlying causal relationship and it is unlikely that introducing another control variable might drastically alter this result. Note, however, that there is no guarantee that such an omitted variable does not exist. All multiple regression models are statistically significant and show a weak to medium adjusted R^2 up to 0.667.

For the regression models using the coarse-grained design heritage metric in Table 4-14, similar tendencies can be observed. However, in some regression models the design heritage categories do not have a statistically significant relationship with ln-specific development cost.

Table 4-13: Multiple regression results for ln-specific development cost (ln Y2005 k$/kg), fine-grained design heritage metric, and different controls, mixed sample. Table entries: correlation coefficient, [standard error], (p-value)

	(1)	(2)	(3)	(4)	(5)	(6)
Intercept	6.7 [0.4] ($8*10^{-24}$)	6.4 [0.3] ($4*10^{-23}$)	6.7 [0.3] ($9*10^{-25}$)	5.4 [0.3] ($4*10^{-18}$)	7.0 [1.2] ($8*10^{-7}$)	7.8 [1.3] ($1*10^{-6}$)
Fine-grained design heritage	-1.9 [0.6] (0.003)	-1.8 [0.6] (0.002)	-1.6 [0.5] (0.0015)	-1.4 [0.5] (0.01)	-1.5 [0.4] (0.001)	-1.6 [0.5] (0.001)
External		0.9 [0.3] (0.008)	0.2 [0.5] (0.3)	0.1 [0.3] (0.7)	0.3 [0.3] (0.3)	0.2 [0.3] (0.4)
Double spacecraft			1.2 [0.4] (0.006)	0.9 [0.5] (0.08)	0.5 [0.4] (0.2)	0.3 [0.5] (0.5)
Launcher serial production			-1.3 [0.3] ($4*10^{-5}$)	-	-0.8 [1.1] (0.5)	-1.5 [1.2] (0.2)
Si solar cells				0.03 [1.3] (0.98)	-	-
GaAs solar cells				-0.2 [1.2] (0.9)	0.9 [0.6] (0.2)	1.1 [0.7] (0.13)
RTG				0.3 [1.0] (0.7)	0.6 [0.7] (0.4)	0.3 [0.8] (0.7)
Mono-propellant				0.8 [0.5] (0.13)	1.1 [0.4] (0.017)	0.8 [0.6] (0.19)
Bi-propellant				0.6 [0.7] (0.4)	0.9 (0.6) [0.14]	0.5 [0.7] (0.5)
Mono & bi-propellant				0.6 [0.6] (0.3)	0.6 [0.5] (0.2)	0.07 [0.7] (0.9)
Year					-0.04 [0.01] (0.0002)	-0.04 [0.01] (0.0001)
Medium class						-1.2 [0.9] (0.2)
Flagship class						-0.6 [0.7] (0.4)
R^2	*0.17*	*0.28*	*0.59*	*0.62*	*0.74*	*0.76*
Adjusted R^2	*0.15*	*0.25*	*0.55*	*0.53*	*0.67*	*0.67*
p-value	*0.003*	*0.0004*	*$3*10^{-8}$*	*$9.6*10^{-6}$*	*$4*10^{-8}$*	*$2*10^{-7}$*
N	*50*	*50*	*50*	*50*	*50*	*50*

Table 4-14: Multiple regression results for ln-specific development cost (ln Y2005 k$/kg), coarse-grained design heritage metric, and different controls, mixed sample. Table entries: correlation coefficient, [standard error], (p-value)

	(1)	(2)	(3)	(4)	(5)
Intercept	6.4 [0.4] ($1*10^{-20}$)	6.2 [0.4] ($1*10^{-21}$)	6.5 [0.3] ($4*10^{-23}$)	6.3 [0.5] ($8*10^{-17}$)	9.0 [1.6] ($3*10^{-6}$)
Design heritage category 1	-0.8 [0.6] (0.18)	-1.0 [0.5] (0.06)	-0.7 [0.4] (0.07)	-0.7 [0.4] (0.08)	-0.9 [0.4] (0.016)
Design heritage category 2	-0.5 [0.6] (0.4)	-0.6 [0.5] (0.3)	-0.5 [0.4] (0.2)	-0.5 [0.4] (0.2)	-1.0 [0.4] (0.03)
Design heritage category 3	-0.8 [0.5] (0.12)	-1.4 [0.5] (0.007)	-1.1 [0.4] (0.006)	-1.0 [0.406] (0.0159)	-1.4 [0.395] (0.00127)
Design heritage category 4	-0.9 [0.8] (0.3)	-1.3 [0.8] (0.11)	-1.3 [0.6] (0.03)	-1.1 [0.7] (0.11)	-1.3 [0.6] (0.03)
External		1.3 [0.4] (0.0016)	0.5 [0.3] (0.12)	0.6 [0.3] (0.097)	0.7 [0.3] (0.045)
Double spacecraft			-1.4 [0.3] ($6*10^{-5}$)	1.3 [0.4] (0.006)	0.08 [0.5] (0.9)
Launcher serial production			-1.4 [0.3] ($6*10^{-5}$)	-	-2.7 [1.4] (0.06)
Interplanetary spacecraft				0.3 [0.4] (0.5)	0.5 [0.4] (0.3)
Launcher				-1.2 [0.4] (0.0098)	-
Si solar cells					-1.3 [0.8] (0.10)
GaAs solar cells					-
RTG					-1.0 [0.9] (0.3)
Mono-propellant					0.2 [0.6] (0.8)
Bi-propellant					-0.3 [0.7] (0.8)
Mono & bi-propellant					-0.8 [0.8] (0.3)
Year					-0.05 [0.01] ($8*10^{-5}$)
Medium class					
Flagship class					
R^2	*0.064*	*0.25*	*0.61*	*0.62*	*0.80*
Adjusted R^2	*-0.018*	*0.17*	*0.55*	*0.55*	*0.69*
p-value	*0.5*	*0.02*	*$3*10^{-7}$*	*$8*10^{-7}$*	*$8*10^{-7}$*
N	*51*	*51*	*51*	*51*	*51*

To summarize, for space systems in general, there is a clear decrease in specific development cost with more design heritage. Note that the year in which the space system was launched has a statistically significant effect on the specific development cost which decreases with each year. This result is consistent with the results from Coonce et al. (2009).

4.3.2 Design Heritage: Development Duration

In the following, the relationship between the degree of used design heritage and the development duration for space systems is elicited. For the mixed sample (interplanetary spacecraft, LEO/GEO spacecraft, launchers) a multiple regression analysis is conducted for analyzing the relationship between the fine-grained design heritage metric and development duration. I use a linear regression function. The results for a linear regression without controls are shown in Fig. 4-2 along with the 95% confidence bounds. The data points around the graph of the linear regression function do not show any obvious pattern and seem to be randomly distributed. Hence, it can be concluded that the linear regression function is an appropriate regression function for the data at hand.

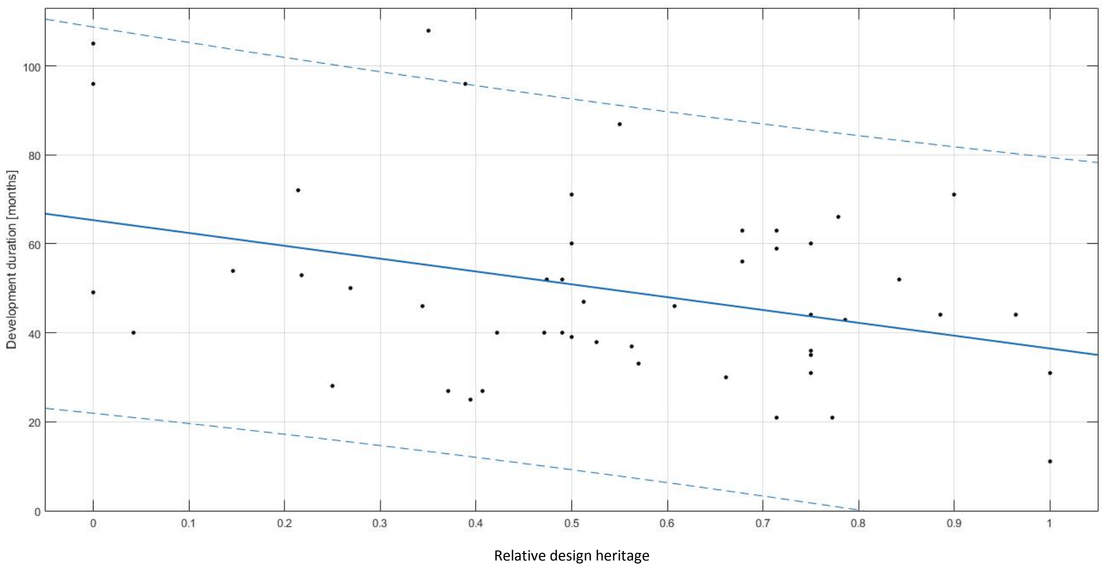


Fig. 4-2: Design heritage and development duration for mixed sample with 95% confidence bounds

Further regressions are run for the fine-grained and the coarse-grained metric. The results for the fine-grained metric are displayed in Table 4-15. With an increased number of controls, the effect of design heritage rather increases. For example, whereas the coefficient for design heritage is about -29 months for (1) without controls, it increases to about -46 months for (6) with the whole range of controls. For all multiple regression models from (1) to (6), design heritage has a statistically significant relationship with development duration. With a mean development duration of about 50 months, the savings in development duration are considerable. Note, however, that a design heritage value of 1 would mean that a space system is produced based on an existing design. Hence, the drastic reduction in development duration is understandable. Compared to other development duration predictors, design heritage is the predictor with the largest effect on reducing development duration. The adjusted R^2 value for the regression models is in general weak with a maximum of 0.39 for the regression model (4). The p-value for the regression models is statistically significant.

Table 4-15: Multiple regression results for development duration in months, fine-grained design heritage metric, and different controls, mixed sample. Table entries: correlation coefficient, [standard error], (p-value)

	(1)	(2)	(3)	(4)	(5)	(6)
Intercept	65 [7] ($8*10^{-13}$)	65 [7] ($8*10^{-12}$)	59 [7] ($4*10^{-10}$)	77 [10] ($5*10^{-10}$)	85 [8] ($3*10^{-13}$)	-
Fine-grained design heritage	-29 [11] (0.014)	-29 [11] (0.015)	-32 [10] (0.004)	-43 [10] (0.0002)	-46 [12] (0.0004)	-46 [12] (0.0005)
External		1 [7] (0.9)	14 [7] (0.04)	9 [6] (0.2)	9 [8] (0.3)	9 [8] (0.3)
Double spacecraft			-23 [10] (0.03)	-15 [10] (0.15)	-17 [12] (0.16)	-17 [13] (0.2)
Launcher serial production			19 [6] (0.004)	-	-	79 [9] ($2*10^{-9}$)
Interplanetary spacecraft				-20 [7] (0.009)	-19 [9] (0.051)	-18 [10] (0.07)
Launcher				7 [7] (0.4)	-	-
3-axis control					-8 [25] (0.7)	-0.06 [26] (0.998)
Si solar cells					16 [30] (0.6)	-
GaAs solar cells					2 [27] (0.9)	-17 [19] (0.4)
RTG					-4 [22] (0.8)	-29 [22] (0.2)
Mono-propellant					0.6 [12] (0.96)	-0.9 [15] (0.95)
Bi-propellant					-2 [16] (0.9]	-7 [19] (0.7)
Mono & bi-propellant					-4 [16] (0.8)	-7 [20] (0.7)
Year						0.3 [0.3] (0.2)
Small class						83 [34] (0.02)
Medium class						82 [35] (0.03)
Flagship class						94 [36] (0.013)

R^2	*0.12*	*0.12*	*0.36*	*0.45*	*0.48*	*0.51*
Adjusted R^2	*0.10*	*0.085*	*0.30*	*0.39*	*0.32*	*0.31*
p-value	*0.014*	*0.048*	*0.0005*	*$6*10^{-5}$*	*0.005*	*0.014*
N	*49*	*49*	*49*	*49*	*49*	*49*

Performing the same multiple regressions for the alternative design heritage metric results in Table 4-16. Note that the p-values for the multiple regression models are only statistically significant for (3) and (4). For these two multiple regression models, only design heritage categories 1 and 4 are unanimously statistically significant. However, the degree of reduction in development duration is about the same as for the fine-grained design heritage metric.

Table 4-16: Multiple regression results for development duration, coarse-grained design heritage metric, and different controls, mixed sample. Table entries: correlation coefficient, [standard error], (p-value)

	(1)	(2)	(3)	(4)	(5)	(6)
Intercept	60 [6.84] ($2*10^{-11}$)	60 [6.91] ($5*10^{-11}$)	55 [7.50] ($6*10^{-9}$)	71 [9.68] ($6*10^{-9}$)	74 [7.39] ($2*10^{-11}$)	73 [40.4] (0.08)
Design heritage category 1	-15 [9] (0.13)	-16 [10] (0.11)	-18 [9] (0.045)	-19 [8] (0.02)	-20 [9] (0.04)	-19 [10] (0.06)
Design heritage category 2	-12 [10] (0.2)	-12 [10] (0.2)	-12 [9] (0.2)	-11 [9] (0.2)	-12 [10] (0.2)	-9 [12] (0.5)
Design heritage category 3	-10 [9] (0.3)	-12 [9] (0.2)	-16 [8] (0.07)	-22 [8] (0.011)	-24 [10] (0.02)	-24 [11] (0.03)
Design heritage category 4	-29 [14] (0.048)	-30 [14] (0.04)	-29 [13] (0.03)	-45 [14] (0.003)	-49 [16] (0.004)	-47 [16] (0.006)
External		6 [7] (0.4)	18 [7] (0.02)	15 [7] (0.04)	13 [9] (0.2)	11 [9] (0.3)
Double spacecraft			-23 [10] (0.03)	-15 [10] (0.12)	-16 [13] (0.2)	-12 [15] (0.4)
Launcher serial production			17 [7] (0.015)	-	-	-6 [37] (0.9)
Interplanetary spacecraft				-21 [8] (0.015)	-20 [11] (0.07)	-21 [11] (0.08)
Launcher				2 [9] (0.8)	-	-
Spin-stabilized					-8 [30] (0.8)	-7 [40] (0.9)
3-axis control					5 [27] (0.8)	12 [28] (0.7)
Si solar cells					12 [33] (0.7)	-
GaAs solar cells					-2 [29] (0.95)	-25 [21] (0.2)
RTG					-1 [25] (0.97)	-11 [25] (0.7)

Mono-propellant					-3 [13] (0.8)	-8 [17] (0.6)
Bi-propellant					-13 [18] (0.5)	-18 [21] (0.4)
Mono & bi-propellant					-9 [17] (0.6)	-11 [23] (0.6)
Year						0.3 [0.3] (0.3)
Small class						3 [30] (0.9)
Medium class						7 [21] (0.7)
Flagship class						-
R²	*0.10*	*0.11*	*0.34*	*0.43*	*0.46*	*0.49*
Adjusted R²	*0.020*	*0.012*	*0.23*	*0.32*	*0.22*	*0.19*
p-value	*0.3*	*0.4*	*0.009*	*0.0017*	*0.054*	*0.11*
N	*50*	*50*	*50*	*50*	*50*	*50*

To summarize, the mixed sample shows a statistically significant decrease of development duration with increased design heritage. Design heritage is by far the largest coefficient among the independent variables. Also note that the results do not necessarily imply a causal relationship between design heritage and development duration. However, the introduction of statistical controls was intended to isolate the causal relationship, although there is no guarantee that there are no other controls that are relevant (Angrist and Pischke, 2014).

4.3.3 Design Heritage: Development Cost and Schedule Overruns

Up to this point, I have looked at the relationship between design heritage and specific development cost. I have also looked at the relationship between design heritage and development duration. However, these two programmatic variables do not say much about the relationship between design heritage and programmatic risk. Programmatic risk is expressed by the two variables development cost and schedule overrun. In the following, I want to illuminate the effect of design heritage on development cost and schedule overrun by performing regression analyses on development cost and schedule overrun data. As no development cost overrun and schedule overrun data was available for launchers, the results are limited to the interplanetary spacecraft sample and LEO to GEO spacecraft sample. Therefore, the analysis is performed on a more limited data set than for specific development cost and development duration.

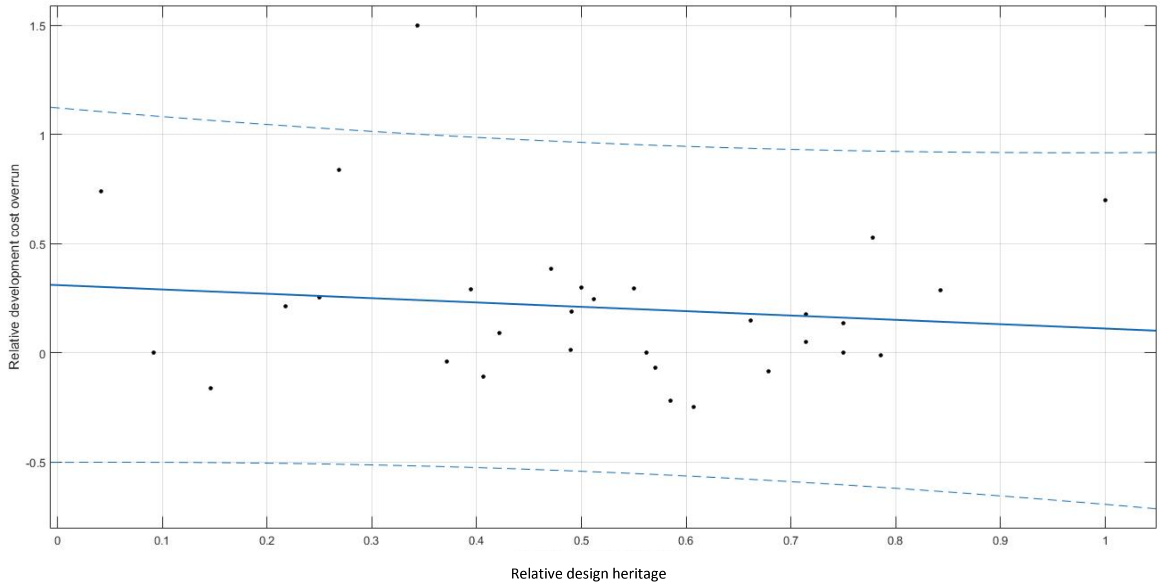


Fig. 4-3: Design heritage and relative development cost overrun for the interplanetary and LEO/GEO spacecraft sample

Table 4-17: Multiple regression results for relative development cost overrun, fine-grained design heritage metric, and different controls, interplanetary spacecraft and GEO to LEO sample. Table entries: correlation coefficient, [standard error], (p-value)

	(1)	(2)	(3)	(4)	(5)	(6)
Intercept	0.30 [0.16] (0.07)	0.29 [0.17] (0.11)	0.31 [0.20] (0.13)	0.23 [0.32] (0.5)	1.21 [0.80] (0.15)	2.08 [0.86] (0.03)
Fine-grained design heritage	-0.20 [0.28] (0.5)	-0.20 [0.29] (0.5)	-0.23 [0.33] (0.5)	-0.17 [0.40] (0.7)	-0.04 [0.51] (0.9)	0.35 [0.54] (0.5)
External		0.04 [0.13] (0.7)	0.05 [0.13] (0.7)	0.06 [0.15] (0.7)	0.12 [0.17] (0.5)	0.16 [0.16] (0.4)
Double spacecraft			-0.05 [0.20] (0.8)	-0.05 [0.21] (0.8)	-0.38 [0.33] (0.3)	-0.16 [0.30] (0.6)
Interplanetary spacecraft				0.05 [0.19] (0.8)	0.06 [0.24] (0.8)	0.06 [0.23] (0.8)
3-axis control					-0.83 [0.50] (0.11)	-1.43 [0.54] (0.017)
GaAs solar cells					-0.05 [0.35] (0.9)	0.67 [0.51] (0.2)
RTG					-0.18 [0.43] (0.7)	0.18 [0.48] (0.7)
Mono-propellant					-0.25 [0.31] (0.4)	-0.10 [0.33] (0.8)
Bi-propellant					-0.45 [0.38] (0.3)	-0.29 [0.40] (0.5)
Mono & bi-propellant					-0.15 [0.37] (0.7)	-0.23 [0.42] (0.6)

Year						-0.03 [0.01] (0.04)
Small class						
Medium class						0.22 [0.38] (0.560)
Flagship class						0.14 [0.55] (0.8)
R^2	*0.016*	*0.019*	*0.021*	*0.024*	*0.19*	*0.38*
Adjusted R^2	*-0.017*	*-0.048*	*-0.084*	*-0.12*	*-0.19*	*-0.065*
p-value	*0.5*	*0.8*	*0.9*	*0.95*	*0.9*	*0.6*
N	*32*	*32*	*32*	*32*	*32*	*32*

Table 4-18: Multiple regression results for development schedule overrun, fine-grained design heritage metric, and different controls, interplanetary spacecraft and GEO/LEO sample. Table entries: correlation coefficient, [standard error], (p-value)

	(1)	(2)	(3)	(4)	(5)	(6)
Intercept	0.61 [0.20] (0.006)	0.47 [0.19] (0.02)	0.39 [0.23] (0.095)	0.28 [0.35] (0.4)	1.10 [0.84] (0.2)	2.60 [1.04] (0.02)
Fine-grained design heritage	-0.63 [0.36] (0.09)	-0.69 [0.32] (0.04)	-0.56 [0.37] (0.2)	-0.47 [0.44] (0.3)	-0.22 [0.52] (0.7)	0.01 [0.54] (0.99)
External		0.39 [0.14] (0.0096)	0.37 [0.15] (0.02)	0.39 [0.16] (0.02)	0.35 [0.17] (0.06)	0.35 [0.17] (0.052)
Double spacecraft			0.15 [0.22] (0.5)	0.14 [0.23] (0.6)	0.09 [0.28] (0.8)	-0.23 [0.29] (0.4)
Interplanetary spacecraft				0.08 [0.20] (0.7)	-0.03 [0.24] (0.9)	-0.07 [0.22] (0.8)
3-axis control					-0.48 [0.56] (0.4)	-1.66 [0.763] (0.04)
GaAs solar cells					-0.46 [0.349] (0.2)	0.86 [0.64] (0.2)
RTG					-0.04 [0.49] (0.9)	-0.42 [0.50] (0.4)
Mono-propellant					-0.05 [0.31] (0.9)	0.15 [0.32] (0.7)
Bi-propellant					0.06 [0.39] (0.9)	0.12 [0.39] (0.8)
Mono & bi-propellant					0.11 [0.38] (0.8)	-0.27 [0.46] (0.6)
Year						-0.04 [0.02] (0.048)

Small class						
Medium class						0.33 [0.44] (0.6)
Flagship class						0.14 [0.55] (0.5)
R^2	*0.098*	*0.29*	*0.31*	*0.31*	*0.48*	*0.63*
Adjusted R^2	*0.067*	*0.24*	*0.23*	*0.20*	*0.22*	*0.35*
p-value	*0.09*	*0.008*	*0.02*	*0.04*	*0.12*	*0.06*
N	*31*	*31*	*31*	*31*	*31*	*31*

To summarize, no statistically significant relationship between design heritage and relative development cost overrun could be identified. The regression analysis for design heritage and relative development schedule overrun yielded the same result. One of the difficulties in applying regression analysis to relative development schedule overrun is that the data is skewed around the line of 0 relative development schedule overrun. The reason is that there are fewer programs finished on schedule or even quicker than programs suffering delays. Applying regression analysis to skewed data violates the normality condition, which requires normally distributed data around the regression line. Moreover, despite the regression model (2) having a statistically significant value for the design heritage coefficient, it does not stay significant when more control variables are added.

Another result is that the launch year of the spacecraft has a statistically significant relationship with both, development cost overrun and development schedule overrun. To the author's knowledge, this results has not been reported in the literature before and might have interesting implications for the systems engineering and project management literature. However, at this point, it is too early to draw any conclusions from this result, as I would need to conduct additional multiple regression runs focused on the launch year for confirming this result.

After having analyzed the relationship between design heritage and the four programmatic variables, the relationship between technological capability and programmatic variables are analyzed in the next step.

4.3.4 Technological Capability: Specific Development Cost

In this section I analyze whether the capability of an organization to develop a certain class of system has an influence on the system's specific development cost. First, I start with organizational capability in terms of organizational "Firsts", i.e. classes of systems that were developed by an organization for the first time and compare the specific development cost with systems developed by experienced organizations. I continue with comparing systems developed by teams that have already worked together and systems developed by new teams, and finish with comparing systems developed by experienced program managers and systems developed by program managers without previous experience.

The results for the mixed sample are shown in Fig. 4-4. The sample size for the space systems developed by organizations with an existing capability is 41 and 11 for the organizations that have developed a space system from a certain class for the first time. The median for the two groups are listed in Table 4-19. The difference between the values is rather small, which is in accordance with the graphical representation of the median in Fig. 4-4 as a red line. Looking at the extreme values, the space system with the highest specific development cost for an experienced organization is 1912 k$/kg which is the specific development cost of the GRAIL spacecraft. By contrast, the highest specific development cost for a space system developed for the first time by an organization is 6312 k$/kg, which corresponds to the Pioneer 11 spacecraft. The variance is also much larger for the space systems developed by the organizations for the first time. The box for the 25th to the 75th quartile for the notched box-whisker plot on the left is rather narrow compared to the plot on the right.

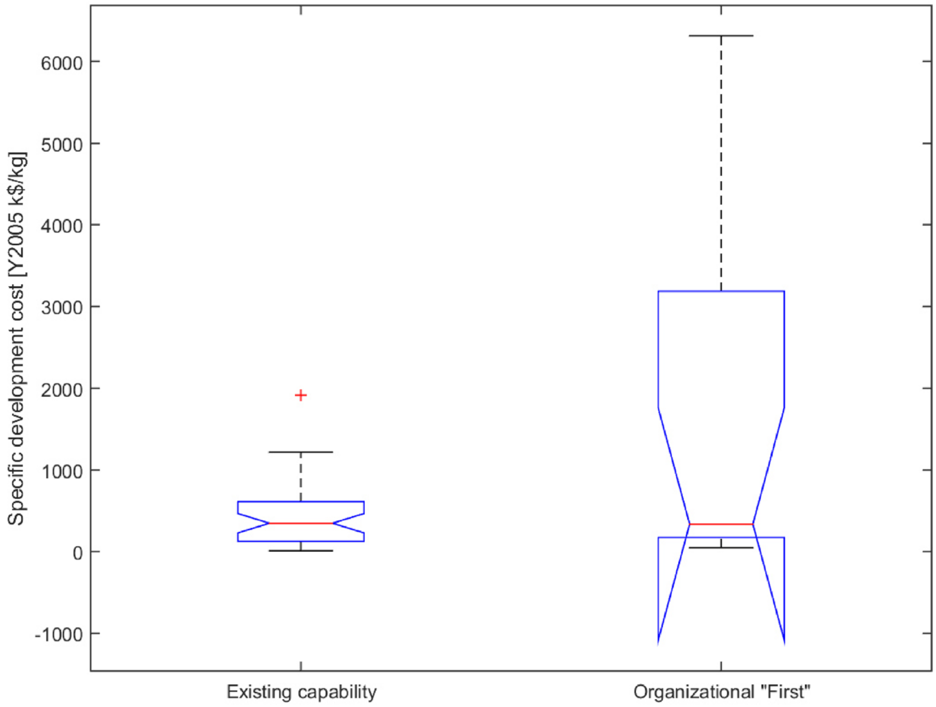


Fig. 4-4: Notched box-whisker plots for organizations with and without experience with a certain class of system, specific development cost, mixed sample

Table 4-19: Median specific development cost values for organizations with and without experience with a class of system, mixed sample

Median value "Existing capability" [Y2005 k$/kg]	349
Median value "Organizational Fist" [Y2005 k$/kg]	337

Up to this point, I have looked at the median of the groups and their variance. In the next step, I will look at the mean value in order to find out if the two groups are distinct in a statistically significant sense. I perform a 2-tailed t-test for the two groups. The results are listed in Table 4-20. The first observation is the drastically different mean value for the specific development cost for the two groups. The value for the space systems developed by their organizations for the first time is much higher than for the experienced organizations. The p-value confirms that the difference in the mean value is statistically significant and I can reject the 0-hypothesis that both samples are drawn from a population with identical mean values.

Table 4-20: Results for a 2-tailed t-test for organizations with and without experience with a class of system and specific development cost, mixed sample

Sample size "Existing capability"	41
Sample size "Organizational Fist"	11
Mean value "Existing capability" [Y2005 k$/kg]	433
Mean value "Organizational Fist" [Y2005 k$/kg]	1609
Standard deviation [Y2005 k$/kg]	247
Confidence interval distance between means [Y2005 k$/kg]	[330, 535]
p-value	$6*10^{-13}$
Degrees of freedom	91

The result from the two-tailed t-test shows that there is a statistically significant difference between the specific development cost of organizations that have developed a certain class of space system and those that have not. However, there could be other reasons than organizational capabilities that are responsible for this difference. For example, I can argue that the first interplanetary spacecraft and launchers were developed decades ago. As I have shown, the specific development cost decreases with time. Hence, it might be that the first space systems developed were more expensive, as they were just built earlier. I could also argue that different technologies than today were used. Therefore, I need to run multiple regressions to control for these potential alternative factors that could explain the difference.

Table 4-21 shows the results for the multiple regression analyses that were performed for the mixed space system sample. I successively introduce controls from (2) to (6). First, I introduce external factors that have reportedly lead to significant cost increases. The resulting regression model in (2) shows that the coefficient for external factors is not statistically significant and the coefficient for "organizational "First"" does not change considerably.

In (3), I introduce the number of spacecraft that were built for the mission and whether a launcher was produced in serial production. Looking at the results in (3), indeed a decrease in specific development cost for launchers can be observed. Controlling for the number of produced spacecraft / serial production of launchers leads to a decrease in the coefficient for organizational "First". This means that part of the effect of organizational "First" can be attributed to the mode of production of a space system.

In (4) I add controls for technologies. It can be seen that spacecraft that are spin-stabilized tend to have a much higher specific development cost than spacecraft with 3-axis control: 4262 k$/kg versus 1372 k$/kg. Another result is that spacecraft using RTGs tend to have a higher specific development cost than spacecraft using GaAs solar cells. Again, it is important to point out that it might not be the spin-stabilization and RTG themselves that cause the cost increase but potentially other underlying factors. For example, I can hypothesize that spacecraft using RTGs tend to be spacecraft flying to the outer Solar System and these spacecraft tend to be subject to much more demanding requirements than spacecraft developed for the inner Solar System. Note that the coefficient for the organizational "First" drastically decreased from 922 in (4) to 440 k$/kg in (5). This means that part of the effect of the organizational "First" in (3) was due to not controlling for the technologies used on the spacecraft.

Finally, in (6) I introduce additional controls such as the year of launch and size class of spacecraft. Interestingly, the negative coefficient for launch year indicates that the specific development cost decreases, the later a spacecraft has been developed. Another observation is that the size class of the spacecraft has a definitive effect on specific development cost with a slight decrease between medium and flagship class spacecraft. Note that between (5) and (6) the coefficient for organizational "First" slightly increases. The p-values of the multiple regression models shows that all models are statistically significant. The adjusted R^2 value for (5) and (6) are high, with values of 0.88 and 0.90. It means that the regression models (5) and (6) quite accurately fit the data.

Table 4-21: Multiple regression results for specific development cost in Y2005 k$/kg, organizational capability, and different controls, mixed sample. Table entries: correlation coefficient, [standard error], (p-value)

	(1)	(2)	(3)	(4)	(5)	(6)
Intercept	433 [160] (0.009)	230 [189] (0.2)	360 [151] (0.02)	255 [217] (0.2)	-1615 [623] (0.014)	-242 [715] (0.7)
Organisational „First"	1176 [347] (0.001)	1325 [347] (0.0004)	913 [256] (0.0009)	922 [258] (0.0009)	440 [164] (0.011)	526 [167] (0.003)
External		595 [313] (0.06)	57 [227] (0.8)	100 [238] (0.7)	189 [151] (0.2)	186 [147] (0.2)
Double spacecraft			2178 [321] ($2*10^{-8}$)	2087 [349] ($3*10^{-7}$)	1143 [250] ($5*10^{-5}$)	957 [257] (0.0007)
Launcher serial production			-483 [238] (0.049)	-	1681 [641] (0.013)	529 [691] (0.4)
Interplanetary spacecraft				170 [251] (0.5)	142 [191] (0.5)	171 [182] (0.4)

Launcher				-381 [283] (0.2)	-	-
Spin-stabilized					4262 [615] ($3*10^{-8}$)	3855 [721] ($7*10^{-6}$)
3-axis control					1372 [510] (0.011)	1111 [493] (0.03)
GaAs solar cells					219 [337] (0.5)	-542 [373] (0.2)
RTG					1595 [401] (0.0003)	1092 [425] (0.015)
Mono-propellant					345 [255] (0.2)	129 [304] (0.7)
Bi-propellant					163 [348] (0.9)	-36 [384] (0.9)
Mono & bi-propellant					0.1 [0.4] (0.6)	-218 [393] (0.6)
Year						-13 [5] (0.013)
Small class						-543 [485] (0.3)
Medium class						-3 [343] (0.99)
Flagship class						-
R^2	*0.19*	*0.24*	*0.67*	*0.68*	*0.91*	*0.93*
Adjusted R^2	*0.17*	*0.21*	*0.65*	*0.64*	*0.88*	*0.90*
p-value	*0.0014*	*0.0011*	*$6*10^{-11}$*	*$3*10^{-10}$*	*$1.01*10^{-16}$*	*$5*10^{-16}$*
N	*52*	*52*	*52*	*52*	*52*	*52*

To conclude, I was able to demonstrate that the specific development cost of a space system developed for the first time by an organization is significantly higher than one developed by an organization that has already developed a space system of the same class before. Although the effect is considerable, there are other factors such as technology choice that have an even larger impact on specific development cost.

At this point, I have represented organizational capability by whether or not an organization has already developed a system of a certain class before or not. However, I do not know what elements of organizational capability are responsible for this effect. In the next step, I will look at specific elements of organizational capability.

Team transfer

In this section, I want to illuminate whether there is a statistically significant relationship between the transfer of a team from one space program to another and specific development cost. I would expect that the team has accumulated experience in the previous space program and transfers this experience to the next. Furthermore, the team has already worked together. Hence, learning on the team level should have taken place, leading to a potentially less costly development.

Data for team transfer was only available for a few interplanetary spacecraft development programs. A sample of 11 programs with team transfer and 10 without team transfer were compared. The notched box-whisker plots for the two samples can be seen in Fig. 4-5. As can be seen from Table 4-22, the median for the sample with team transfer is slightly lower than for the sample with a new team. However, the 95% confidence intervals (notched part) in Fig. 4-5 overlap and I cannot expect that there is a statistically significant difference between the median of the two groups.

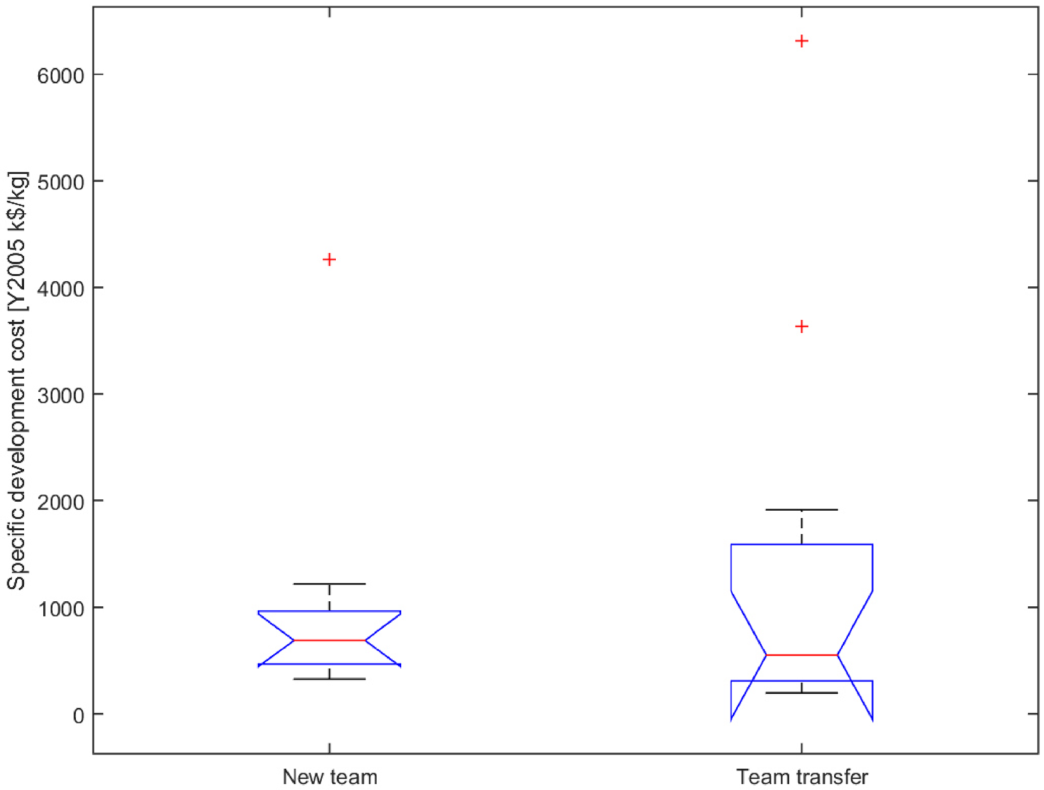


Fig. 4-5: Notched box-whisker plots for organizations with and without team transfer, specific development cost, interplanetary spacecraft sample

Table 4-22: Median values for specific development cost, interplanetary spacecraft sample with and without team transfer

Median with team transfer [Y2005 k$/kg]	550
Median for new team [Y2005 k$/kg]	688

This result is also confirmed for the mean values of the two samples in Table 4-22. The results of the 2-tailed t-test are shown in Table 4-23. The p-value of 0.6 indicates that the difference between the mean of the two samples is not statistically significant.

Table 4-23: Results for a 2-tailed t-test for the interplanetary spacecraft sample with and without team transfer

Sample size team transfer	11
Sample size new team	10
Mean with team transfer [Y2005 k$/kg]	1380
Mean for new team [Y2005 k$/kg]	1034
Standard deviation [Y2005 k$/kg]	1615
Confidence interval distance between means [Y2005 k$/kg]	[-1131, 1822]
p-value	0.6
Degrees of freedom	19

Program manager experience

As I was not able to find a statistically significant relationship between team transfer and specific development cost, I look at another independent variable that may capture organizational capability. I select "program manager experience" as the independent variable. If the program manager has previously participated in a space program in the same class, as a program manager, I categorize this program into the first group. If the program manager has no previous experience in that role for the same class of program, the program is categorized in the second group. The notched box-whisker plots for the two groups are shown in Fig. 4-6.

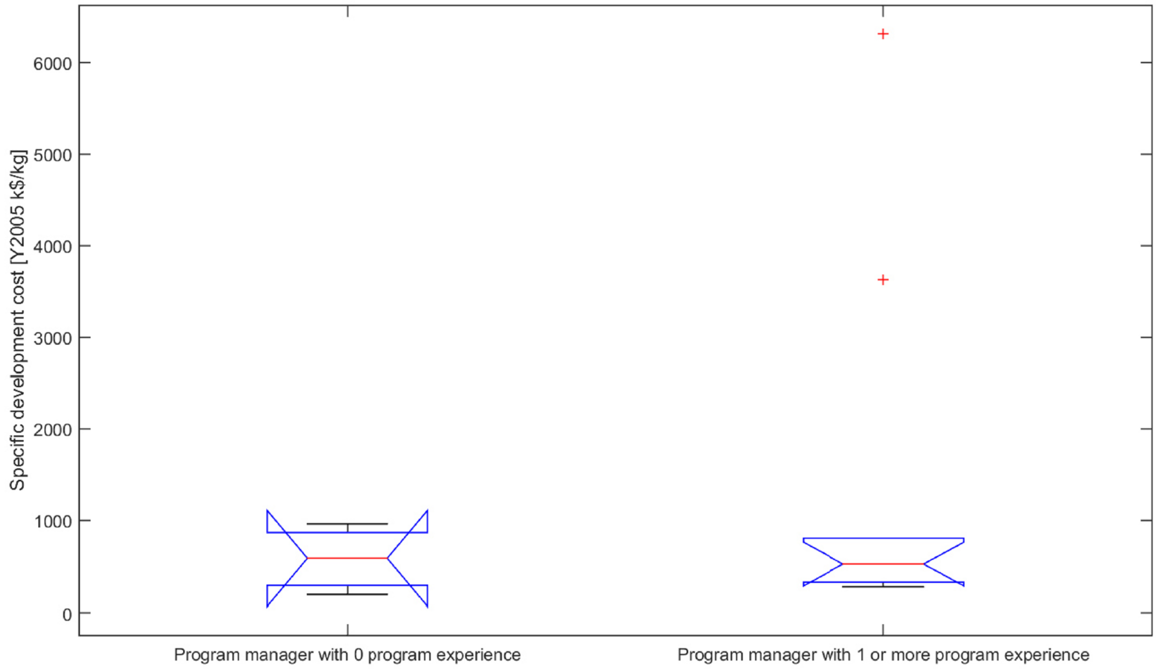


Fig. 4-6: Notched box-whisker plots for organizations with and without experienced program manager, specific development cost, interplanetary spacecraft sample

The median values in Table 4-24 do not show a considerable difference. The 95% confidence interval, represented as the notched part of the blue box plot in Fig. 4-6 also does not indicate that there is a statistically significant difference between the median values. The notched parts overlap. Can I also confirm this result for the mean values?

Table 4-24: Median values for the interplanetary spacecraft sample with and without experienced program manager

Median with program manager experience [Y2005 k$/kg]	474
Median without program manager experience [Y2005 k$/kg]	641

Table 4-25 shows the results of a 2-tailed t-test for the difference in the mean values of the two groups. The mean value for the group with program manager experience is drastically higher than for the group without. The reason for this large difference between the mean and median can be explained by the two outliers that are depicted as red crosses in Fig. 4-6. The large confidence interval for the distance between the means between -1119 and 3202 indicates that the difference between the two groups is not statistically significant. This result is confirmed by the p-value of 0.3.

Table 4-25: Results for a 2-tailed t-test for the interplanetary spacecraft sample with and without experienced program manager

Sample size of program manager with experience	7
Sample size without program manager experience	6
Mean with program manager experience [Y2005 k$/kg]	1683
Mean without program manager experience [Y2005 k$/kg]	641
Standard deviation [Y2005 k$/kg]	1764
Confidence interval distance between means [Y2005 k$/kg]	[-1119, 3202]
p-value	0.3
Degrees of freedom	11

To summarize, I was able to find statistically significant relationships between organizational capability and specific development cost but was unable to find statistically significant relationships for other indicators of technological capability. None of the differences between the group with and without team and program manager transfer yielded a statistically significant result. The reason for this result is likely the small sample size, combined with the large variation in the data. Future investigations should focus on collecting a larger sample for team and program manager transfer to yield a statistically significant difference between median and mean values of the groups.

To conclude, organizational capability is an excellent predictor for specific development cost. For other variables, such as team similarity and program manager experience, this result could not be confirmed.

4.3.5 Technological Capability: Development Duration

Analogously to section 4.3.4, in this section I analyze whether the capability of an organization to develop a certain class of system has an influence on the system's development duration. First, I start with organizational capability in terms of organizational "Firsts", i.e. classes of systems that were developed by an organization for the first time and compare the development duration with systems developed by experienced organizations. I continue with systems developed by teams that have already worked together, and finish with systems developed by experienced program managers.

Looking at the notched box-whisker plots for the mixed space systems sample in Fig. 4-7, it can be seen that there is a clear difference between the median of the two groups. Table 4-26 shows the numerical values for the median. However, the 95% confidence interval for the organizational "Firsts" is quite large and overlaps with the 95% confidence interval of the group of space systems that were developed by experienced organizations, indicating that the difference is not statistically significant.

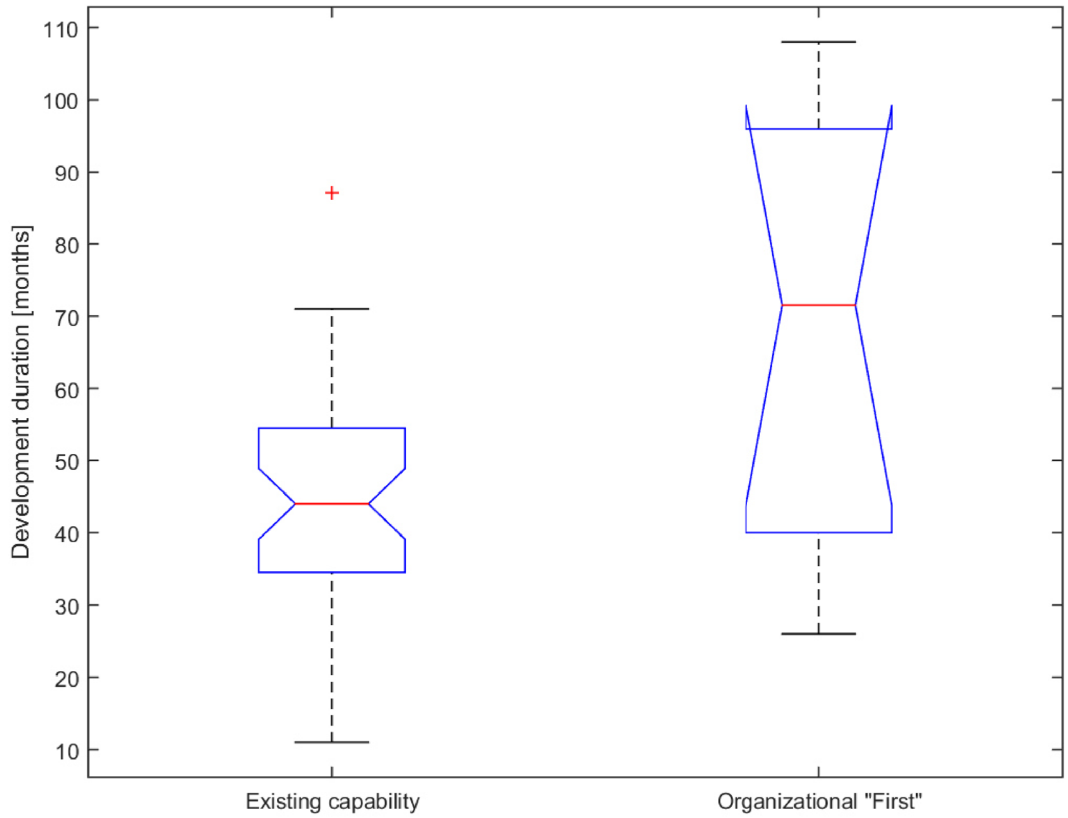


Fig. 4-7: Notched box-whisker plots for organizations with and without experience with a certain class of system, development duration, mixed sample

Table 4-26: Median values for organizations with and without experience with a certain class of system, development duration, mixed sample

Median value for existing capability [months]	44
Median value for organizational First [months]	72

A 2-tailed t-test is conducted in order to confirm this result for the mean. Table 4-27 shows the results. Contrary to the results for the median, the confidence interval for the distance between the means is statistically significant, with an extremely low p-value. Note that the difference between the values for the median and mean are small. This is a sign that the two groups do only contain few outliers.

Table 4-27: Results for a 2-tailed t-test for the mixed sample for organizations with and without experience with a class of system

Sample size existing capability	41
Sample size organizational First	10
Mean value for existing capability [months]	45
Mean value for organizational First [months]	69
Standard deviation [months]	10
Confidence interval distance between means [months]	[40, 49]
p-value	$1*10^{-35}$
Degrees of freedom	90

In order to control for other variables that may have an influence on development duration, I conduct several multiple regression runs. The results are shown in Table 4-28. Note that the "organizational "First"" variable is one of the few variables that are consistently statistically significant in all regression models (1) to (6). Looking at the effect of the variable on development duration, the coefficient value fluctuates between 24 months for (1) to 36 months for (6). Adding control variables changes the coefficient by about 50% compared to no controls. However, the tendency is clearly an increase in development duration. Note that the adjusted R^2 values for the regression models is in general poor. All regression models are statistically significant.

Table 4-28: Multiple regression results for development duration, organizational capability, and different controls, mixed sample. Table entries: correlation coefficient, [standard error], (p-value)

	(1)	(2)	(3)	(4)	(5)	(6)
Intercept	45 [3] ($1*10^{-19}$)	42 [4] ($3*10^{-15}$)	37 [4] ($2*10^{-12}$)	42 [5] ($1*10^{-9}$)	50 [5] ($2*10^{-11}$)	-
Organisational „First"	24 [7] (0.001)	26 [7] (0.0005)	27 [7] (0.0002)	27 [7] (0.0002)	31 [7] (0.0002)	36 [8] ($5*10^{-5}$)
External		9 [6] (0.2)	19 [6] (0.003)	17 [6] (0.008)	15 [7] (0.04)	11 [7] (0.14)
Double spacecraft			-26 [9] (0.004)	-22 [9] (0.02)	-16 [11] (0.18)	-15 [12] (0.2)
Launcher serial production			14 [6] (0.02)	-	-	40 [7] ($1*10^{-6}$)
Interplanetary spacecraft				-7 [6] (0.3)	-12 [9] (0.2)	-10 [9] (0.3)
Launcher				10 [7.0] (0.2)	-	-
Spin-stabilized					-39 [28] (0.2)	-31 [34] (0.4)
3-axis control					-27 [25] (0.3)	-17 [24] (0.5)
Si solar cells					26 [30] (0.4)	77 [32] (0.02)
GaAs solar cells					13 [26] (0.6)	54 [34] (0.12)
RTG					4 [22] (0.9)	51 [25] (0.05)
Mono-propellant					8 [12] (0.5)	-10 [14] (0.5)
Bi-propellant					3 [16] (0.9)	-16 [18] (0.4)
Mono & bi-propellant					10 [16] (0.5)	-7 [19] (0.7)
Year						0.4 [0.24]

						(0.13)
Small class						-26 [23] (0.3)
Medium class						0.01 [16] (0.999)
Flagship class						-
R^2	*0.20*	*0.23*	*0.45*	*0.46*	*0.51*	*0.58*
Adjusted R^2	*0.18*	*0.20*	*0.40*	*0.40*	*0.35*	*0.40*
p-value	*0.001*	*0.002*	*$1*10^{-5}$*	*$3*10^{-5}$*	*0.003*	*0.002*
N	*51*	*51*	*51*	*51*	*51*	*51*

To summarize, the results from the statistical analysis show that, in general, space systems that were developed by experienced organizations have a shorter development duration than space systems developed by organizations that do not have prior experience with the same class of space system. The effect of this variable on development duration is a more than 50% increase, compared to the experienced organization.

Team transfer

I want to know if team transfer has an effect on development duration. First, I analyze if there is a statistically significant difference between the median / mean values of space programs with development teams that have already worked on a similar programs before and space programs developed by new teams. Fig. 4-8 shows the notched box-whisker plots for the median values for the two groups. The median value for the group based on a new team is higher than for the group based on an existing team, as the values in Table 4-29 show. However, in Fig. 4-8 the 95% confidence interval overlaps, which indicates that the difference between the groups is not statistically significant.

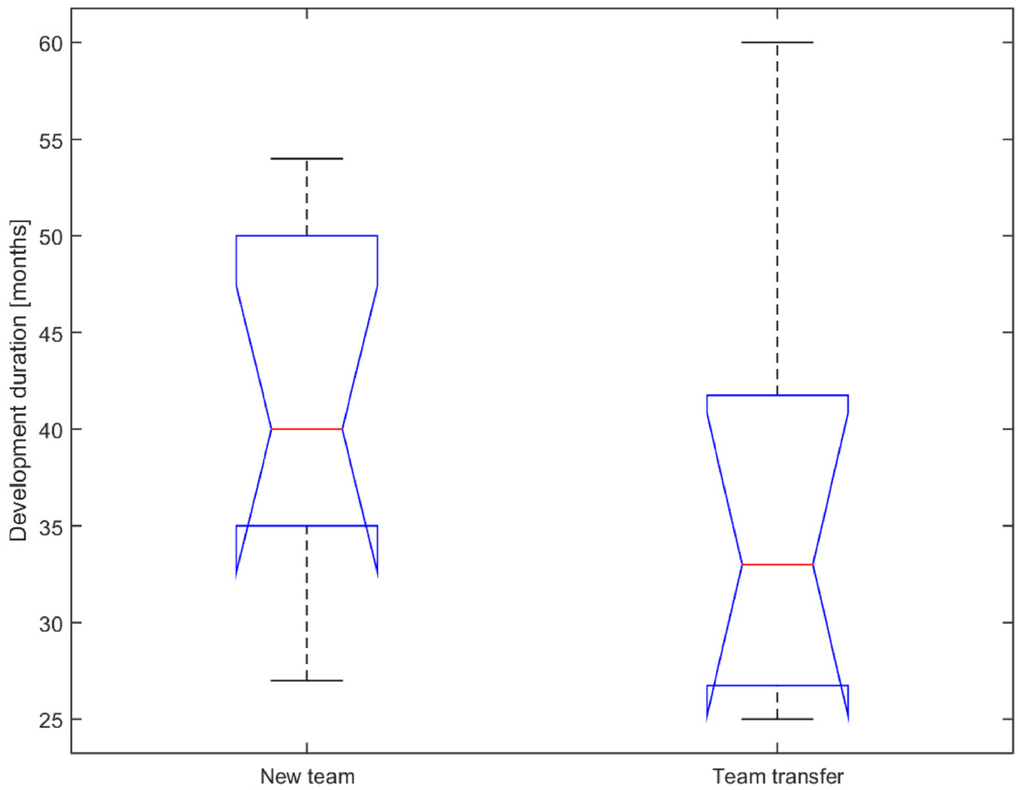


Fig. 4-8: Notched box-whisker plots for organizations with and without team transfer, development duration, interplanetary spacecraft sample

Table 4-29: Median values for organizations with and without team transfer, development duration, interplanetary spacecraft sample

Median value with team transfer [months]	33
Median value with new team [months]	40

The results for the 2-tailed t-test for the difference in mean values of the two groups confirm this result. The difference between the mean values is roughly similar to the median value, which indicates that there are few data points with extreme values in the groups. The difference in the 95% confidence intervals of the two groups shows a negative result, which means that they overlap. The p-value is consequently above the 5% threshold value.

Table 4-30: Results for a 2-tailed t-test for the interplanetary spacecraft sample with and without team transfer

Sample size team transfer	9
Sample size new team	10
Mean value with team transfer [months]	36
Mean value with new team [months]	41
Standard deviation [months]	11
Confidence interval distance between means [months]	[-15, 5]
p-value	0.3
Degrees of freedom	17

To summarize, interplanetary spacecraft that are developed by a team that has already worked together seems to decrease development duration. However, the difference between the group with an existing team and a new team is not statistically significant.

Program manager experience

I analyze if there is a statistically significant difference in development duration between interplanetary spacecraft development programs with and without an experienced program manager. The notched box-whisker plots for the two groups are shown in Fig. 4-9. The median value for the group on the left is higher than for the group on the right, which is confirmed by the values in Table 4-31. However, looking at the 95% confidence interval shows that the difference between the mean values is not statistically significant at the 5% level.

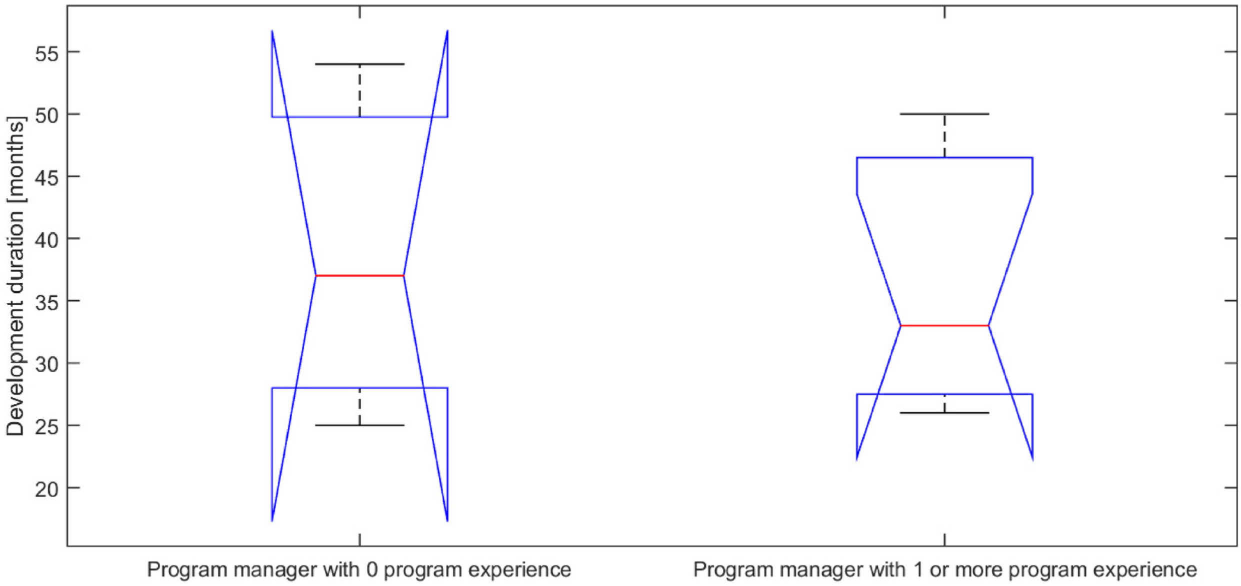


Fig. 4-9: Notched box-whisker plots for organizations with and without experienced program manager, development duration, interplanetary spacecraft sample

Table 4-31: Median values for organizations with and without experienced program manager, development duration, interplanetary spacecraft sample

Median with program manager experience	30
Median without program manager experience	41

The results for the difference in the mean value is also not statistically significant, as shown in Table 4-32. The negative distance between the means indicates that there is an overlap of the 95% confidence intervals. Hence, the difference in means is not statistically significant. This is confirmed by the p-value of 0.289 which is above the threshold value of 0.05.

Table 4-32: Results for a 2-tailed t-test for the interplanetary spacecraft sample with and without experienced program manager

Sample size program manager experience	5
Sample size without program manager experience	6
Mean with program manager experience [months]	33
Mean without program manager experience [months]	40
Standard deviation [months]	11
Confidence interval distance between means [months]	[-22, 7]
p-value	0.3
Degrees of freedom	9

To summarize, program manager experience is not statistically significant for the interplanetary spacecraft sample. For launchers and LEO / MEO spacecraft no data about program manager experience was available.

4.3.6 Technological Capability: Development Cost and Schedule Overrun

The last two hypotheses are that using heritage technologies leads to a reduction in cost and schedule overruns. In this section, I will analyze if technological capabilities, represented by organizational "First", team similarity, and program manager experience, have an effect on cost and schedule overruns. I start with organizational "Firsts", i.e. classes of systems that were developed by an organization for the first time and compare the cost and schedule overrun with systems developed by experienced organizations. I continue with systems developed by teams that have already worked together, and finish with systems developed by experienced program managers.

The results for organizational capabilities and cost overrun are presented in the following. The notched box-whisker plot for the cost overrun of organizations with experience in developing a system of a certain class and without is shown in Fig. 4-10. There is a visible difference between the median values of the two groups. The numerical median values are listed in Table 4-33. The 95% confidence interval for the median value of the organizational "Firsts" is large and indicates that the difference of the median values is not statistically significant. The large confidence interval is explained by the small sample size of the organizational "Firsts" comprising three data points.

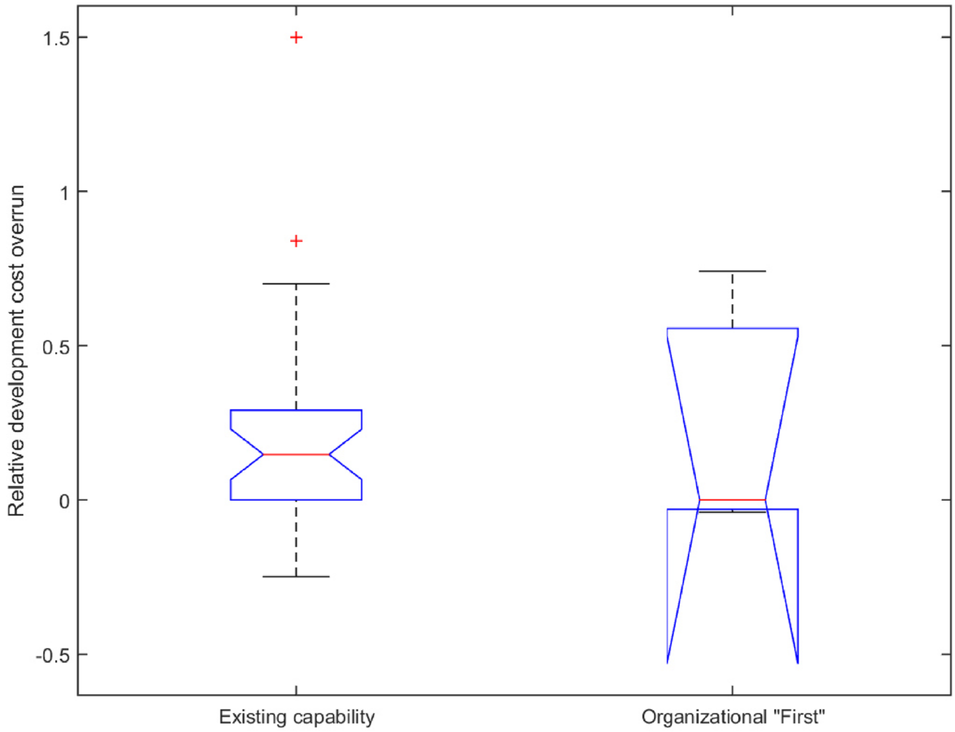


Fig. 4-10: Notched box-whisker plots for organizations with and without experience with a certain class of system, relative development cost overrun, interplanetary and LEO/GEO spacecraft sample

Table 4-33: Median values for relative development cost overrun for the mixed sample for organizations with and without experience with a class of system.

Median value for existing capability	0.15
Median value for organizational First	0

The result for the mean values of the two groups is shown in Table 4-34. The mean value of the organizational "Firsts" is higher than for the group of systems developed by experienced organizations. The p-value indicates that the difference between the means is not statistically significant at the 5% level.

Table 4-34: Results of a 2-tailed t-test for relative development cost overrun, mixed sample, organizations with and without experience with a class of system

Sample size existing capabilitye	31
Sample size "Organizational First"	3
Mean value for existing capability	0.20
Mean value for organizational First	0.23
Standard deviation	0.32
Confidence interval distance between means	[-0.05, 0.26]
p-value	0.2
Degrees of freedom	63

I perform an additional multiple regression analysis in order to confirm the result. The results in Table 4-35 show that none of the regression models from (1) to (6) returns a statistically significant coefficient for organizational "Firsts". Note that except for the year of launch, there are no other statistically significant coefficients present in all regression models. Consequently, all regression models are not statistically significant with p-values larger than 0.05.

Table 4-35: Multiple regression results for relative development cost overrun, organizational capability, and different controls, interplanetary and LEO/GEO spacecraft sample. Table entries: correlation coefficient, [standard error], (p-value)

	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Intercept	0.20 [0.06] (0.004)	0.18 [0.08] (0.04)	0.18 [0.09] (0.049)	0.11 [0.14] (0.5)	0.67 [0.54] (0.2)	1.90 [0.67] (0.01)
Organisational „First"	0.04 [0.21] (0.9)	0.04 [0.22] (0.8)	0.03 [0.24] (0.9)	0.01 [0.24] (0.96)	0.07 [0.34] (0.8)	-0.90 [0.48] (0.07)
External		0.03 [0.12] (0.8)	0.02 [0.13] (0.8)	0.06 [0.14] (0.7)	0.10 [0.17] (0.6)	0.13 [0.15] (0.4)
Double spacecraft			0.18 [0.09] (0.049)	-0.02 [0.19] (0.9)	-0.07 [0.23] (0.8)	-0.36 [0.28] (0.2)
Interplanetary spacecraft				0.11 [0.15] (0.5)	0.06 [0.21] (0.8)	0.01 [0.20] (0.96)
3-axis control					-0.37 [0.38] (0.4)	-0.70 [0.37] (0.07)
GaAs solar cells					-0.07 [0.43] (0.9)	1.07 [0.58] (0.08)
RTG					-0.07 [0.43] (0.9)	0.72 [0.50] (0.2)
Mono-propellant					-0.09 [0.28] (0.7)	0.34 [0.32] (0.3)
Bi-propellant					-0.27 [0.36] (0.5)	0.12 [0.38] (0.8)

Mono & bi-propellant					-0.03 [0.37] (0.9)	-0.10 [0.39] (0.8)
Year						-0.04 [0.02] (0.016)
Medium class						-0.255 [0.371] (0.5)
Flagship class						-0.0926 [0.528] (0.9)
R^2	*0.0010*	*0.0025*	*0.0033*	*0.020*	*0.13*	*0.37*
Adjusted R^2	*-0.030*	*-0.062*	*-0.096*	*-0.12*	*-0.25*	*-0.034*
p-value	*0.9*	*0.96*	*0.99*	*0.96*	*0.96*	*0.6*
N	*34*	*34*	*34*	*34*	*34*	*34*

To conclude, no statistically significant relationship between organizational capability and cost overrun could be identified. The main reason for this result is the small sample size for organizations that developed a certain class of space system for the first time. A larger sample size may lead to a different result.

How do specific elements that constitute organizational capability impact development cost overruns? I first look at the difference in development cost overruns between space systems that were developed by teams that have been transferred from one program to another and those developed by new teams. The notched box-whisker plot for the two groups of space systems is shown in Fig. 4-11. There is a visible difference in the median of the two groups, indicated by the horizontal line in the notched part. The numerical median values in Table 4-39 confirm this observation. The relative development cost overrun for the systems developed by a new team is considerably higher than for the systems developed by a transferred team. The 95% confidence interval for the new team group is rather large and clearly overlaps with the 95% confidence interval of the team transfer group. The difference between the median is therefore not statistically significant.

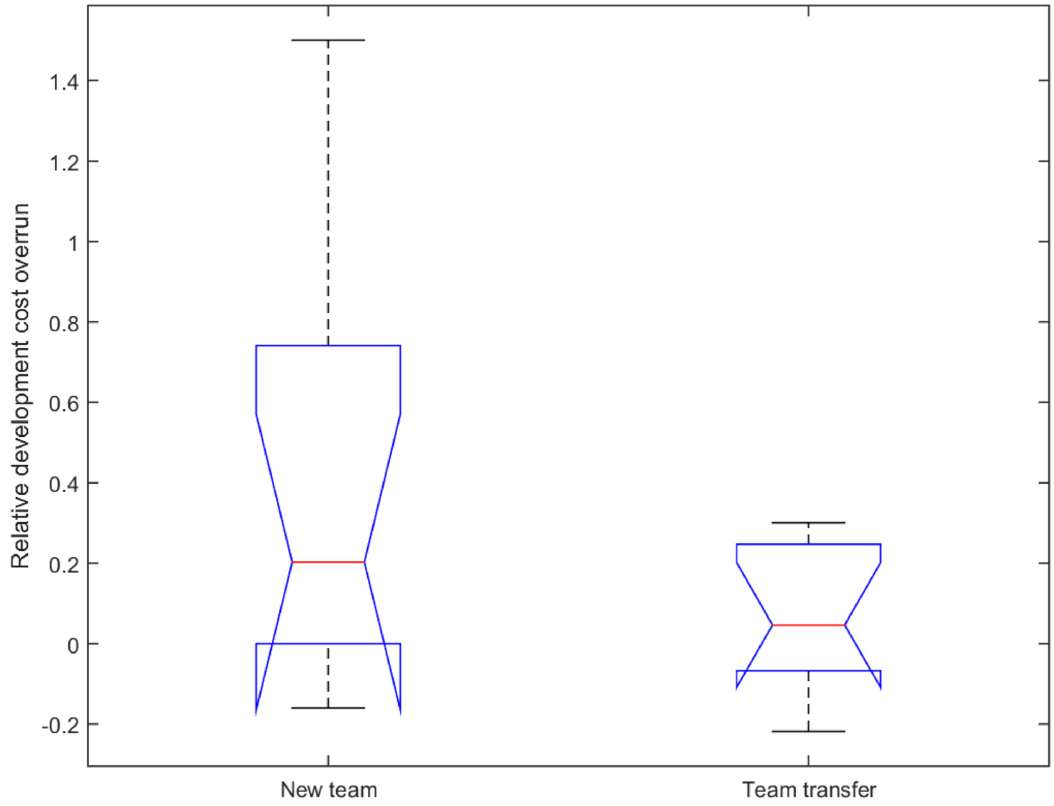


Fig. 4-11: Notched box-whisker plots for programs with a new team or transferred team, relative development cost overrun, interplanetary spacecraft sample

Table 4-36: Median values for programs with a new team or transferred team, relative development cost overrun, interplanetary spacecraft sample

Median team transfer	0.05
Median new team	0.20

Table 4-37 shows the results for the 2-tailed t-test for the difference in means. The mean for the team transfer group is close to the median. Hence, extreme values are not present, as is confirmed by Fig. 4-11. For the new team group, the difference between mean and median is larger, which can be explained by the skewed distribution of the data. Looking at the results of the 2-teailed t-test shows that the difference in means is not statistically significant, with a p-value of 0.097 which is above the 0.05 level.

Table 4-37: Results for a 2-tailed t-test for the interplanetary spacecraft sample for transferred teams and new teams

Sample size team transfer	10
Sample size new team	10
Mean team transfer	0.07
Mean new team	0.37
Standard deviation	0.38
Confidence interval distance between means	[-0.66, -0.06]
p-value	0.097
Degrees of freedom	18

Another element of organizational capability is the program manager. In the following, I analyze, if there is a statistically significant difference between the development cost overrun of systems that were developed by experienced program managers and those that were developed by one without prior experience. As previously defined, a program manager is considered "experienced", if she has acted as a program manager in a development program of the same class (here: an interplanetary space program) before. The notched box-whisker plots are shown in Fig. 4-12. The median for the experienced program manager group is considerably higher than for the program mangers without experience. Fig. 4-12 shows that the experienced program manager group suffers from a development cost overrun of roughly 20%, which is confirmed by the numerical values in Table 4-38. However, as the 95% confidence intervals for the median overlap, this difference is considered not statistically significant. Note that there are two extreme values in the experienced program manager group, indicated as crosses.

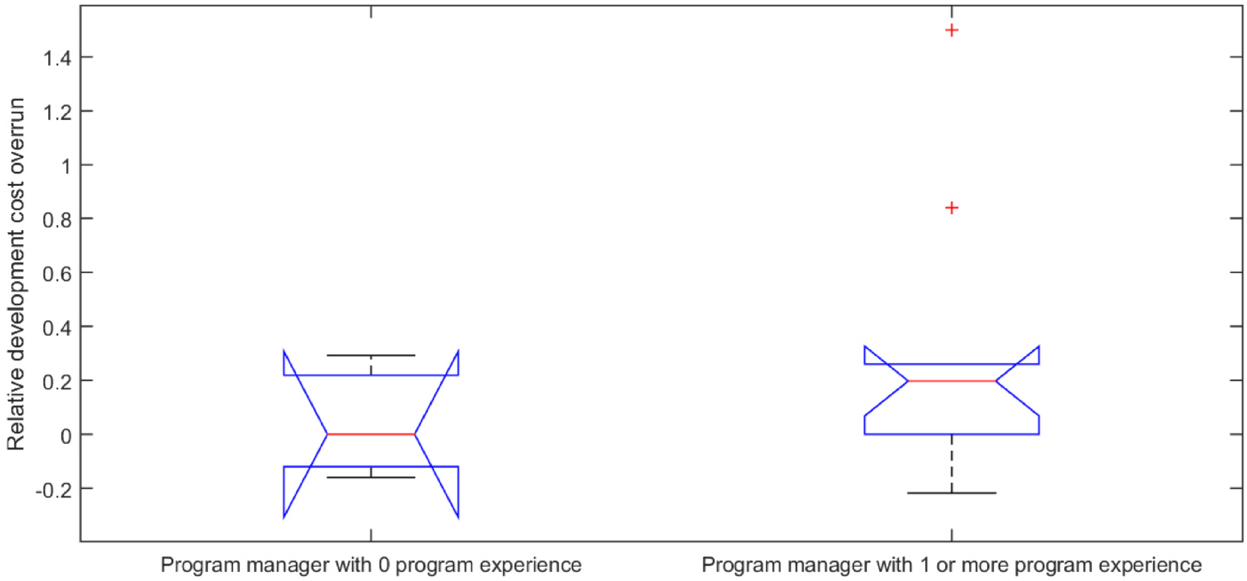


Fig. 4-12: Notched box-whisker plots for program managers with and without experience, specific development cost overrun, interplanetary spacecraft sample

Table 4-38: Median values for program managers with and without experience, specific development cost overrun, interplanetary spacecraft sample

Median with program manager experience	0
Median no program manager experience	0.2

The result for the median is confirmed by the 2-tailed t-test for the difference in mean values. Table 4-39 shows that there is no statistically significant difference between the means.

Table 4-39: Results for a 2-tailed t-test for the mixed sample for organizations with and without experience with a class of system

Program manager experience	10
No program manager experience	3
Mean with program manager experience	0.30
Mean no program manager experience	0.04
Standard deviation	0.47
Confidence interval distance between means	[-0.43, 0.94]
p-value	0.4
Degrees of freedom	11

To summarize, I was not able to show that there is a statistically significant difference between space systems developed by neither experienced teams nor experienced program managers. The reason for this result is probably the small sample size for the space programs with inexperienced program managers. For the difference between transferred and new teams, the sample size is probably too small for both groups.

Development Schedule overrun

A statistical analysis for the relationship between organizational capability and schedule overrun is performed in this section. Fig. 4-13 shows the notched box-whisker plot for organizations with the experience of developing a certain class of system and without. There is no visible difference in the median of the two groups. Both median values are close to 0. This observation is confirmed by the numerical values for the median in Table 4-40. Due to the relatively large sample size of 30 for the organizations with an existing capability, the 95% confidence interval (notched part of the box) is rather narrow. By contrast, the 95% confidence interval for the organizational "First" group is large and overlaps completely with the confidence interval of the other group. Hence, the difference in median is very likely not statistically significant.

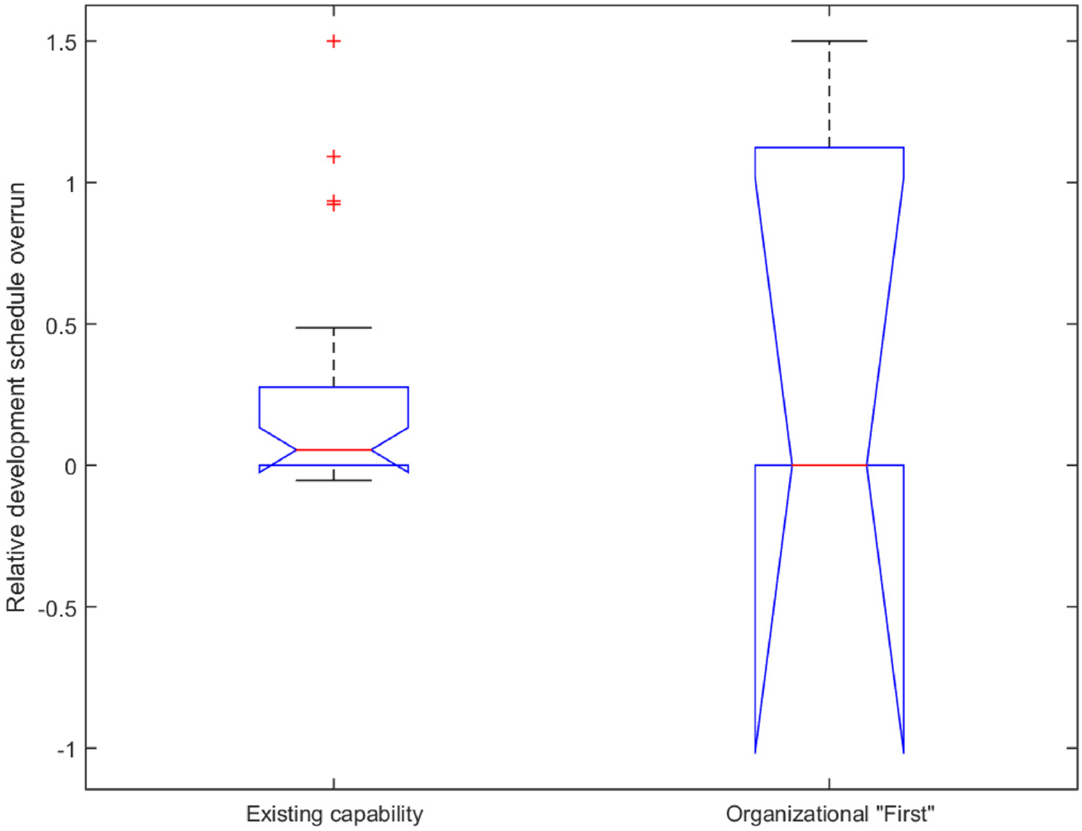


Fig. 4-13: Notched box-whisker plots for organizations with and without experience with a certain class of system, relative development schedule overrun, mixed sample without launchers

Table 4-40: Median values for organizations with and without experience with a certain class of system, relative development schedule overrun, mixed sample without launchers

Median existing capability	0.05
Median organizational First	0

A 2-tailed t-test is performed for the difference in mean values between the two groups. The results are listed in Table 4-41. First, I observe that the mean values are quite different from the median values, which indicates that there are several extreme values in the samples. Looking at Fig. 4-13 I can see four outliers indicated by crosses above the whisker of the left plot. Regarding the mean values, the organizations with experience have a lower schedule overrun than organizations without. The difference of 0.27 is relatively large. However, the 95% confidence intervals of the two groups overlap and hence, the difference between the means is not statistically significant, as is confirmed by the p-value of 0.1 which is above the threshold of 0.05.

Table 4-41: Results for a 2-tailed t-test for the mixed sample for organizations with and without experience with a class of system

Sample size existing capability	30
Sample size organizational First	3
Mean existing capability	0.23
Mean organizational First	0.50
Standard deviation	0.34
Confidence interval distance between means	[-0.03, 0.31]
p-value	0.1
Degrees of freedom	61

At this point, I may conclude that there is no statistically significant relationship between organizational capability and schedule overrun. However, the multiple regression models in Table 4-42 yield an unexpected result. The regression models (1) to (5) confirm the previous result that there is no statistically significant relationship between organizational "First" and schedule overrun. However, the situation changes when the launch year is introduced in the regression model (6). It results in a drastic reduction for schedule overrun for organizational "First". There are two other variables that have a statistically significant relationship with schedule overrun: external factors for schedule overrun and the launch year. External factors increase the schedule overrun and the launch year decreases the schedule overrun. In other words, schedule overrun is decreasing over time.

How can I explain the drastic decrease in schedule overrun for organizational "First"? It is likely that the sample size of 33 is too small for the number of independent variables in the multiple regression. Hence, effects such as overfitting might be the cause of the unexpected result. Another explanation for this effect is that the sample for organizational "First" only consists of three individuals. Two of the individuals have 0 development schedule overrun (Voyager and Mars Pathfinder) and one has a significant overrun (Viking Lander). With this small sample size for "Firsts", any additional individual may have the potential to change this result. In the following, I decide to discard this result until a larger sample size is available.

Table 4-42: Multiple regression results for relative development schedule overrun, organizational capability, and different controls, interplanetary and LEO to GEO sample. Table entries: correlation coefficient, [standard error], (p-value)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Intercept	0.23 [0.08] (0.006)	0.08 [0.10] (0.4)	0.06 [0.10] (0.6)	-0.09 [0.15] (0.6)	0.54 [0.55] (0.3)	1.63 [0.68] (0.03)	1.77 [0.63] (0.011)
Organisational „First“	0.27 [0.26] (0.3)	0.30 [0.24] (0.2)	0.19 [0.27] (0.5)	0.16 [0.26] (0.6)	-0.10 [0.37] (0.8)	-0.73 [0.43] (0.1)	-1.12 [0.45] (0.02)
External		0.35 [0.14] (0.02)	0.34 [0.14] (0.03)	0.42 [0.16] (0.01)	0.34 [0.17] (0.05)	0.32 [0.15] (0.048)	0.39 [0.14] (0.01)
Double spacecraft			0.22 [0.20] (0.3)	0.12 [0.21] (0.9)	0.007 [0.23] (0.98)	-0.26 [0.24] (0.3)	-0.35 [0.26] (0.2)
Interplanetary spacecraft				0.22 [0.17] (0.2)	0.05 [0.21] (0.8)	-0.02 [0.20] (0.9)	0.02 [0.18] (0.9)
3-axis control					-0.09 [0.41] (0.8)	-0.45 [0.40] (0.3)	-0.52 [0.37] (0.2)
GaAs solar cells					-0.49 [0.34] (0.2)	0.47 [0.51] (0.4)	1.03 [0.54] (0.07)
RTG					0.24 [0.50] (0.6)	0.78 [0.51] (0.4)	0.73 [0.51] (0.2)
Mono-propellant					-0.005 [0.29] (0.99)	0.33 [0.30] (0.3)	0.52 [0.29] (0.09)
Bi-propellant					0.11 [0.36] (0.8)	0.44 [0.36] (0.2)	0.48 [0.35] (0.2)
Mono & bi-propellant					0.14 [0.37] (0.7)	0.04 [0.34] (0.9)	-0.01 [0.36] (0.97)
Year						-0.04 [0.02] (0.03)	-0.05 [0.02] (0.008)
Medium class							-0.37 [0.36] (0.3)
Flagship class							0.30 [0.52] (0.6)
R²	*0.032*	*0.20*	*0.23*	*0.27*	*0.46*	*0.58*	*0.68*
Adjusted R²	*0.001*	*0.14*	*0.15*	*0.16*	*0.22*	*0.35*	*0.46*
p-value	*0.3*	*0.04*	*0.05*	*0.06*	*0.1*	*0.03*	*0.01*
N	*33*	*33*	*33*	*33*	*33*	*33*	*33*

Team similarity

I perform a statistical analysis for the difference in schedule overrun for space systems developed by teams that have worked together before on a similar system and a new team. Fig. 4-14 shows the notched box-whisker plots for the two groups. There is a visible difference in the median value of the two groups, represented by a horizontal line in the notched part. The group with a new team has a higher median value than the group with team transfer. Furthermore, the 25 and 75 percentile of the groups is very different, although the sample size is similar, with 9 data points in the new team group and 10 data points in the team transfer group. The 95% confidence interval, represented by the notched part of the blue box, is considerably larger for the new team group than for the team transfer group. As the confidence intervals of both groups overlap, the difference between the median of the two groups is not statistically significant.

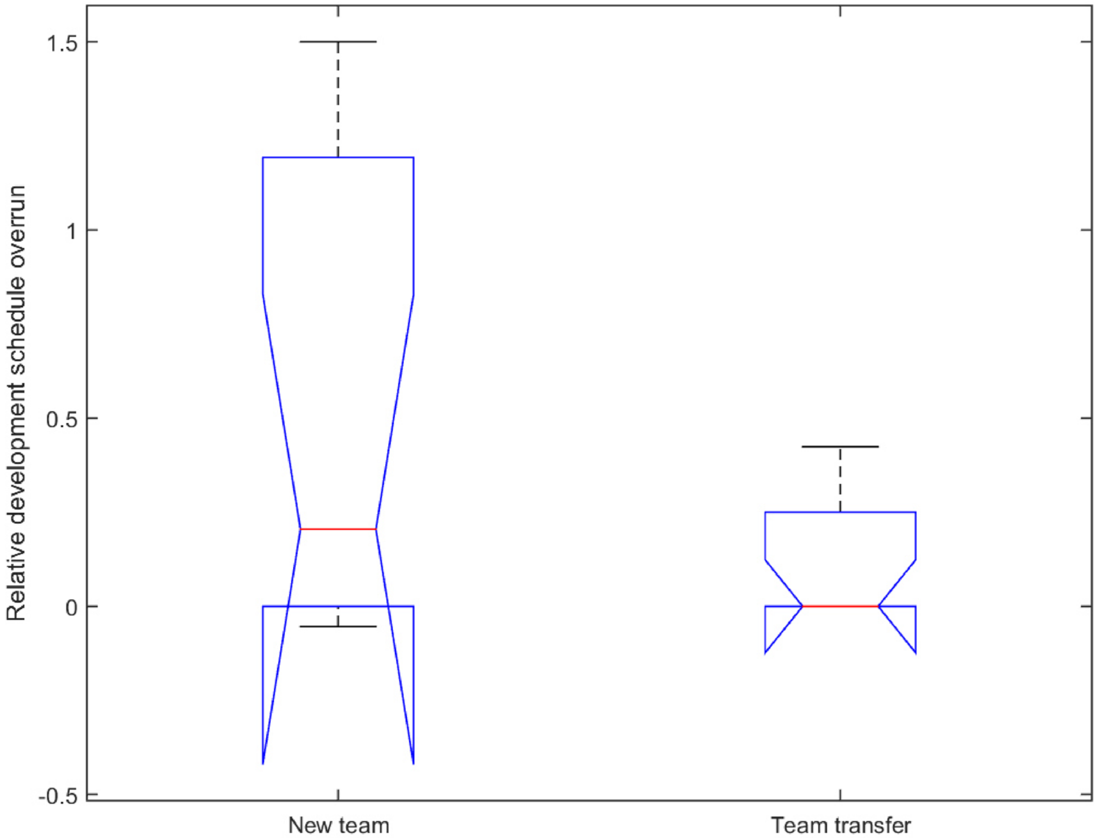


Fig. 4-14: Notched box-whisker plots for relative development schedule overrun, a new team or transferred team, interplanetary spacecraft sample

Table 4-43: Median values for organizations with and without team transfer, relative development schedule overrun, interplanetary spacecraft sample

Median team transfer	0
Median new team	0.2

A 2-tailed t-test is conducted for the difference in the mean value in order to confirm this result. The mean value for the new team group is more than twice as large as the median, which indicates that there are extreme data points in the group. The p-value yields 0.04 which indicates that the difference is statistically significant, contrary to the result for the median.

Table 4-44: Results for a 2-tailed t-test for relative development schedule overrun, transferred teams and new teams, interplanetary spacecraft sample

Sample size team transfer	10
Sample size new team	9
Mean team transfer	0.1
Mean new team	0.6
Standard deviation	0.5
Confidence interval distance between means	[-0.9, -0.02]
p-value	0.04
Degrees of freedom	17

To summarize, there is a statistically significant difference between the mean of the new team group and the team transfer group. The schedule overrun for the new team group is significantly larger than for the team transfer group.

Program manager experience

In the following, a statistical analysis for the relationship between program manager experience and schedule overrun is performed. Fig. 4-15 shows the notched box-whisker plots for the group with program managers without experience in leading the development of a space system and the group with program managers with experience in leading the development of a space system. The plot for the group with inexperienced program managers is a straight line. The group consists of two data points that have both a schedule overrun of 0. Hence, the variance and the median are 0. For the second group the median is close to the 0 line, which is confirmed by the numerical median value in Table 4-45. The 95% confidence interval of this group clearly overlaps with the median of the inexperienced group. Hence, the difference between the groups is not statistically significant.

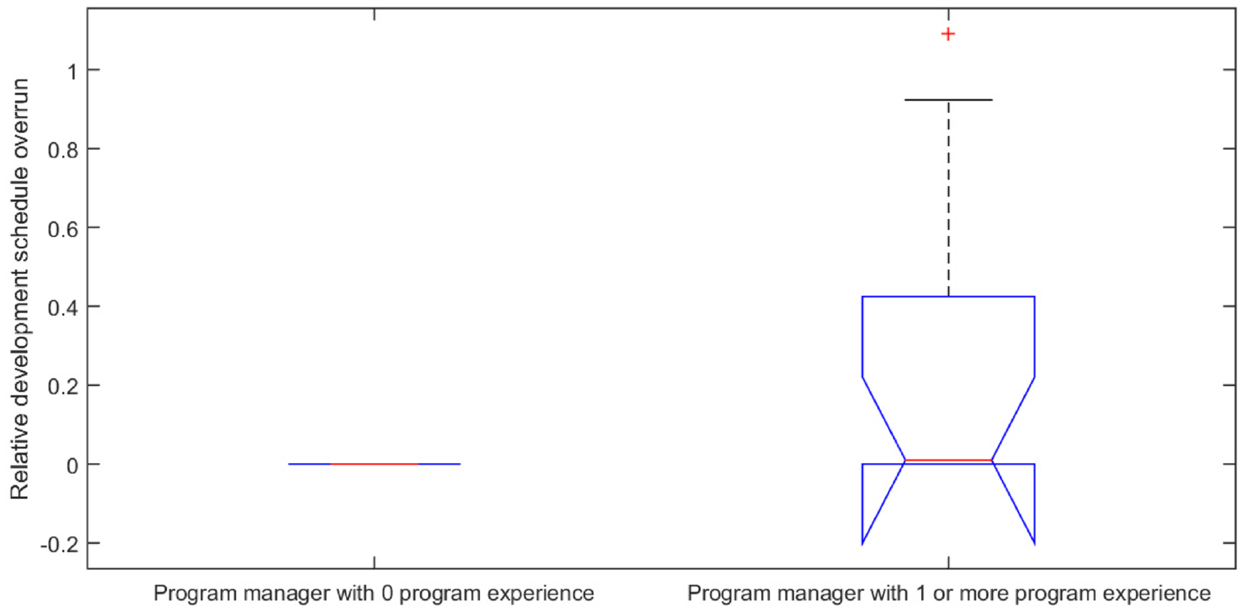


Fig. 4-15: Notched box-whisker plots for a program manager with and without program management experience, relative development schedule overrun, interplanetary spacecraft sample

Table 4-45: Median values for program managers with and without experience, development schedule overrun, interplanetary spacecraft sample

Median with program manager experience	0
Median no program manager experience	0.010

For confirming this result for the means of the two groups, a 2-tailed t-test is performed. The result is shown in Table 4-46. As expected, the p-value of 0.4 is clearly above the 0.05 threshold.

Table 4-46: Results for a 2-tailed t-test for relative development schedule overrun, mixed sample, organizations with and without experience with a class of system

Program manager experience	10
No program manager experience	2
Mean with program manager experience	0.25
Mean no program manager experience	0
Standard deviation	0.40
Confidence interval distance between means	[-0.45, 0.94]
p-value	0.4
Degrees of freedom	10

To summarize, there is no statistically significant difference between the group with inexperienced and experienced program managers. The reason for this result is the small number of data points for the inexperienced group of 2.

4.3.7 Combining Design Heritage and Technological Capability

After having assessed design heritage and technological capability separately, both variables are now combined and a single heritage variable is created. The results for this combined heritage variable are shown in Table 4-47 and Table 4-48. A weighting of 0.5 is used for the design heritage variable and for technological capability in the form of organizational capability, as it resulted in the best fit for specific development cost and development duration. This time only additional control variables that I have shown to be statistically significant are included. Table 4-47 shows the results for specific development cost and the heritage metric. Adding the variable “year” does not significantly change the effect of the heritage metric. The results show that large savings (87%) are possible if full heritage is present in the form of design heritage and technological capability.

Table 4-47 Multiple regression results for specific development cost (Y2005 k$/kg), combined heritage metric, mixed sample. Table entries: correlation coefficient, [standard error], (p-value)

	(1)	(2)
Intercept	1331 [252] ($3*10^{-6}$)	1412 [298] ($2*10^{-5}$)
Heritage	-1155 [345] (0.002)	-1096 [366] (0.004)
Year		-3.4 [6.5] (0.6)
R^2	*0.19*	*0.19*
Adjusted R^2	*0.17*	*0.16*
p-value	*0.002*	*0.006*
N	*50*	*50*

Table 4-48 shows the result for heritage and development duration. The impact of using heritage is still large with a decrease in development duration of about 50% if full heritage is present. This value does not change significantly if another significant variable, the class of space system is added as a control variable.

Table 4-48: Multiple regression results for development duration, combined heritage metric, mixed sample. Table entries: correlation coefficient, [standard error], (p-value)

	(1)	(2)
Intercept	75 [7] ($2*10^{-14}$)	82 [9] ($3*10^{-12}$)
Heritage	-38 [9] (0.0002)	-38 [9] (0.0001)
Interplanetary		-18 [6] (0.007)
Launcher		1 [7] (0.9)
R^2	*0.26*	*0.43*
Adjusted R^2	*0.24*	*0.39*
p-value	*0.0002*	*$2*10^{-5}$*
N	*48*	*48*

Development cost and schedule overruns are not considered, as no statistically significant relationship could be identified for both.

For specific development cost and development duration, estimation relationships are derived, based on the statistical results. The resulting estimation relationships for specific development cost in k$/kg is:

$$C_{dev} = (1331 - 1156 \cdot H)[\frac{k\$}{kg}] \quad (41)$$

The relative specific development cost c_{dev} can be obtained by dividing the equation by the intercept:

$$c_{dev} = 1 - 0.869 \cdot H \quad (42)$$

The estimation relationships for the absolute development duration in months is:

$$t_{dev} = (75 - 38 \cdot H)[months] \quad (43)$$

Similar to the relative specific development cost, the specific development duration τ_{dev} can be obtained by dividing the equation by the the intercept:

$$\tau_{dev} = 1 - 0.507 \cdot H \quad (44)$$

To summarize, in this section I used a combined design heritage – technological capability metric with equal weights. The results indicate that large savings in specific development cost and development duration are possible. Savings of about 87% in specific development cost and 51% in development duration for full heritage were obtained.

4.4 Summary of Results and Discussion

The results from 4.3 are summarized in terms of their statistical significance, tendency, and effect size on the dependent variables. I start with statistical significance. Table 4-49 provides an overview of various heritage metrics and their statistical significance on program management variables. "Yes" indicates that the metric has a statistically significant relationship with the program management variable at the α = 0.05 level. "No" indicates that there is no statistically significant relationship.

I first start with the design heritage metrics. Table 4-49 shows that hypotheses tests for both design heritage metrics have a statistically significant relationship with respect to specific development cost. The same results are yielded for both design heritage metrics and development duration. As both metrics yielded the same results, the relationship between design heritage and specific development cost and development duration should be fairly robust. For development cost and schedule overrun, no statistically significant relationship was identified.

I continue with organizational capability. Organizational capability has a statistically significant relationship with specific development cost and a significant relationship with development duration. An additional statistically significant relationship was discovered for schedule. Team similarity has no statistically significant relationship except with development schedule overrun for the interplanetary spacecraft sample. No statistically significant relationship was identified for program manager experience. For team similarity and program manager experience, small sample sizes of 10 or below are used. Hence, additional data points could change the result.

Table 4-49: Statistical significance (0.05 level) of heritage indicators and program management variables for different samples

	Specific development cost	Development duration	Development cost overrun	Development schedule overrun
Fine-grained design heritage metric	Yes	Yes	No	No
Coarse-grained design heritage metric	Yes	Yes	No	No
Organizational capability	Yes	Yes	No	No
Team similarity	No	No	No	Yes
Program manager experience	No	No	No	No
Combined heritage metric	Yes	Yes	No	No

To summarize, it was shown that design heritage and organizational capability have a statistically significant relationship with specific development cost and development duration.

I continue with the tendency between the heritage variables and the programmatic variables. Table 4-50 shows if there is an increase or decrease for a heritage metric and a program management variable. Almost all heritage metrics lead to a decrease in specific development cost or development duration.

Table 4-50: Heritage indicators and increase / decrease of program management variables for different samples

	Specific development cost	Development duration	Development cost overrun	Development schedule overrun
Fine-grained design heritage metric	Decrease	Decrease	-	-
Coarse-grained design heritage metric	Decrease	Decrease	-	-
Organizational capability (experience)	Decrease	Decrease	-	-
Team similarity	-	-	-	Decrease
Program manager experience	-	-	-	-
Combined heritage metric	Decrease	Decrease	-	-

Another important question is how large the effect of using heritage technologies is, compared to other independent variables. Table 4-51 provides an overview of coefficients for different heritage metrics with respect to the considered programmatic variables. The range is the maximum effect on the programmatic variable for different regression models. For example, design heritage (fine-grained metric) can lead to a maximum effect on specific development cost reduction between 75.3 to 84.7% for a design heritage value of 1. For a design heritage value of 0.5, the predicted cost reduction would be half of these values: 37.7 to 42.4%. Note that the values are calculated for each of the heritage variables independently. As the design heritage variable and organizational capability are correlated, the resulting total savings are smaller than the sum of the individual savings.

Table 4-51: Effects of different heritage metrics on program management variables (ranges defined by different regression models)

		Specific development cost [%]	Development duration [%]	Development cost overrun [%]	Development schedule overrun [%]
Fine-grained design heritage metric for the value 1		-75.3% to -84.7%	-44.2% to -56.2%	-	-
Coarse-grained design heritage metric	**Category 1**	-50.1% to -62.8%	- 26.9% to -32.5%	-	-
	Category 2	-38.9% to -63.1%	(not significant)	-	-
	Category 3	-55.2% to -75.6%	-30.6% to 32.6%	-	-
	Category 4	-61.1% to -73.3%	-48.1% to -65.5%	-	-
Technological capability (experience)		-71.7% to -85.2	-34.8% to -41.9%	-	-
Team similarity		-	-	-	-83.3%
Program manager experience		-	-	-	-
Combined heritage metric for the value 1		-77.6% to -86.7%	-46.3% to -50.0%	-	-

In general, the savings from using design heritage and using existing organizational capabilities is large. This is not surprising, as the values in the table are for the extreme case, where an existing space system with its design and organization is used one-to-one for a new program. Intuitively, even larger savings would be expected when a system has already been developed before by an organization. However, note that there are recurring costs in the form of manufacturing cost that are incurred, even when no development takes place.

Besides the findings regarding heritage technologies, other statistically significant relationships were uncovered. In particular, the year in which the space system was launched had a consistently statistically significant effect on almost all programmatic variables. More specifically, from 1959 to 2015, the specific development cost of space systems has decreased by 4.32% each year. Note that this is an exponential decrease. **A space system launched in 1959 was 11 times more expensive per kg than a space system launched in 2015.** This result is remarkable, as at the same time, the technology used in these systems has made considerable advances such as light-weight materials and electronic components.

How can this decrease be explained? One explanation is similar to the one from Hamaker and Componation (2005) and attributed to productivity increases in an industry or economy. Such a productivity increase is commonly termed "experience curve effect". The experience curve effect is attributed to the introduction of new technologies, economy of scale effects, organizational learning, organizational efficiency, investments, and specialization (Abernathy and Wayne, 1974; Colpier and Cornland, 2002; Hall and Howell, 1985; Henderson, 1974). Although the phenomenon has been confirmed numerous times, it is less clear how the various factors contribute to the effect.

Another, yet unknown phenomenon I have discovered is the reduction of cost and schedule overruns over time. For cost overruns, there is a constant decrease of cost overruns of 3.16% each year between the years 1975 and 2013. This decrease is linear. Similarly, for development schedule overruns, there is a decrease of 4.42% between the years 1977 and 2013. Note that these values are only valid for the indicated periods and by using the respective regression models. Note that a negative cost and schedule overrun value is possible and occurred on several occasions. It just means that the system has been developed cheaper or quicker than expected. Nevertheless, this decrease over time is unexpected, as the project management and systems engineering literature is full of examples where projects suffered from overruns. To the author's knowledge, this is the first time that statistical evidence for decreasing cost and schedule overruns has been found. One might attribute this phenomenon to better project management methods, tools, and practices. However, I can only speculate and remark that more extensive regressions need to be run for confirming this result.

Table 4-52: Effect of launch year on programmatic variables

	Specific development cost reduction per year	**Development duration [months]**	**Relative cost overrun reduction per year**	**Relative schedule overrun reduction per year**
Year of (first) launch subtracted by 1959	-4.32%	-	-3.16%	-4.42%

At this point, I come back to the initial hypotheses. I wanted to find statistical evidence for the relationship between heritage technology and program management variables. Table 4-53 provides an overview of the hypotheses for heritage benefits and how far they were confirmed. Note that a "No" in the table only means that I cannot reject the 0-hypothesis. It does *not* mean that I have shown that no relationship exists. A relationship may still exist, but based on the statistical significance criteria, I was not able to confirm such a relationship.

First, I was not able to confirm the existence of a relationship between heritage technology use and cost and schedule overrun. Second, I was able to show that there is a statistically significant relationship between heritage technology use and development cost and development duration. The more heritage technologies are used, the lower the specific development cost and the shorter the development duration.

Table 4-53: Hypothesis for heritage benefits and confirmation by statistical evidence

Hypothesis	Confirmed?
H1: The more heritage technologies used, the lower the development cost.	Yes
H2: The more heritage technologies used, the shorter the development duration.	Yes
H3: The more heritage technologies used, the lower the development cost overrun.	No
H4: The more heritage technologies used, the smaller the development schedule overrun.	No

What conclusions can be drawn from this result? First of all, I need to argue why conclusions from this sample can be generalized. As mentioned in Section 4.2.3, the sample is geographically (USA, EU, Japan) and temporally (1959 to 2015) limited. Regarding the geographical limitation, I argue that many significant launcher development programs are included in the sample. Due to the, in general, low number of launcher development programs, having covered a large portion of these should be sufficient for claiming representativeness. Regarding the temporal limitation, almost the entirety of modern spaceflight has taken place between 1959 and 2015. However, there is a bias towards spacecraft developed after 2000 and a bias towards launchers developed in earlier decades. Nevertheless, this bias is likely small for the launcher sample, as most launcher development programs indeed took place in earlier decades. For the spacecraft sample, a larger number of spacecraft developed before 2000 could influence the results obtained for the launch year presented in Table 4-52. A more balanced sample would be needed for generalizing these results. One way to correct for the bias would be the introduction of weightings, where spacecraft developed earlier would be assigned a higher weighting than spacecraft developed after 2000 (Cuddeback et al., 2004). For the following conclusions, these limitations should be kept in mind.

In the introduction chapter, the ambiguity of using heritage technologies was shown. Their successful use has reportedly lead to successful space systems development programs. Their inappropriate use has reportedly lead to significant cost and schedule overruns and mission failures.

First, it can be claimed that using heritage technologies is indeed an *in general* effective way of reducing development cost and development duration. I make two assumptions to arrive at this generalization. The first assumption is that the sample is representative for the population of space systems. As the sample was not selected randomly but selected based on convenience, this is a potential threat to validity. Hence, I can still object that these results might be due to sampling bias. The second assumption is that the list of controls in the statistical analysis is sufficiently complete that I can safely say that there is not only a correlation but a causal relationship between heritage technology use and both, specific development cost and development duration.

Second, I was not only able to show that the use of heritage technologies leads to shorter development durations and lower specific development cost but I was furthermore able to show that it has a large effect on these two variables. The effect is comparable to other technology choices for the space system.

If there is indeed no statistically significant relationship between heritage technology use and cost and schedule overrun, one conclusion would be that *in general* the benefits of using heritage technologies in terms of specific development cost and development duration do not come at an increase in programmatic risk. However, as the sample size for cost and schedule overrun was significantly smaller than for specific development cost and development duration, a larger sample would be needed to confirm this conclusion.

Future work should focus on confirming the results for a random sample, in order to provide a more rigorous confirmation for these results. Furthermore, a larger sample for the indicators of technological capability is recommended, specifically the transfer of teams from one project to another and the experience of program managers. That way, it might be possible to identify which elements of organizational capability have an impact on program management variables.

5 Assessment Methodology

A methodology can be defined as a "collection of related processes, methods, and tools" (Estefan, 2008). In this chapter, I present a heritage assessment methodology that addresses four of the thesis objectives:

- Enable the assessment of heritage technologies with respect to a new set of requirements, constraints, and environments;
- Enable evaluating the effects of modifications on heritage technologies;
- Enable assessing capabilities related to the development, manufacturing, and operation of a heritage technology;
- Enable the measurement of heritage in order to compare technology options.

The methodology builds on the definition and conceptual model of heritage technology presented in Chapter 1. Furthermore, the three frameworks presented Chapter 3 provide the basis for the methodology. Contrary to the descriptive frameworks, the methodology intends to prescribe how to assess heritage technologies.

5.1 Methodology Overview

Fig. 5-1 depicts the methods used in the heritage assessment methodology. The methodology consists of four methods: compliance assessment, VVTO assessment, design heritage assessment, and technological capability assessment.

The *compliance assessment* is a high-level method for evaluating requirements and constraints satisfaction for the application *at hand*, based on the VVTO framework in Chapter 3.3. Detailed requirements and constraints are often unknown during the early stages of systems development. In this situation, the method provides the means for systematically identifying issues relevant for compliance. In case compliance satisfaction cannot be verified due to a lack of information, the issue is documented and assessed at a later point in time when sufficient information is available.

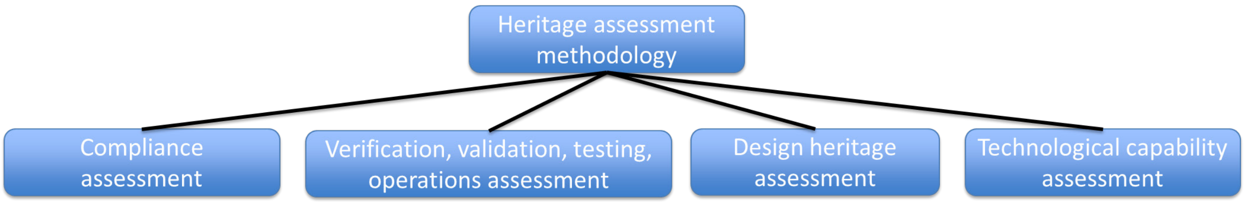


Fig. 5-1: Methods within the heritage assessment methodology

The *verification, validation, testing, and operations (VVTO) assessment* evaluates the existing heritage of a technology with respect to its verification, validation, testing, and operations *history*. This assessment evaluates if the VVTO history can be transferred to the new application. How does the VVTO assessment differ from compliance assessment? Compliance assessment evaluates if a technology satisfies the requirements and constraints of a new application. It does not deal with the VVTO history of a technology.

Design heritage assessment has the objective of evaluating the impact of design changes to a heritage system design. Planned changes are assessed by the similarity assessment method, where the similarity between the existing and modified heritage technology is determined.

Technological capability assessment has the purpose to assess if a certain technological capability is present and if present, how mature this capability is.

A methodology would not be complete without a process. The top-level process of the methodology is depicted in Fig. 5-2. The respective inputs and outputs of each process step are shown in Table 5-1.

First, the objectives of the assessment are defined. This step is crucial, as depending on the objectives, the effort of performing the assessment can widely differ. Sample objectives are:

- Compare technology options for a subsystem with respect to heritage;
- Identify potential adaptation issues of heritage technologies into a spacecraft architecture;
- Develop a heritage report for a project proposal.

Depending on the objective(s), the depth of assessment is defined. The depth of assessment is the granularity or level of detail that is considered satisfactory for making a decision. A higher level of detail usually means a higher effort to collect the data and conducting the analysis.

In a second step, the systems and technologies under consideration are defined. This step determines the scope of the technologies that are going to be assessed. For example, when a heritage technology for a spacecraft needs to be selected, several heritage technologies are under consideration. In other cases, such as assessing the heritage of a single technology, there is only one technology under consideration. Furthermore, systems and technologies that do not satisfy the following criteria are eliminated:

- The technology is not accessible due to, for example, political reasons such as sanctions, export restrictions, geographic return etc.
- The price for acquiring the technology is prohibitive.
- The technology cannot be acquired due to strategic reasons such as competition with the customer, decision to favor in-house development instead of using a supplier.
- The supplier may not be able or willing to engage in a relationship with the customer.
- The technology is obviously not available as the supplier or all available suppliers went out of business.
- The technology is available but due to legal / normative reasons cannot be used. For example, a supplier has not been recertified and the prime contractor is no longer allowed to procure from this supplier. A technology might no longer be compliant with existing regulations.

This prescreening avoids spending efforts on a more detailed assessment when it is clear that the technology is not available.

Once the systems and technologies under consideration have been defined, a compliance assessment is performed, using system-level requirements and constraints. A heritage technology passing the compliance assessment can directly move forward to the combined VVTO, design heritage, and technological capability assessment. However, if the technology does not pass, there are two options. Either the technology is removed from the set of technologies under consideration or modifications are identified, which would enable the technology to meet the requirements and constraints. In case modifications are required, the heritage impact of these modifications needs to be assessed. This is done in the design heritage assessment step. In parallel, the modified technology undergoes the VVTO and technological capability assessment.

Based on the quantitative results of the VVTO, design heritage, and technological capability assessment, the heritage metric value is calculated. The heritage metric value for the technology options can then be used for a variety of heritage-based comparisons of these options.

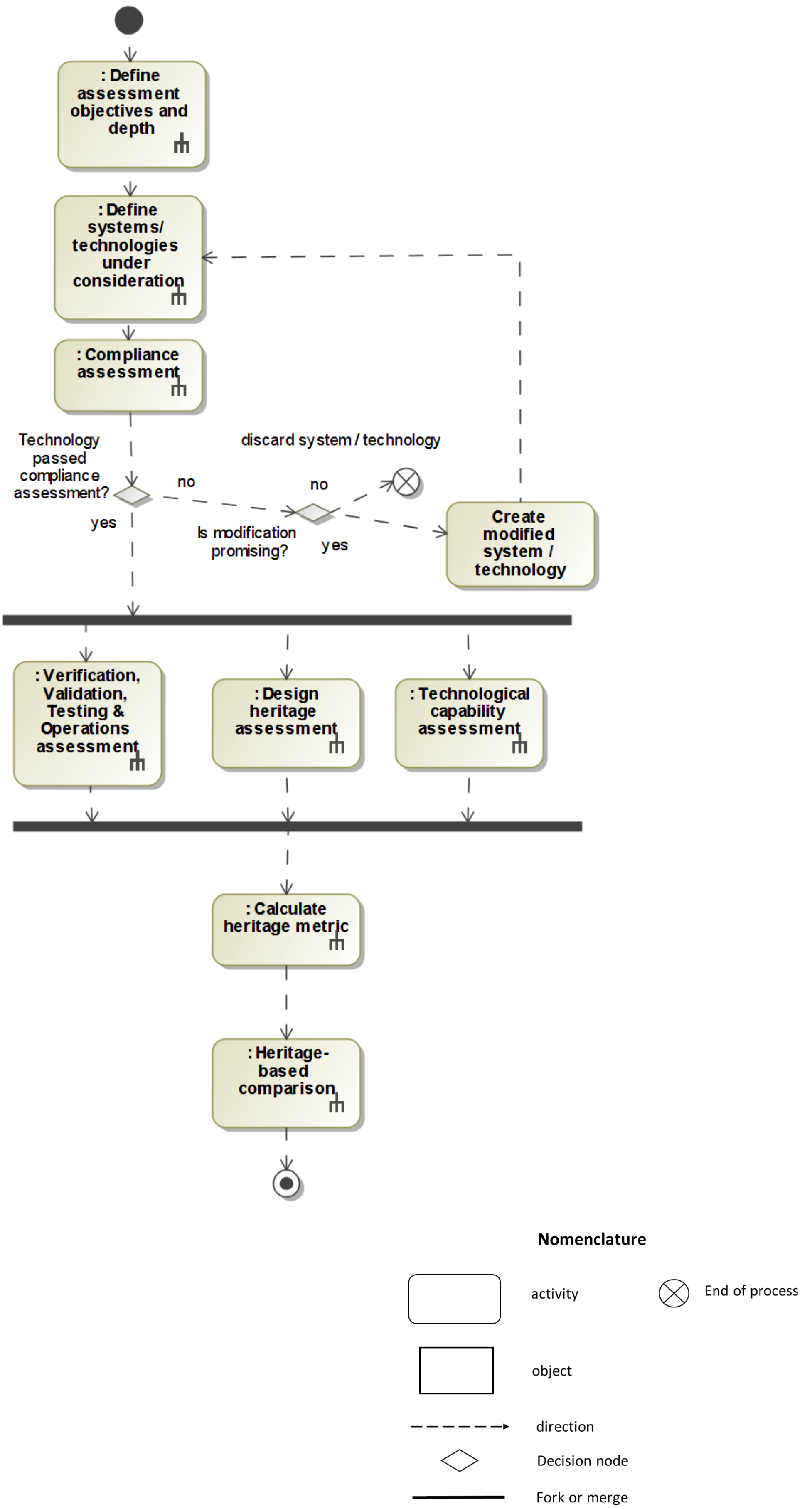


Fig. 5-2: Heritage assessment process

Table 5-1: Inputs and outputs of heritage assessment process steps

Process step	Inputs	Outputs
Define assessment objectives and depth	Initial objectives for heritage technology assessment	Prioritized objectives and required level of detail for decision making
Define systems / technologies under consideration	Prioritized objectives and required level of detail for decision making	Set of existing or planned technologies and systems for further assessment
Compliance assessment	• Set of existing or planned technologies and systems for further assessment • Set of system-level requirements and constraints	For each technology / system: compliance, non-compliance, conditions for resolution, to be defined (tbd)
VVTO assessment	• VVTO data for compliant technologies / systems • System-level TRL	VVTO classification and extent for technologies / systems to the level of detail required
Design heritage assessment	DSMs of system architecture of original system, system architecture(s) of modified systems	Impact of modifications on design heritage
Technological capability assessment	Capability list	Capability levels for technologies / systems to the level of detail required
Calculate heritage metric	For each system / technology: • VVTO metric value • Design heritage metric value • Capability metric value	Heritage metric value for each system / technology
Heritage-based comparison	Values for other system / technology evaluation criteria, e.g. development cost, utility, etc.	Set of ranked or Pareto-optimal systems / technologies

Tools

A tool is "an instrument that, when applied to a particular method, can enhance the efficiency of the task" (Estefan, 2007, p.3). A number of tools is used for supporting each of the heritage assessment steps. Table 5-2 shows the main heritage assessment steps and the tools used in them.

- *Context model:* The context model represents the technology's context. The context consists of supporting systems, environmental characteristics, contextual systems and the wider cultural and societal context. The purpose of the context model is to systematically identify potential issues in the context of the technology that may impede or support the modification and use of the heritage technology. The model can be just a list, a concept map, SysML diagram or any other suitable representation of these elements.
- *Compliance matrix*: The compliance matrix is a matrix that maps requirements and constraints to parameter values or characteristics of a technology to assess its compliance.
- *VVTO history matrix:* The VVTO matrix documents in which contexts a technology has performed its functions, processes, modes, and mode transitions. The purpose of the VVTO matrix is to support the evaluation where heritage exists and where not. It furthermore provides the basis for assessing heritage changes when the technology is modified.
- *Change DSM:* The change DSM is an adjacency matrix that represents anticipated or implemented changes to a system architecture. It is similar to the Delta-DSM (Suh et al., 2010) except that a set of change representation rules is provided for creating the matrix. Its purpose is to represent modifications and to provide the basis for a later quantitative assessment of modifications.
- *Architectural similarity algorithm:* The algorithm uses two DSMs and evaluates their similarity by calculating the similarity metric. The algorithm can be used for different purposes. It is used for assessing how different two system architectures are with respect to their components and relationships.

- *Capability-system matrix:* The capability matrix maps knowledge and resources that constitute a capability to the technologies or systems under consideration. The purpose of the matrix is to identify where capabilities are missing or what capability options exist. The matrix provides the basis for assessing capability acquisition options in case capabilities are missing. The matrix was previously introduced in Hein et al., (2014).
- *Heritage metric:* The heritage metric aggregates the VVTO, design heritage, and technological capability metric into a single heritage value for a technology.

Table 5-2 shows the mapping between the activities in the heritage assessment process and the tools. During the compliance assessment step, I need a representation of the context for the heritage technology. This context is provided by the context model. I furthermore need a tool for assessing if the heritage technology complies with this context. The compliance matrix is used for that purpose. The VVTO assessment needs a representation of a technology's VVTO history and its extent. The VVTO history matrix maps the VVTO history relevant to the new application. For assessing modifications, I need a representation of modifications and a way to measure the similarity between two designs. The change DSM is used for the former, and the architectural similarity algorithm for the latter. Finally, for assessing the capabilities associated with a technology, again, a tool for representing the capability is needed. The capability-system matrix is used for this purpose. Finally, the heritage metric is used for calculating a single heritage value for a technology that can be used for the heritage-based comparisons of technology options.

Table 5-2: Heritage assessment activities and tools used in them

	Context model	**Compliance matrix**	**VVTO history matrix**	**Change DSM**	**Capability-system matrix**	**Architectural similarity algorithm**	**Heritage metric**
Compliance assessment	X	X					
VVTO assessment			X				
Design heritage assessment				X		X	
Technological capability assessment					X		
Heritage metric calculation							X
Heritage-based comparison							X

The heritage metric quantifies / measures heritage. As defined in Chapter 1 and 2, technological heritage consists of the design heritage, verification, validation, testing, and operational history, and the technological capabilities of the organization(s) responsible for one or more of the technology's life cycle phases. Hence, heritage can be measured in three complementary ways. It can be measured either by the extent of the design reused, the verification, validation, testing, and operations history, or the capabilities of the organization(s). Comparing the two first and the last case, the units of analysis are different. Measuring a system or system design's heritage and its VVTO history is a system-centric measurement approach to heritage. Thus, the system is the unit of analysis. Measuring an organization's capability is an organization-centric measurement approach to heritage. In this case, the organization(s) are the unit of analysis. These two measurement approaches are combined.

Fig. 5-3 shows how the various aspects of a technology that are addressed by the heritage assessment methodology. For measuring heritage, each of these areas has to be assessed with respect to constituting elements of heritage. A heritage technology inherits a design that may be subject to change. For example, new component technologies might be infused into the technology or component technologies may get obsolete. Hence, the life cycle of the technology as well as its component technologies have to be assessed. VVTO assessment looks at how far the design or artifacts of the technology have been verified, validated, tested, or operated. Compliance is not a component of heritage but determines whether or not existing heritage is dependent on a certain context.

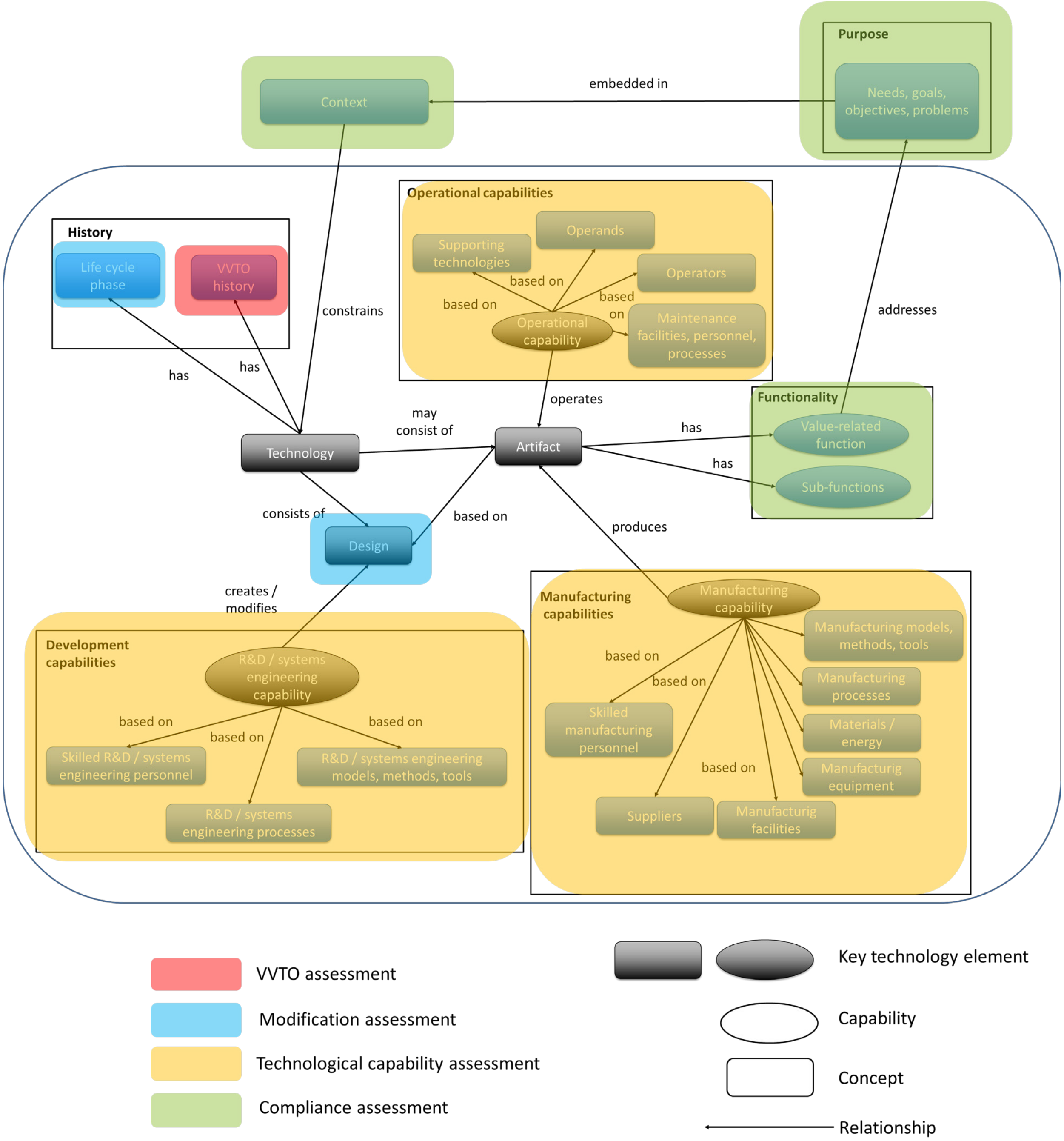


Fig. 5-3: Technology aspects addressed by heritage assessment methodology

The goal of measuring heritage is to provide an estimate of how far the use of a heritage technology results in the heritage benefits introduced in Section 1.4. As depicted in Fig. 5-4, the heritage measurement intends to support the estimation of heritage benefits and issues. The quantitative heritage measurement is complementary to the qualitative heritage assessment. The qualitative heritage assessment intents to identify potential heritage issues by covering a variety of aspects. The quantitative heritage measurement captures some of these aspects and assigns a heritage quantity to them. The calculated heritage values can then be used to compare technologies. Combined, the quantitative and qualitative assessment provide the decision-maker with guidance.

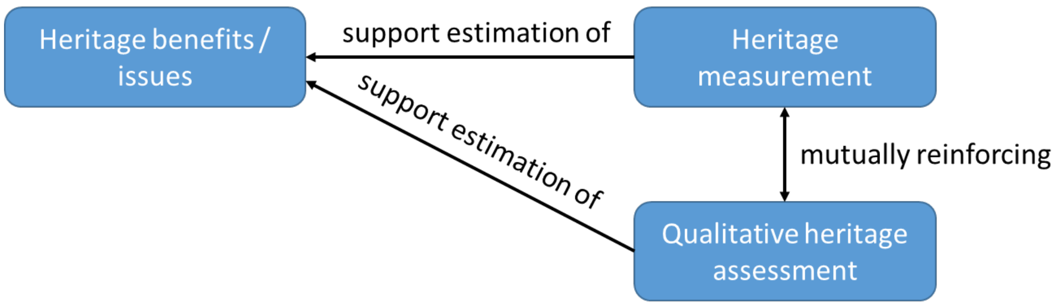


Fig. 5-4: Interplay between heritage measurement, qualitative heritage assessment, and heritage benefits and issues

The challenge is to find proper indicators for heritage within each of the areas shown in Fig. 5-3. A further challenge is then to find a proper approach for aggregating these indicators in order to arrive at a single heritage metric.

5.2 Compliance Assessment

Heritage compliance assessment helps to verify if a heritage system design satisfies requirements and constraints at an early stage. As mentioned in Section 1.1, compliance is important as heritage systems are used in a different surrounding system and environment than in which they were used before. Consequently, compliance assessment deals with the compliance of the heritage system design with requirements and constraints of the new application. The basic difficulty of compliance assessment at an early stage of development is that the system into which the heritage system is going to be integrated is still ill-defined and uncertainties about other technologies, interfaces, and supporting and contextual systems are large. On the other hand, knowledge about the heritage technology is rather detailed, as it has already been developed. Hence, the heritage technology imposes constraints on the system to be developed. These constraints can be the existing interfaces of the heritage system design, design parameters such as size and mass, as well as the way how the system works. The main purpose of the compliance assessment approach is therefore to assist systems engineers in identifying potential compliance issues without necessarily resolving them. If the issues are not expected to be resolved, the technology is removed from the set of options.

Assessment objectives and dimensions

First, objectives needs to be defined that the assessment method needs to satisfy. The main objective is to identify compliance issues in a new use context at an early stage of development. Which assessment dimensions need to be taken into account? First, the system's main function needs to be considered.

- Execution of **functions** within certain **environments**, taking system modes, nominal, contingent, and emergency operating conditions into account.
- **Performance** requirements of the functions.
- **Interfaces / interactions** with **supporting systems**, e.g. electric propulsion with power subsystem.
- **Interfaces / interactions** with **context systems.**
- **Constraints from natural and man-made environment**: new standards, public perception, regulations, norms, etc. For example, nuclear propulsion was acceptable during the 60s but is unacceptable today. NASA human spaceflight standards are much more restrictive today than during the 60s. Examples for constraints from the natural environment are weather, radiation, vacuum. The natural and man-made environment can be distinguished from the other entities as they are usually not stakeholders of the system under consideration. Thus, they are neither affected nor have an interest in the value the system delivers. For example, the governing bodies of engineering standards have the purpose to control and enforce standards. If an aircraft does not adhere to regulations, it is not allowed to fly. However, the governing body of regulations does not benefit from the aircraft flying, neither is it affected by the flying aircraft.

The "compliance matrix" is introduced for capturing the compliance with these entities, which is shown in Table 5-3. The rows of the matrix represent various compliance criteria. These criteria can be categorized into criteria related to system-level requirements and constraints from the surrounding system and environment. The matrix entries represent particular characteristics of the system or technology and an indication if they satisfy the requirement or constraint.

Table 5-3: Structure of compliance matrix

Requirement / constraint type	System / technology 1	System / technology 2
System-level requirements		
Main function	Compliance yes/no/conditions for resolution/tbd	Compliance yes/no/conditions for resolution/tbd
Other system-level functions	Compliance yes/no/conditions for resolution/tbd	Compliance yes/no/conditions for resolution/tbd
Performance requirements	Compliance yes/no/conditions for resolution/tbd	Compliance yes/no/conditions for resolution/tbd
Interface requirements		
Interfaces with supporting systems	Compliance yes/no/conditions for resolution/tbd	Compliance yes/no/conditions for resolution/tbd
Interfaces with contextual systems	Compliance yes/no/conditions for resolution/tbd	Compliance yes/no/conditions for resolution/tbd
Environmental constraints		
Constraints from natural environment	Compliance yes/no/conditions for resolution/tbd	Compliance yes/no/conditions for resolution/tbd
Constraints from man-made environment	Compliance yes/no/conditions for resolution/tbd	Compliance yes/no/conditions for resolution/tbd

An example for a compliance matrix is shown in Table 5-4 for assessing the compliance of a heritage ChipSat for a new application. A ChipSat is a small spacecraft of the size of a credit card, as shown in Fig. 5-5. The heritage ChipSat design is planned to be upgraded by a small solar sail, as shown in Fig. 5-6. The assessment stems from an existing project in the context of a non-profit organization. It is done from the perspective of the non-profit organization that aims to contract out the development of a ChipSat with solar sail. The main objective for the organization is to test a new solar sail material in space. ChipSats have been previously developed at Cornell University (Manchester, 2015). They are ejected in large numbers from a 3U-CubeSat by a deployment mechanism.

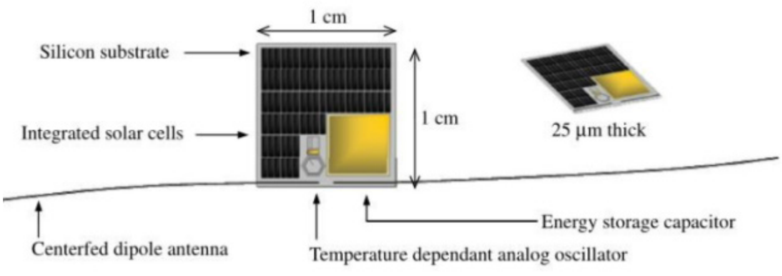


Fig. 5-5: ChipSat schematics (Hein et al., 2016)

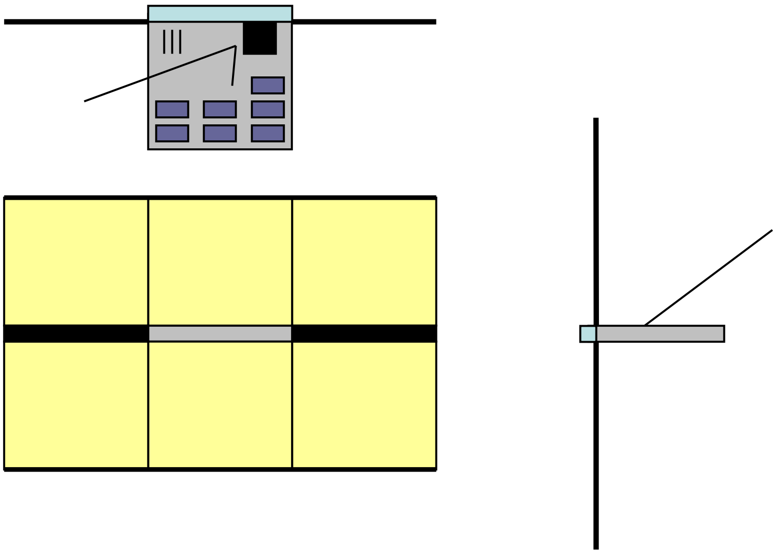


Fig. 5-6: ChipSat concept with deployable solar sail from Hein et al. (2016)

Table 5-4: Compliance matrix for ChipSat with solar sail

Requirement / constraint	**Requirement / constraint type**	**ChipSat with solar sail**
	System-level requirements	
Transmit telemetry data to ground station	Main function	Yes
	Other system-level functions	
UHF/VHF data transmission	Performance requirements	Yes
	Interface requirements	
Interface to ChipSat deployer on 3U-CubeSat	Interfaces with supporting systems	No
Fit of foldable antennas with ChipSat deployer	Interfaces with contextual systems	Yes
Compatibility with ground station equipment	Interfaces with contextual systems	Yes
Compatibility with existing AIT and VVT equipment and facilities	Interfaces with contextual systems	Condition: Depends on prime contractor choice
	Environmental constraints	
LEO space environment	Constraints from natural environment	Yes for ChipSat, no for solar sail
Compatibility with parts of the CubeSat standard	Constraints from man-made environment	Yes

The example matrix shows that most of the requirements and constraints for the new application are satisfied. However, due to the added solar sail, there are potential problems with the deployment mechanism that ejects the ChipSat from the CubeSat. The deployment mechanism offers only limited space for an added sail and it is likely that there are compatibility issues. Note that at this point no specific technology for the solar sail deployment mechanism has been selected. Depending on the choice, the sail might be more or less easily storable within the CubeSat. The compliance matrix allows for documenting these potential issues without the necessity of resolving them. The resolution of the issue may take place much later in the design process.

Furthermore, some requirements are quite precise, such as requirements imposed by the CubeSat Standard (Lee et al., 2009). Although most of the requirements in the standard do not directly apply to the ChipSat, there are requirements that apply to the ChipSat. For example, the standard requires that all electronic components are switched off until the CubeSat is deployed in space. As the ChipSat is equipped with electronic components, they also need to be switched off. This requirement is satisfied, as the ChipSat is entirely powered by its solar cells that do not produce any power until the ChipSat is ejected from the CubeSat in orbit.

Other requirements and constraints are not detailed at this point. For example, the compliance with AIT and VVT equipment of the prime contractor does depend on which prime contractor is selected. At the current stage, only one university has developed a ChipSat but as this development program dates back a few years, it is unclear if there would be issues with their equipment and facilities.

The example demonstrates that the compliance matrix is able to:

- Represent compliance issues well before these issues are resolved;
- Represent requirements and constraints at different levels of detail.

There are two potential results from the compliance assessment:

- Compliance issues that indicate that the heritage system or technology cannot be used for the application at hand;
- Compliance issues that can only be resolved at a later stage of design.

For the first case, the technology is not further considered or modifications are proposed and assessed as described in Section 5.4. For the second case, the compliance issues are documented for informing later design stages.

5.3 Verification, Validation, Testing, and Operations Assessment

An element of a heritage technology is its verification, validation, testing, and operations (VVTO) history. A general challenge in assessing VVTO is that the VVTO data cannot be used directly but needs to be mapped to a value function. For example, for one type of system one successful instance operated in space might indicate significant VVTO history. Examples are common satellite subsystems or bus systems that are produced in small lots. For other systems that are produced in series, only operating several systems successfully indicates sufficient VVTO. Examples are space launchers. Hence, the way VVTO data is interpreted depends on the specific type of system. Furthermore, what is considered insufficient, sufficient, or extensive VVTO includes an inherent value judgement. As a consequence, the VVTO data needs to be mapped to a scale that represents a value judgement, i.e. a value function.

In the following, a value function for VVTO history is developed. A value function is used, as value judgements regarding VVTO history can be captured by the concept of “value”. “Value” is used here interchangeably with “utility” and defined in the sense of Alchian (1953) as the assignment of "a set of numbers (measures) to the various entities and (to) predict that the entity with the largest assigned number (measure) will be chosen.” (Brackets in original text) For the TRL-based approach, the entities are individual TRLs and the numbers represent the value associated with a TRL in terms of confidence. “Value” in the context of VVTO history is understood as the subjective probability that a technology will function in its intended environment and context. It can also be interpreted as confidence. The higher the confidence, the better. The basic question is then how to map VVTO history to value. To answer this question, quantitative and qualitative elements of VVTO history can be distinguished. First, it is assumed that VVTO history basically consists of events in the broadest sense. A simulation that has been conducted, the qualification test passed, a unit flown in space are all events of VVTO history. VVTO history events have quantitative and qualitative characteristics:

- *Quantitative:* Events have a quantitative element. In the binary case the event has either occurred or not. If an event is cumulative, then it might follow the rule “more is better”. Examples are hours of operation or number of launches. In general, events are cumulative if they belong to a certain event category and can be counted with respect to this category. For example, hours of operation is one category and the number of hours can be counted. “Launches” is another category where the “number of launches” can be counted. There are likely diminishing returns to quantity. A component that has been operated successfully 100 times might already be considered to have extensive VVTO history and operating it 1000 times only leads to incremental improvements in value.
- *Qualitative:* An event can also have a qualitative element besides its quantity. For example, the number of hours a component is operated in a particularly harsh environment is different from the same number of hours a component is operated in a benign environment. The former is likely to be considered more valuable than the latter. Furthermore, a test that has been passed by a wide margin is different from a test passed by a narrow margin. Again, the former is likely to be considered more valuable than the latter.

Using the combination of quantitative and qualitative measures, VVTO history can be mapped to value. In other words, the events are interpreted as evidence that contribute more or less to the confidence in a technology. Such a mapping can be defined as

$$M: E \times E \times \ldots \times E \rightarrow W \tag{45}$$

where M is a function that maps n events e_i that are elements of a set of events E to a set of values W indicating the confidence in the VVTO history. The mapping M would tell how much an event contributes to confidence for a specific context. Ideally, for each domain and each technology, a value function needs to be defined that properly reflects the contribution of VVTO history to confidence. The general form of the value function is:

$$M(e_1, e_2, \ldots, e_n) = w \quad e_i \in E;\ w \in W \tag{46}$$

For example, what are the quantitative and qualitative characteristics of TRL? For the sake of simplicity, each TRL can be interpreted as a binary event. Either a technology has a certain TRL or it has not. Looking at individual TRLs, each TRL has a set of conditions assigned to it. For example, according to the ESA TRL handbook a TRL 4 is reached once “Component and/or breadboard validation in laboratory environment” has taken place (ESA, 2008). In this case, the event would be either the component or breadboard validation in a laboratory environment or both. All other TRLs can also be interpreted as a set of events that need to take place in order for a technology to reach a specific TRL. Furthermore, the sequence of these events is equally defined. However, According to the NASA TRL assessment sequence depicted in Fig. 2-13, a technology that is at a certain TRL does not need to remain at that level. It can also be downgraded, in particular when the context changes. Hence, the relevant event is the current TRL for a specific context and previous TRL are not taken into consideration.

Regarding the qualitative aspect of TRL, first, TRL represents an ordinal scale that is fully ordered. “Ordinal” means that the levels in the scale are rank-ordered but there is no distance measure between individual levels. This means that the difference, whatever this means for TRLs, between TRLs is not defined. For example, a statement such as “The difference between TRL 4 and TRL 5 is the same as between TRL 7 and TRL 8” would be meaningless. “Fully ordered” means that a higher TRL is always preferred over a lower TRL and there are no two TRLs that are equally preferred. These statements about TRLs are rather uncontroversial.

TRL is focused on the maturity and readiness of a system up to the point where it is operated. It does not extend further into operations. A launcher that has been operated successfully once or multiple times both have a TRL of 9. However, I hypothesize that the greatest increase in VVTO history takes place between between TRL 1 to 9, as existing publications seem to confirm (Conrow, 2011; Szajnfarber, 2011). I further hypothesize that further increases during the operational phase are rather incremental compared to the increase between TRL 1 to 9.

At this point the mapping between relevant VVTO history and confidence has been defined. Furthermore, I have shown that TRL prescribes a set of events that allows for a technology to be assigned a specific TRL.

In the following, two confidence levels for VVTO are presented. The first is an ordinal scale and the second an interval scale. The ordinal scale can be used for a quick assessment of VVTO history, independently of TRL, only presupposing a sequence of events. The interval scale has been specifically developed for the TRL scale and cannot be easily transferred to other event sequences.

Four generic levels for VVTO history are defined, that are shown in Fig. 5-7. For a specific technology, certain conditions are defined that indicate what insufficient and sufficient VVTO history means. For a commercial product such as a laptop, I could argue that sufficient VVTO history is when a sufficient number of customers have rated the laptop with a passing grade which is a form of validation that the laptop satisfies customer needs. Note that this is an interpretation of confidence in the sense of customer satisfaction. "Sufficient" just means that the VVTO history of the technology is just "good enough". It is a "passing grade" which means that the margin by which it has passed is not wide. "Substantial successful VVTO history" indicates that the technology has proven its usefulness by accumulating VVTO history that is considered "substantial" by a wide margin. For the laptop example, this could mean that product reviews by customers and professional testers have resulted in good grades. "Extensive successful VVTO history" goes even further and indicates that the technology's successful operation in certain environments is "beyond doubt".

	Extensive successful VVTO history for context
	Substantial successful VVTO history for context
	Sufficient successful VVTO history for context
	Insufficient successful VVTO history for context

Fig. 5-7: Four VVTO history levels for a specific context

There is no general definition for these VVTO categories. The criteria differ from domain to domain and case to case. For example, aircraft engines have to pass extensive testing under operational conditions before they are used on passenger flights. Spacecraft on the other hand are seldom tested in space before entering service. They are usually tested in simulated environments, for example inside a thermal vacuum chamber. Thus, an aircraft engine might be deemed to have sufficient heritage if it is certified and extensive heritage if it has been operated for thousands of hours, a spacecraft has extensive heritage, if two or three spacecraft of similar types have already been flown. Similarly, a spacecraft has sufficient heritage if it has passed qualification and acceptance tests. Therefore, engineering judgement is required in order to put a technology into one of these categories.

Furthermore, a quantification of these categories is required. It is clear that there is at least an ordinal preference order for the four categories. Extensive heritage is preferred over substantial heritage, substantial heritage is preferred over "sufficient" and so on. Again, note that the construction of such an ordinal scale is only possible in case a strict preference order for the technologies under consideration can be established. Such a preference order can be based on a specific interpretation or consensus after a discussion in a group.

For constructing a mapping between the VVTO events and the categories, the following steps can be taken:

1. Choose a set of events that represents successful VVTO history for a specific technology in a specific context;
2. Assess the quantitative and qualitative dimensions of the events and define how the events are aggregated;
3. Define thresholds for each VVTO category;
4. Test the mapping by using concrete examples.

In order to avoid the mathematical limitations of the ordinal scale, it is desirable to construct an interval scale, as introduced in Section 2.5.2. Recall that with an interval scale, the statement "the difference between technology A and B's VVTO history is twice the difference of VVTO history between A and C" is meaningful. With a ratio scale, the statement "technology A has twice as much VVTO history as technology B" is meaningful.

In order to measure confidence, events for VVTO history need to be selected. It was decided to use the TRL scale as a reference, due to its widespread use in various engineering domains. Recall that TRL is an ordinal scale. In order to construct an interval scale, a value function that maps between TRL and confidence has to be found. This relationship between TRL and VVTO history was determined by conducting a survey among a small, random sample of engineers working on life-support systems at NASA (Rösner, 2014). Drawing from utility theory, a lottery was constructed where the survey participants could distribute a budget of $1000 between technology success and failure (von Neumann and Morgenstern, 1944). The lottery has the purpose of eliciting the subjective probabilities the participants assign to a certain event.[17]

[17] Note that for a more accurate elicitation of subjective probabilities, the results should be corrected for the risk acceptance of participants.

The survey was conducted for a generic technology and a specific technology the sample group is familiar with. 13 surveys were returned for the generic technology and 10 surveys were returned for the specific technology, an environmental control and life support system component. The results are shown in Fig. 5-8, along with the respective standard deviations. One can observe a slight difference between the general technology and the specific technology. However, the general trend that a higher TRL translates into a higher confidence that the technology will function in operation is confirmed. The standard deviation is smaller for higher TRLs. Furthermore, the standard deviation for the generic technology is in general larger than for the specific technology, which can be explained by the lack of specificity for the generic technology. The important point, however, is that the pattern of increase in confidence is similar for both technologies, with a levelling off between TRL 8 and 9, compared to TRL 7 and 8. For the specific technology the initial confidence at TRL 6 is higher than for the generic technology. However, the confidence at TRL 9 is about the same for both cases. Detailed data from the survey is reported in Rösner (2014).

Fig. 5-8: Difference in confidence with respect to a specific and generic technology (dashed line: specific technology, straight line: generic technology)

These results are compared to results from Conrow (2011) where an interval scale for TRL was derived using Analytic Hierarchical Process (AHP). The resulting interval scale showed a more exponential shape without the levelling off between TRL 8 and 9. However, comparing the data reveals that the data points for the respective TRLs 6 to 9 are about in the same range and the deviation can be explained by the use of different methods and the small sample size.

Based on the results from the survey, a logistic value function was selected that approximates the data but also allows for extrapolating the confidence values to lower TRLs.

A logistic value function can be defined as:

$$V(x) = \frac{L}{1 + \exp(-c(x - x_0))}$$

c determines the steepness of the curve. L defines the curve's maximum value. x_0 is the mid-point of the logistic curve. For determining the parameters, the results from the TRL – confidence survey are used and the logistic function is manually fitted to the data. The manual fitting seems to be suitable due to the relatively large uncertitudes resulting from the small sample size. For L, the value of 0.95 was selected, which is equivalent to a bet of \$928 on system success. The mid-point x_0 was selected as 6.5, which is equivalent to a bet of \$500 on system success. The parameter values that define the logistic function are shown in Table 5-5. For VVTO assessment, x is the TRL and $V(x)$ the value of VVTO history.

Table 5-5: Parameters of logistic function

Logistic function parameter	Parameter value
L	0.95
c	1.5
x_0	6.5

Fig. 5-9 shows the resulting logistic function for all TRL values. This logistic function is asymptotic to 1 and additional VVTO events after reaching TRL 9 have diminishing returns. The function is also extrapolated to TRL values lower than 6, which was the minimum TRL value in the survey.

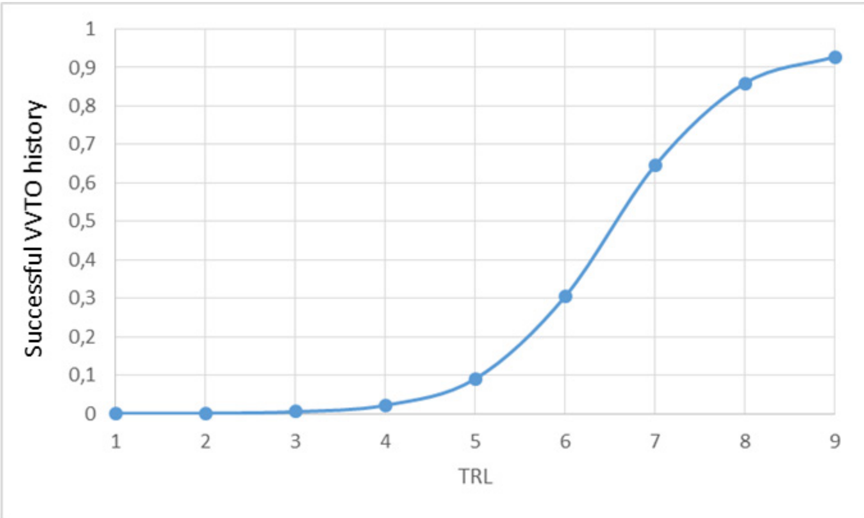


Fig. 5-9: Logistic function for TRL- VVTO history mapping

A diminishing return is consistent with the results from Rösner (2014), where he demonstrated that increasing levels of TRL yield diminishing returns in confidence that the technology works under operational conditions. Note further that the largest increase in confidence takes place between TRL 6 and 7, followed by large increases from TRL 5 to 6 and 7 to 8. For TRL 1 to 4, the function yields only very small increases in confidence. These results differ from the mean values presented in Fig. 5-8, where the largest increase takes place between TRL 7 and 8. However, due to the large standard deviation for TRL 7, I consider the logistic function a reasonable approximation of the empirical results. Different technologies may also yield different results for the TRL-VVTO history mapping. In the absence of further empirical evidence, the logistic function is a priori considered as a reasonable approximation.

To illustrate the link between the TRL-based confidence metric and the VVTO categories, the VVTO history values can be mapped to the four VVTO heritage categories, as shown in Table 5-6. The thresholds for the confidence values are selected for small-lot space systems such as satellites. For space launchers, “sufficient successful VVTO history” would likely start at TRL 9 and “substantial” and “extensive” VVTO history are likely to be measured by the number of successful launches after this point. For example, the US Air Force requested three successful launches of the Falcon 9 launcher in order to qualify for Air Force contracts. Furthermore, two successful launches needed to be consecutive. Hence, for the US Air Force, sufficient VVTO history exists beyond three successful launches (Butler, 2014).

Table 5-6: Heritage categories and respective heritage values

Color indicator	Successful VVTO history category	Confidence value
	Extensive	> 0.9
	Substantial	≥ 0.6
	Sufficient	≥ 0.3
	Insufficient heritage	< 0.3

Note that these categories are supplementary but useful for "tuning" the value function. For small-lot space systems, 0.3 is selected as the limit for sufficient heritage, as a TRL 6 is usually considered a threshold for incorporating a technology into a flight mission. 0.9 is considered extensive, as the technology has been operated at least once in its intended environment and context. Further, note that a direct mapping between TRL and the confidence categories (TRL 6 is sufficient etc.) is possible but in this case no value function would be defined.

Note that the NASA Systems Engineering Handbook proposes an approach for assessing component technologies used in a changed context (Kapurch, 2010). In such a case, the TRL of the technology is initially reduced to 5.

As with other elements of the heritage metric, a proper aggregation approach needs to be selected. The following aggregation approach is used:

Sufficient VVTO history cannot be reached without a minimum TRL of 6 for each component technology.

In case interactions between component technologies are challenging, metrics for integration should be used as well, such as the Integration Readiness Level (IRL) (Sauser et al., 2006).

Application example: ChipSat

The VVTO history assessment approach is illustrated by using the aforementioned ChipSat system. The solar sail ChipSat consists of two major components: the ChipSat and the solar sail. First, the events are identified that are considered important for the VVTO history. TRL is chosen for representing the VVTO history. Second, the TRL is a set of binary events. Either events associated with a certain TRL have taken place or they have not. Third, the threshold values are already defined by the TRL-based confidence metric. As there are two major components with different TRLs, the results for the solar sail and the ChipSat need to be aggregated.

For the ChipSat, three prototypes were part of the MISSE-8 experiment payload flown into space on the Space Shuttle Flight STS-134 in 2011, mounted on the ISS, and returned to Earth in 2013, as shown in Fig. 5-10. According to Manchester (2015, p.21) the proper functioning of the communication systems of the ChipSats could not be verified, due to the location of the experiment on the ISS. However, all ChipSats functioned properly after having been returned to Earth. Manchester goes on to remark that the functional testing after the return of the ChipSats to Earth does not "quantify radiation damage to individual semiconductor components…"

Furthermore, the first 3U-CubeSat with 104 ChipSats was successfully launched into space in April 2014 (Krebs, 2016). However, due to a radiation-induced malfunction, the ChipSats could not be deployed before the 3U-CubeSat reentered the atmosphere. This means that the ChipSats could not be operated in the space environment.

As the ChipSats have been tested in the space environment, a TRL of 7 is assigned to the ChipSat design. A higher TRL is not assigned, as the MISSE-8 experiment did not represent the operating conditions of the ChipSat. The two reasons are that the ChipSats were mounted, hence, the magnetotorquers could not be tested, and the communication system was not verified.

For the solar sail, things are quite different. At this early stage, no decision on the actual solar sail material, its structural elements, and the deployment mechanism have been made. Hence the TRL is set to level 2. The basic principle of a solar sail is well known and has been demonstrated in space. Hence, it has at least TRL 1. Furthermore, the basic concept of using a solar sail with a ChipSat has previously been formulated by Atchison and Peck (2010), Weis and Peck (2014). However, experimental verification of the concept has not yet been performed for a ChipSat. The results of the VVTO history assessment for the solar sail ChipSat are shown in

Table 5-7.

Table 5-7: VVTO history assessment for solar sail ChipSat

Solar sail ChipSat component	TRL
ChipSat	7
Solar sail	2

There are three approaches from the literature for aggregating TRLs. First, to choose the median TRL value, second, the lowest TRL value (Kujawski, 2013), and third, to calculate the mean value (ESA, 2008; Sauser et al., 2006). Calculating the mean value of an ordinal scale is questionable from a measurement theoretic point of view and therefore excluded. The median value can be obtained from an ordinal scale without measurement theoretic problems. ESA (2008) proposes to take the average of the component TRLs and the lowest TRL and to present both. In the following the lowest TRL is used, as only two components are considered. This results in a confidence value of close to 0: $1.17*10^{-4}$.

Fig. 5-10: MISSE-8 experiment with three ChipSats on the left side of the panel on the bottom-middle, taken from Manchester (2015, p.21)

In this section I have developed an assessment method for VVTO history. VVTO history is represented as events that can be mapped to a subjective metric that the system will function as intended in its operational environment. Two VVTO history metrics were developed. The first is defined by four ordinal confidence levels and the second is an interval scale. The ordinal confidence levels allow for an ad-hoc evaluation of VVTO history without the necessity of defining a value function. By contrast, the interval scale requires the definition of a value function. Furthermore, the application of the value function was demonstrated by an example. One limitation of the interval scale is that the scale might be different for specific technologies. The presented scale is an approximation for a generic technology. Up to this point, I have not dealt with assessing the effect of modifications on a heritage technology. This issue will be subject of the next section.

5.4 Design Heritage Assessment

A "design" in this context is the set of design drawings, specifications, etc. and other representations that are required for producing a system or any other artifact. For example, the design of a metal cylinder consists of its radius, length, and material. If the design of a system or technology is changed, its heritage is reduced, as the degree to which the design was inherited is reduced. Two basic design heritage assessment cases can be distinguished, as shown by a simple example in Fig. 5-11. In the first case an existing design is changed. On the left hand side of Fig. 5-11 component 1 is a component that has been replaced in a heritage system design. The relationships between the replaced component and other components are changed accordingly. For example, first, it needs to be verified if the new component works with the existing components. In the second, a new system is developed, using components with design heritage. On the right hand side of Fig. 5-11 three components with heritage designs are combined to form a new system design. For example, a CubeSat is developed where all components are bought off-the-shelf but integrated in a new way. All relationships between components are newly defined. Intermediate cases can be imagined where more or less relationships between components are inherited. Therefore, whether or not relationships have been inherited is important in assessing design heritage.

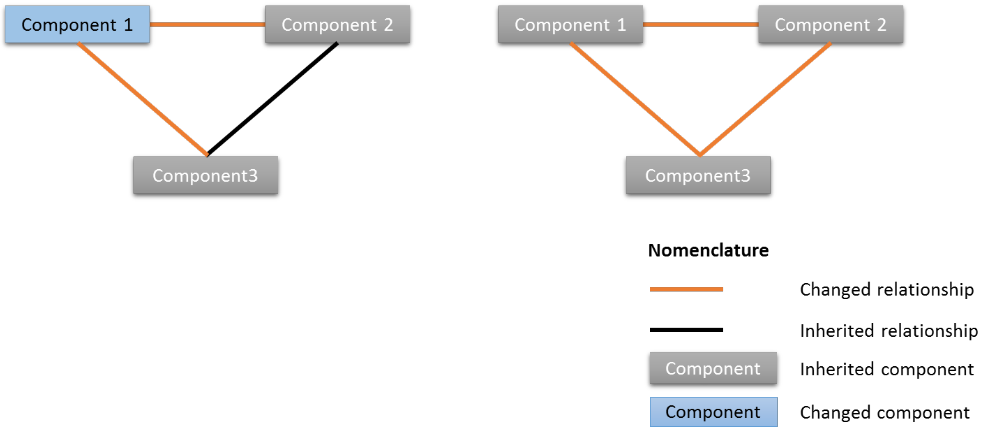


Fig. 5-11: Change of heritage system (left) and system composed of heritage components (right)

Although "design" was defined as the representations necessary for manufacturing the system, it is possible to work with more abstract representations of the design to *anticipate* and *plan* design changes. Commonly, more abstract representations are used until design drawings that can be implemented are available. For an assessment at the early stages of systems development, design descriptions are often limited to the description of the system's architecture.

In this section a method for quantifying design change is introduced. Key concepts used are "component", "relationship", and "architecture". As previously defined, a "component" is just a part of a system and a "relationship" is a relation between two components. Relationships are often defined at different degrees of detail, e.g. "electric" means that electric power is exchanged between components but it does not specify the voltage. "5V, 1.2A, AC" would be a more precise specification. In the following, the relationship between two components is considered as the more or less detailed interface specification between two components. The way how the components are related with each other via relationships is called the "architecture" of the system. In other words, an architecture encompasses the components and their relationships. Note that this is a narrow definition of "architecture", compared to the definition given in Section 2.1.3.

"Change" is defined with respect to the original system design. A changed system design is different from the original system design. The more similar a system design is to the original system design, the less it was changed. Therefore, assessing change can be interpreted as assessing similarity. Note that the opposite is not true. A system design that is different from another system design is not necessarily a changed version of that system design. An aircraft and a spacecraft are different but a spacecraft is not a changed version of an aircraft. What different types of change can be assumed in the component, relationship, architecture framework? In the following, I define a few basic forms of change and their relationship to heritage.

Requirements

In the following, a set of requirements is defined, based on common sense statements about change.

a) All other factors being equal, the more a design is changed, the lower its degree of design heritage.
b) A change can be:
    - Adding a component;
    - Removing a component;
    - Substituting a component;
    - Changing the specifications of a component with respect to function, form, and fit, e.g. material, performance range, tolerances;
    - Changing the interface between two components;

- Changing the way how two components interact.

c) No *general* importance weighting can be assigned to changes in interfaces/relationships and components, as they are domain-dependent. Therefore, equal weightings for components and interfaces/relationships are assigned a priori.

d) All other factors being equal, a system design with the same architecture (same components and same relationships) as its predecessor has the same design heritage as its predecessor.

e) A system design that does not share any component and relationship with another system design has no design heritage with respect to that system design.

With these assumptions in place, the most relevant algorithms for similarity assessment are evaluated in the following.

Similarity metrics

For a practical quantification of similarity, an algorithm for calculating the similarity value is required. Such algorithms have been developed in Condat et al. (2012), Dijkman et al. (2011, 2009), Smaling and de Weck (2007), and Suh et al. (2010). Due to the importance of similarity assessment in domains such as image recognition and neuro sciences, numerous algorithms have been developed (Gao et al., 2010). Here, I focus on algorithms that are relevant for assessing the similarity of system architectures. An overview of these algorithms is shown in Table 5-8. The Delta-DSM and matrix distance approach both stem from the domain of systems engineering. The data is represented in the form of an adjacency matrix. The matrix distance metric is based on the incidence matrix that maps functions to modules. The graph-edit similarity metric stems from computer science and is based on the steps needed for transforming one system's business process graph into another.

Table 5-8: Similarity algorithms from the literature

Reference	**Metric**	**Architecture model**	**Change types for use case in literature**	**Change metric**
(Smaling and de Weck, 2007; Suh et al., 2010)	*Delta-DSM*	Adjacency matrix	Component changes, relationship changes	Weighted sum of entries in Delta-DSM
(Condat et al., 2012)	*Matrix distance*	Incidence matrix	Difference in function to module allocation	Weighted sum of matrix distances for similarity types
(Dijkman et al., 2009)	*Graph-edit similarity*	Labeled graph	Difference in functions, events, and connectors	Weighted and normalized sum of change operations

The Delta-DSM approach from Smaling and de Weck (2007) and Suh et al. (2010) takes changes to components and to relationships between components into account. The change metric is calculated via the sum of the changed entries in the Delta-DSM. The Delta-DSM quantifies similarity by a Technology Invasiveness (TI) metric T_i for a technology concept *i*, defined as:

$$T_i = \sum_{j=1}^{8} w_j \sum_{k=1}^{N} \sum_{l=1}^{N} D_{j,k,l}^{i} \tag{47}$$

Where w_j represents weights for a certain type of relationship between components. $D_{j,k,l}^{i}$ are entries in the design structure matrix (DSM) where *i* represents a technology concept. *j* represents a type of change. *k* and *l* "collects the individual changes of each type across the system in the ΔDSM." (Smaling and de Weck, 2007) From a measurement theoretical perspective, it is not clear what the Delta-DSM is actually measuring, as the underlying empirical relationships are not properly defined. For example, what is the relationship between changed components and their relationships? Does a changed component automatically change all its relationships or is it conditional? Furthermore, the TI metric implicitly assumes that the more a system is changed, the higher the risk of performing that change.

The distance metric developed in Condat et al. (2012) is based on an incidence matrix representation of an architecture. Columns represent modules and rows functions. For two systems, the number of different entries in the matrix are counted for the respective incidence matrices. The normalized difference between the two matrices is called "architectural similarity". Apart from the similarity of two architectures, the distance between architectures is based on a matrix distance formulation, which is a generalized form of the Euclidian distance. Using such a distance measure has properties of a mathematical metric such as the triangular inequality. One shortcoming of the existing method is that the matrix entries are binary. This means that either a specific function exists on a module or it does not. Degrees of similarity of functions are not considered. The reason is that the approach was developed for the similarity assessment of avionic systems where functions are either allocated to a module or they are not. Hence, the approach in its current form does not satisfy the requirements for a general similarity measure for system architectures.

Next, similarity algorithms in domains outside systems engineering are briefly presented. In computational neurology, software engineering, and bioinformatics, graph edit distance metrics have been developed, in order to measure the distance between biological data sets (Gao et al., 2010). Such metrics are used for measuring the similarity of patterns in brain activities or protein structures. To put it simply, graph edit distance metrics are based on the number of edit operations it takes to transform one graph into another. Edit operations are elementary such as "remove node", "add node", "remove edge", "add edge". One of the challenges of graph edit distance metrics is that there is usually an infinite number of possibilities how one graph can be transformed into another, with various numbers of edit operations. Hence, graph edit distance metrics are usually based on calculating the smallest number of edit operations to transform one graph into another.

The most relevant graph edit distance metric for the context of this thesis is the "graph edit similarity metric", developed by Dijkman et al. (2009) that is used as a starting point for an architecture similarity metric. Graph edit similarity is a normalized graph edit distance.

For two labeled graphs

$$G_1 = (N_1, E_1, \tau_1, \lambda_1) \tag{48}$$

and

$$G_2 = (N_2, E_2, \tau_2, \lambda_2) \tag{49}$$

where N is a set of nodes and $E \subseteq N \times N$ a set of edges. $\tau: N \to \mathfrak{T}$ is a function that maps nodes to types and $\lambda: N \to \mathfrak{L}$ is a function that maps nodes to labels.

For two nodes

$$n_1 \in N_1 \tag{50}$$

$$n_2 \in N_2 \tag{51}$$

The edit-distance is defined as:

$$|S_n| + |S_e| + 2\sum_{(n_1,n_2)\in M} (1 - Sim(n_1, n_2)) \tag{52}$$

Where S_n is the set of all inserted and deleted nodes and S_e the set of all inserted and deleted edges. $|S_n|$ is the cardinality of the node set (number of nodes in the set) and $|S_e|$ is the cardinality of the edge set (number of edges in the set). Their component similarity function Sim is defined as:

$$Sim(n_1, n_2) = \begin{cases} 1.0 - \dfrac{ed(\lambda_1(n_1), \lambda_2(n_2))}{\max(|\lambda_1(n_1)|, |\lambda_2(n_2)|)} if\ cs(\tau_1(n_1), \tau_2(n_2)) \\ \perp\ otherwise \end{cases} \tag{53}$$

ed is the string edit distance between two node labels $\lambda_1(n_1)$ and $\lambda_2(n_2)$ which returns the minimum number of atomic string operations for transforming $\lambda_1(n_1)$ into $\lambda_2(n_2)$. The atomic string operations are inserting or deleting a character, and substituting a character for another. cs means 'can stustitute' and returns 'true' or 'false', depending on the substitutability of the type of node $\tau_1(n_1)$ by the type of node $\tau_2(n_2)$.

The graph edit similarity is defined as:

$$S_{ged}(G_1, G_2) = 1.0 - \frac{w_n f_n + w_e f_e + w_{sub} f_{sub}}{w_n + w_e + w_{sub}} \tag{54}$$

where

$$f_n = \frac{|S_n|}{|N_1| + |N_2|} \tag{55}$$

is the fraction of inserted and deleted nodes with $|N_1|$ and $|N_2|$ the number of nodes of graph 1 and 2.

f_e is the fraction of inserted and deleted edges:

$$f_e = \frac{|S_e|}{|E_1| + |E_2|} \tag{56}$$

where $|E_1|$ and $|E_2|$ are the number of edges in graph 1 and 2.

f_{sub} is based on the sum of all string edit similarity values divided by the number of substituted nodes S_{subn}.

$$f_{sub} = \frac{2\sum_{(n,m)\in M}(1 - Sim(n,m))}{S_{subn}} \tag{57}$$

For the simple case of a single substituted node, f_{sub} would return 0 if both strings are identical. If the strings are completely different, f_{sub} would be 2. It is 2 due to the factor 2. This factor is based on the interpretation that a substitution operation consists of a deletion and insertion operation. Otherwise, this factor would be unnecessary. The function Sim defines degrees of substutition.

$w \in \mathbb{R}$ are weightings.

The graph edit similarity metric has several advantages. First, it is normalized and produces similarity values within the interval [0, 1]. This allows for comparing similarity values of pairs of systems. For example, there is a system A and a changed version of system A, denoted as system A'. Furthermore, there is a system B and a changed version of system B, system B'. Using the graph edit similarity metric statements such as A and A' are more similar than B and B' are valid.

Table 5-9 shows the introduced similarity metrics and whether or not they satisfy certain criteria. The first criteria is normalization, which is required for comparing pairs of systems. The matrix distance and graph-edit similarity metrics are normalized and different similarity values can be compared. Furthermore, changes in the nodes (components) and in the edges (relationships between components) need to be represented. Only the Delta-DSM currently captures degrees of node and edge changes. Certain ground rules that define what happens to relationships when components are changed and vice versa need to be established. This depends on the specific interpretation of node and edge changes. None of the existing metrics seem to be based on adequate ground rules.

Table 5-9: Similarity metrics and their assessment criteria

Metric \ criteria	**Normalized?**	**Degrees of node / edge change?**	**Node / edge change dependencies**
Delta-DSM	No	Yes	No
Matrix distance	Yes	No	No
Graph-edit similarity	Yes	No	No

In the following, a graph-edit similarity metric is proposed with elements from the Delta-DSM metric to fill this gap. The matrix distance metric is not directly used, as it is based on an incidence matrix representation of the architecture.

The graph-edit similarity metric is modified in two ways. First, node and edge changes are represented. Second, some ground rules for dependencies between node and edge change are defined.

The current version of the graph-edit similarity metric cannot be used directly, as its similarity assessment function $Sim(n_1, n_2)$ is based on comparing the number of operations on a string to transform one string into another. For example, the string 'car' can be transformed into the string 'van' by replacing 'c' by 'v' and 'r' by 'n'. For this example, the $ed(\lambda_1(n_1), \lambda_2(n_2))$ function would return 2, as two operations are required. It is obvious that this form of node similarity assessment does not make sense in comparing components of a system architecture. Instead, a representation of different degrees of similarity of nodes and edges is desired.

First, a continuous node and edge change metric is defined. 0 means that the node or edge is not changed. 1 means that there is no resemblance between two nodes or two edges. They are completely different. All other changes to a component or relationship are rated between 0 and 1. For a better guidance, the following three component change categories are defined, shown in Table 5-10. Contrary to the five fixed values that were used in the statistical analysis in Table 4-3, ranges are assigned to each change category. Note that the classification criteria allows for a recursive similarity assessment on different hierarchical levels, as it focuses on the parts of a component and their relationships. The corresponding design heritage values are calculated by subtracting the change value from 1. Hence, I assume that the changes made to a component are proportional to the reduction of design heritage.

Table 5-10: Component change categories and their value range

Component change category	Change value range	Corresponding design heritage value range
Minor change: Component is used off-the-shelf or with minor changes to its parts and relationships.	$0 \leq D_{change} \leq 0.33$	$0.67 \leq D_{heritage} \leq 1$
Significant change: A significant fraction of parts of the component and relationships are changed or newly developed.	$0.33 < D_{change} \leq 0.67$	$0.33 \leq D_{heritage} < 0.67$
Developed from scratch: Relationships of the parts of the component and the components are newly developed.	$0.67 < D_{change} \leq 1$	$0 \leq D_{heritage} < 0.33$

However, there are cases where the component change categories might not be appropriate. For example, one key part of a component is changed and that change has a severe impact on the whole component. One way to deal with such a case is to assign a higher weighting to the change for representing its severity. A pragmatic way to estimate the weighting of changes in components is by looking at the change of key component attributes that are likely to have a large impact on the component's architecture. For example, a rocket engine's thrust chamber pressure that is increased by 1 bar can result in a large change to the engine. A value between 0 and 1 can be chosen for expressing the severity of this change. It is up to the engineer to estimate the severity of the change, as it is highly context dependent and there is no general rule to estimate it. If increasing the chamber pressure is likely to lead to a complete redesign of the engine, a value between 0.67 and 1 should be chosen.

Another case that needs to be treated is when a component design that already exists is inserted into a system design. In such a case only the relationships that relate the component design to other components of the system design are considered. The component is treated as if already being "part" of the system at the beginning, as shown in Fig. 5-12.

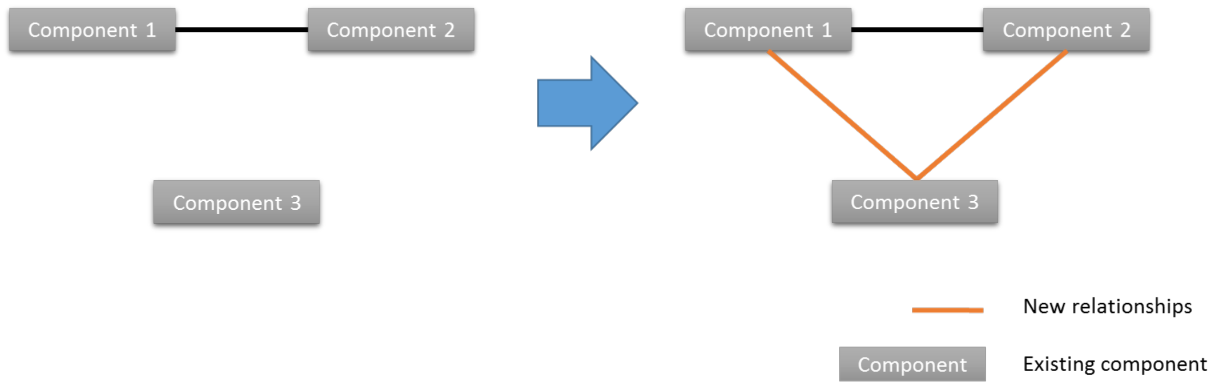


Fig. 5-12: Already existing component is integrated into a system

The next question is then, what happens if a newly developed component is brought into the system? Intuitively it would be expected that a system is changed "more" if the component did not exist before. In this case the component is treated as "developed from scratch" and the relationships between the component and other components of the system are newly introduced, as shown in Fig. 5-13. Hence, the change is larger in this case compared to the first. Components with minor and significant change that are added to a system are treated analogously.

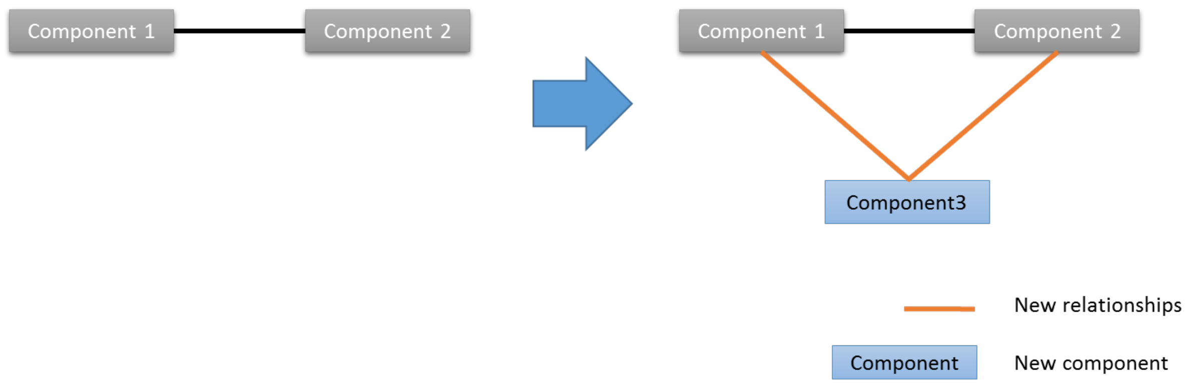


Fig. 5-13: A component developed from scratch is introduced into the system

Note that differentiating between these two cases is not only a question of semantics but leads to different similarity values, as shown in Table 5-11. The values make intuitive sense, adding a pre-existing component to a system is a less severe form of change than adding a component developed from scratch. Hence, the ground rule to treat pre-existing components as elements of the initial set of components captures this intuition.

Table 5-11: Graph-edit similarity values for the two example architectures

Case	Graph-edit distance similarity value
Existing component introduced into system	0.83
"From scratch" component introduced into system	0.7

What happens with the relationships between components when a component is changed? A component may or may not have an effect on its relationships with other components. For example, in object-oriented programming, objects communicate via interfaces and potential changes to an object are hidden behind this interface. As long as the changes do not change the behavior of the object, the relationships between components are not changed. An example where a component change changes the relationships to other components is a change to a wing of an aircraft. Although the interface between the wing and the fuselage is not changed, a larger or smaller wing changes the lift and drag of the wing which leads to different forces that act on the fuselage. Furthermore, a heavier wing might necessitate a change in the interface to the fuselage.

In the following, it is assumed a priori that a change to a component changes its relationships, as illustrated in Fig. 5-14. Furthermore, it is assumed that a change to the component leads to an equivalent change of the relationship(s). For most components changes to its parts and relationships between them result in renewed VVT activities for integrating the component into the system. Therefore, a change of 0.5 of a component leads to a change of 0.5 of the relationships between the component and other components. In case these assumptions do not apply to the system at hand, appropriate values for the relationship change can be introduced.

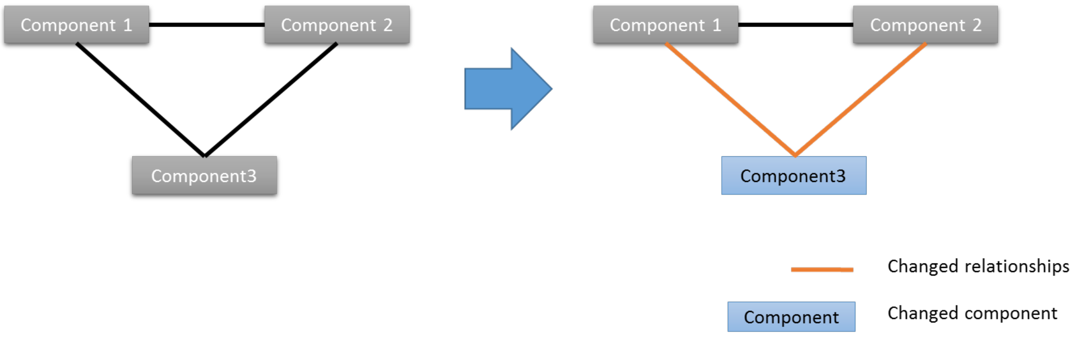


Fig. 5-14: Default change of relationships when component is changed

What if a relationship is impacted by the change of two components? Should the change value for each of the changed components be summed up or should one out of the two change values be chosen? Let us take two components and a relationship between the two components. With the default assumption that the relationship change is the same as component change, a change in one component of 0.6 would lead to a relationship change of 0.6. Now, it is assumed that both components are changed. One has a change value of 0.5 and the other a change value of 0.6. Summing up these values would lead to a relationship change of 1.1. However, introducing a new component into a system with a new relationship results in a relationship change of 1. It is unclear why changing two components should lead to a higher change value than introducing a new relationship. Thus, instead of summing up, the two component changes are compared and the largest change value of the two components is used. In the example, this would be 0.6.

The resulting equation for similarity is shown in the following:

For two labeled graphs

$$G_{sys\_0} = (N_0, E_o, \tau_0, \lambda_0) \tag{58}$$

and

$$G_{sys\_1} = (N_1, E_1, \tau_1, \lambda_1) \tag{59}$$

where N_0 represents a set of components of system 0 and N_1 represents a set of components of system 1, which is the changed system 0. $\tau: N \to \mathfrak{T}$ is a function that maps nodes to types and $\lambda: E \to \mathfrak{L}$ is a function that maps edges to types. N is a set of nodes and $E \subseteq N \times N \times \mathfrak{L}$ a set of edges. Note that the edge set is no longer defined on the Cartesian product of the node set alone but also on the set of edge types. A pair of nodes can be connected by one edge of a certain and several edges of different types. The maximum number of edges between nodes is the number of edge types in $\mathfrak{L}$. Extending the original graph-edit similarity metric, types for edges are introduced as different types of interfaces / relationships that need to be modeled. Similar to Smaling and de Weck (2007) four types of interfaces / relationships between components are used: physical connection, mass flow, energy flow, and information flow.

The graph-edit similarity metric of two systems G_{sys_0} and G_{sys_1} is defined as:

$$S_{ged}\left(G_{sys\_0}, G_{sys\_1}\right) = 1.0 - \frac{w_c f_c + w_r f_r}{w_c + w_r} \tag{60}$$

where

$$f_c = \frac{\sum_{i=1}^{m} D_{ci} S_{ci}}{|N_0| + |N_1|} \tag{61}$$

$$f_r = \frac{\sum_{i=1}^{n} D_{ri} S_{ri}}{|E_0| + |E_1|} \tag{62}$$

D_c and D_r are component and relationship change degrees, where

$$D_c \in [0,1] \quad (63)$$

$$D_r \in [0,1] \quad (64)$$

w are weightings with

$$0 \leq w \leq 1 \quad (65)$$

and

$$w_c + w_r = 1 \quad (66)$$

By default the weightings 0.5 are used for w_c and w_r but other weightings can be used when considered appropriate. Furthermore, a summary of the ground rules is given that were introduced before:

- *Rule 1:* When a change operation S_{ci} is performed on a component i with a change degree of D_{ci}, all associated edges of that component are also subject to a change degree D_{ci}. Fig. 5-15 shows an example application of rule 1. In a 3-component system, component 3 is changed with a change degree of 0.5. All relationships with component 3 are also changed with the same change degree of 0.5.

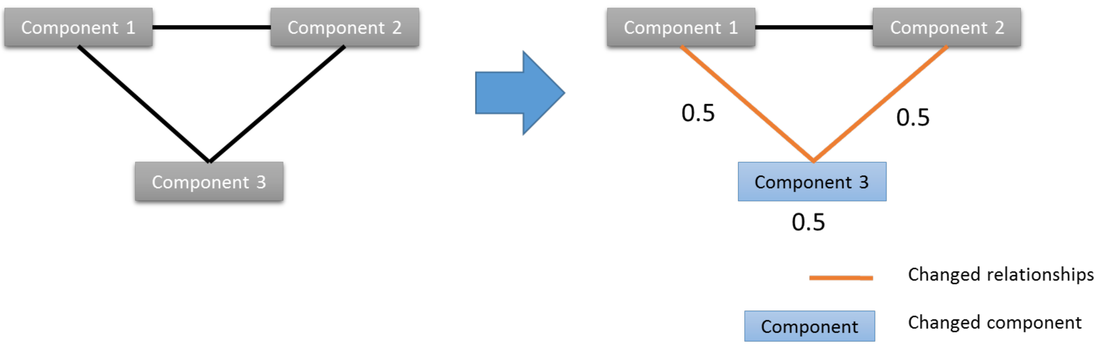


Fig. 5-15: Component change implies relationship change

- *Rule 2:* If two components i and j, where $i \neq j$, linked via a relationship are changed, the larger change degree of the two components is selected for the relationship change degree D_r. Fig. 5-16 illustrates this rule by an example. Component 1 is changed by 0.7 and component 3 by 0.5. By rule 1, all relationships to a changed component are changed to the same degree as the changed component. In the case of the relationship between component 2 and 3 this results in a change of 0.5. In the case of the relationship between component 1 and 2, this results in a change of 0.7. For the relationship between component 1 and 3, rule 2 applies. As component 1 is changed 0.7 and component 3 0.5, the larger change degree is selected, which is 0.7. Hence, the relationship between component 1 and 3 has a change degree of 0.7.

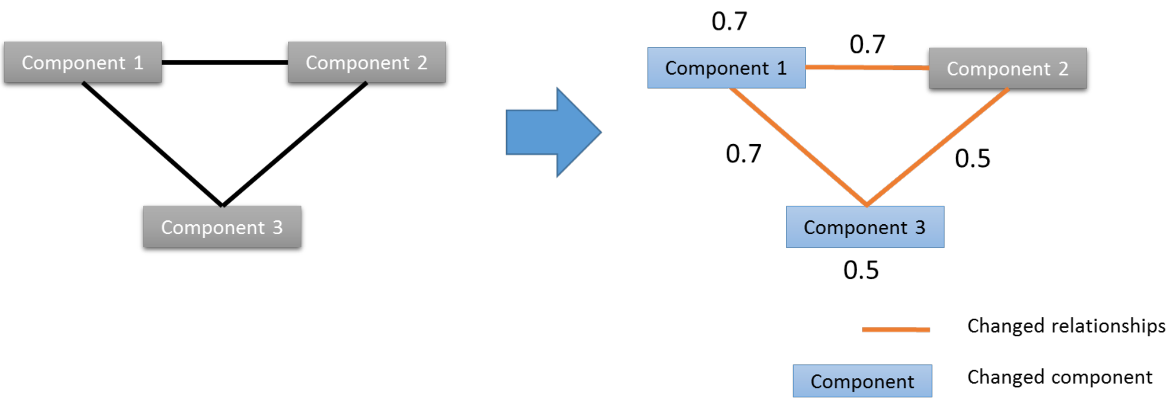


Fig. 5-16: The larger component change propagates to the relationship change

In the next step it is assessed if the newly developed graph-edit similarity metric satisfies some properties. The first property is normalization. The value of the similarity metric is expected to be between 0 and 1. The next property is that removing all edges leads to a similarity value of 0.5 if the weighting for nodes and edges is 0.5. This property makes intuitive sense if it is reversed. To a set of components relationships are added. Intuitively, the similarity between the set of components and the components with relationships should be higher than if all components are developed from scratch, including all the relationships between them. On the other hand, removing all components from a system should automatically lead to the removal of their relationships. The similarity between a system with components and without should be 0. Another property is related to the substitution of relationships. Again, the question is if the subtraction of a relationships counts as two operations. First, the removal of the prior relationship. Second, the introduction of the new relationship. In the following, I decide against this interpretation and consider a substitution as a single operation. The reason is that it is difficult to find a proper interpretation for removing a relationship. Thinking about a relationship as an interaction or interface between two components, removing a relationship would just be to leave the existing specification of the relationships as it is and just designing a new relationship. Hence, substitution is treated as introducing a new relationship. Finally, a trivial property is that a system that is not changed in its components and relationships has the similarity metric value 1.

Table 5-12: Requirements verification for metric

Property	**Result for graph edit similarity metric**	**Has property?**	**Interpretation**
Normalized between 0 and 1 for graphs	$0 \leq S_{ged}(G_1, G_2) \leq 1$	yes	
0.5 if all edges are removed	0.5	yes	All relationships are removed
0 if all nodes are removed	0	yes	All components removed
0 if all nodes are replaced	0	yes	All components replaced
0.5 if all edges are replaced	0.5	yes	All relationships replaced
1 if no changes occur in nodes and edges	1	yes	No change to relationships and components

As the use of the graph-edit similarity metric requires a substantial effort to create the DSMs, an alternative design heritage metric is proposed. The metric allows for a quick assessment of design heritage, based on the results of the design heritage categories from the statistical analysis in Chapter 4. The basic idea is to map the design heritage categories to the interval scale of the fine-grained design heritage metric. Using the sample from Chapter 4, the mean value and standard deviation of the fine-grained design heritage metric is calculated for each category. The results are shown in Table 5-13. For estimating the design heritage, an appropriate design heritage category is selected, for example, category 1. The corresponding design heritage value is 0.56. As only few components are based on heritage designs, the value is discounted by 0.2, resulting in a design heritage value of 0.36. Hence, subjective adjustment to the mean value can be made. As the standard deviation indicates, large variations in the mean values are possible, in particular for category 1. Note that category 4 has the smallest standard deviation.

An obvious argument against using this mapping are the large uncertainties associated with it. However, I still argue that the mean values allow for reflecting the non-linear character of the design heritage with respect to the categories, which would be lost when only categories or an ordinal scale are used.

Table 5-13: Design heritage categories mapped to fine-grained design heritage metric

Category	Design heritage description for spacecraft	Design heritage description for launcher	Corresponding fine-grained metric range min / max from sample	Mean value from sample	Standard deviation
0	New development	New development	0 – 0.2	***0.17***	0.15
1	Heritage components but no heritage subsystem	Heritage components but no heritage stage	0.05 – 0.85	***0.56***	0.24
2	Heritage subsystem(s)	One heritage stage or modified heritage stages	0.25 – 0.9	***0.58***	0.17
3	Heritage bus	Heritage stages	0.2 – 0.98	***0.61***	0.18
4	Carbon copy	Carbon copy	0.85 – 1	***0.95***	0.09

Application example: ChipSat

As an application example, the design heritage of four system designs are assessed: a ChipSat, a ChipSat with a solar sail, and a PocketQube with laser that propels a ChipSat with a solar sail. A PocketQube is a femto-satellite with about one-eigths to one-fourth the mass of a CubeSat (1.33kg). The idea is to equip either a PocketQube or CubeSat with a small laser emitter that is able to propel the ChipSat with the solar sail, as shown in Fig. 5-17. Such a mission could demonstrate the feasibility of laser sail propulsion.

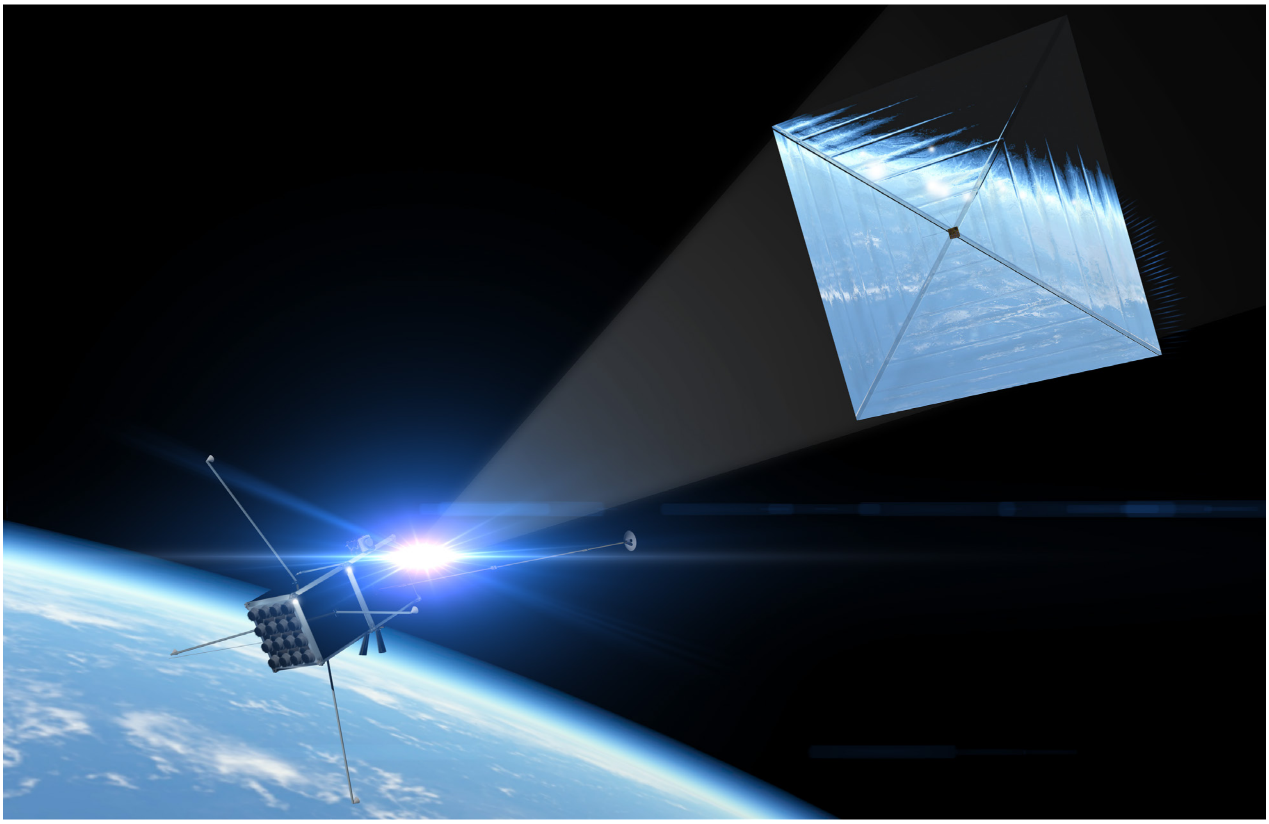


Fig. 5-17: CubeSat-based laser sail demonstration mission (Image courtesy: Adrian Mann)

There are two approaches for conducting the assessment. The first approach is to use the design heritage categories. The second, detailed approach is to model the architecture of the systems and to use the graph-edit similarity metric.

For the design heritage categories, each of the system concepts is put into one of the categories. Using the mean values from Table 5-13 yields the values in Table 5-14.

Table 5-14: Design heritage category metric values for small satellite system concepts

	Design heritage category	**Corresponding design heritage [0,1]**
ChipSat	4	0.95
ChipSat with solar sail	2	0.58
PocketQube with laser sail	1	0.56
CubeSat with laser sail	2	0.58

Next, these values are compared to the values yielded with the graph-edit similarity metric. The results for the graph-edit similarity metric are shown in Table 5-15. The values are mostly lower than for the design heritage categories. However, the values remain within the range of minimum and maximum value from the sample used for determining the mean values. The values obtained via the graph-edit similarity metric are more accurate, as the system is represented at a more detailed level.

Table 5-15: Graph-edit similarity metric values for small satellite system concepts

	Graph-edit similarity value for design heritage
ChipSat	1
ChipSat with solar sail	0.25
PocketQube with laser sail ChipSat	0.17
CubeSat with laser sail ChipSat	0.31

5.5 Technological Capability Assessment

Technological capability measurement deals with the measurement of the capabilities that are associated with a certain technology. These capabilities are often organizational capabilities, e.g. of component technology suppliers or the system integrator. A technological capability is measured via the availability of its constituting knowledge, resources, and its maturity. However, especially when technologies and systems are developed, the development itself is rarely repeated. Instead, new technologies and systems are developed from existing knowledge and resources. The ability of an actor to acquire an ability was defined previously as "potentiality". The AD² methodology by Bilbro (2008) provides difficulty levels for potentialities. In the following, we adapt the AD² aproach for capability and potentiality assessment. For this purpose, the AD² approach is simplified by combining the criteria into one single metric.

In general, the more similar a needed capability is to the existing capability, the lower the development risk. For example, modifying an existing system design requires in-depth knowledge of the design. If this knowledge has been lost, it will be difficult for the organization to modify the design without facing challenges. Developing a technology that is outside of the existing knowledge base is more risky than adopting a technology to a new context. In such a case, knowledge is lacking and has yet to be developed. Depending on how far outside of the organization's experience base the technology is, the more or less risky the development.

Assessing the maturity of a capability is important, as capability maturity is usually related to the repeatability of a process and its quality. An organization may have developed a certain technology once but if the processes were ad-hoc and knowledge was not captured, it is unclear if the organization would be capable of repeating the process. Maturity is particularly relevant for manufacturing capabilities, as repeatability is essential for meeting quality standards.

Several capability metrics are proposed for each of the technological capability types defined in 3.2.1 but are slightly modified:

- *Technology development and systems engineering capability metric:* The capability of a prime contractor or supplier to develop a technology or system in a context.
- *Manufacturing capability metric:* The capability of physically implementing a system in a context.
- *Client-supplier capability metric:* The capability of client and supplier or partners to work together in a context.
- *Operational capability metric:* The capability to operate a system in a specific environment and context.

As capabilities by definition cannot be directly observed, indicators have to be constructed. Possible indicators are for example:

- Technology development and systems engineering capability:
    - Similar systems developed in the past;
    - Experience in developing technologies that have been outside the organization's experience base;
    - Existence of resources that embody the knowledge that forms the basis of a capability, e.g. skilled personnel, tools, data bases;
    - Existence of resources such as equipment and materials that are necessary for development;
    - Existence of roles within an organization that perform activities required for a certain capability.
- Production / manufacturing capabilities:
    - Instances of the manufactured system;
    - Existence of physical assets that embody the knowledge that form the basis of the capability, e.g. production line, facility, personnel, equipment, tools, data bases;
    - Achieved quality standards, e.g. manufacturing tolerances, manufacturing variance, number of deficient products.
- Customer - supplier relationship capabilities:
    - Past compliance and conformity with customer requirements;
    - Personal relationships between customer and supplier;
    - Past alignment or misalignment of working culture;
    - Past customer satisfaction;
    - Trust;
    - Alignment of objectives.

- Operational capabilities:
    - Experience with operating similar systems;
    - Existence of assets that embody the knowledge, e.g. operations manuals, personnel.

Another crucial question is, how capabilities can be assessed at an early stage of systems development, when the prime contractor and suppliers have not yet been selected. Usually they are selected after the initial proposal phase, notably during Phase B (Interview I19). Still, I argue that capability assessment is possible at an early stage, as for most space technologies the number of contractors is rather limited, in some cases even unique. There are also cases where a preferred supplier for a technology already exists (Interview I19). Hence, a preliminary list of potential suppliers for key technologies can be established. In case a preferred supplier exists, its capability is assessed first. In case there are several suppliers for one technology, a worst and best case assessment could be performed. A more exhaustive approach would be to perform a full-factorial combinatorial assessment of supplier capabilities.

Next, I present the concrete metric values for each of the capability categories. Table 5-16 shows capability metric values for technology development and systems engineering capabilities with their respective numerical values. The indicated value range for each category provides ample leeway for expert judgement. The highest values are assigned if a similar technology has been developed by the organization. More specifically, this means that the class of technology is the same, for example a rocket engine, rocket launcher, or satellite. It depends on the objectives of the analysis how broad or narrow the technology class is defined. A narrow definition would be "F-1 rocket engine". A broader definition would be "small satellite" or "satellite". Furthermore, the performance range, quality and reliability have to be similar. Again, it depends on the objectives of the assessment how narrow or broad these are defined and where to put the emphasis. For small satellites, "reliability" could indicate how many satellites the organization has produced actually worked as intended in space. That performance would be considered nominal. It is therefore not enough to be able to develop a similar technology which has inferior performance characteristics. Similar quality and reliability means that the technology is capable of satisfying customer and stakeholder needs and requirements and is as reliable as the technology with which it is compared. This category corresponds to the AD^2 levels 1 to 4 (Bilbro, 2008).

The next lower similarity level indicates that the class of technology must be similar but the performance, quality, and reliability may differ. Depending on how much they differ, values between 0.9 and 0.5 can be chosen. The application of the technology also needs to be similar. A change in the application context often renders previous knowledge useless. For example, the use of avionic units from aeronautics for space applications was challenged, as the design knowledge was not easily transferrable to the space context (Goodman, 2002). This category corresponds to the AD^2 level 5 (Bilbro, 2008).

The next lower level indicates that the technology class may differ but some of the capabilities used are similar to the technology with which it is compared. Such a case would be the development of the NK-9 and NK-15 rocket engines by the Kuznetsov Design Bureau, which had only experience in developing jet engines (Harford, 1997). Jet engines and rocket engines share related components such as turbopumps and combustion chambers. However, the requirements for these components differ significantly. Depending on the level of similarity of the capabilities, values between 0.5 to 0.2 can be selected. This category corresponds to the AD^2 levels 6 to 8 (Bilbro, 2008).

Finally, if the capabilities related to a technology have only marginal or no similarity with the technology to which they are compared, values between 0.2 and 0 are chosen. This is particularly the case when the technology is outside of the experience base of the organization. This category corresponds to the AD^2 level of 9 (Bilbro, 2008).

Note that all categories define criteria related to capability and potentiality. The capability is represented by the list of resources. The maturity of the capability with respect to the new technology is represented by the questions pertaining to the similarity of the technology to previously developed technologies. If the technology is different, the question is how far it is within or outside the experience base. This question pertains to potentiality. In other words, the resources are enabling factors for the capability, as without them the capability would not exist. Maturity and potentiality can be understood as the performance of the capability. Whenever resources are not available, the capability metric value drops to the range of the lowest category.

Table 5-16: Technology development & systems engineering capability similarity metric

Technology development / systems engineering capability categories	Values for capability C
- A similar technology has been developed by the organization. - The class of technology, its application, performance range, quality and reliability are similar. - The technology is within the experience base of the organization. All of the following conditions must be true: - Data and documentation exists - Access to skilled key personnel that is the same as for the previous development - Proven development processes exist. - Proven development methods, tools, and models exist.	$0.9 < C_{dev} \leq 1.0$
- A similar technology has been developed by the organization. - The class of technology has to be similar, as well as its application. - The performance range, quality and reliability may differ. - The technology is within the experience base of the organization. All of the following conditions must be true: - Data and documentation exists - Access to skilled key personnel that is the same as for the previous development - Proven development processes exist. - Proven development methods, tools, and models exist.	$0.5 < C_{dev} \leq 0.9$
- A technology based on similar capabilities has been developed. - The class of technology is different, e.g. jet engine versus rocket engine. - The technology or parts of the technology are outside the experience base of the organization. All of the following conditions must be true: - Data and documentation exists - Access to skilled key personnel that is the same as for the previous development - Proven development processes exist. - Proven development methods, tools, and models exist.	$0.2 < C_{dev} \leq 0.5$
One or more of the following conditions are true: - Marginal to no capability similarity. - The technology is significantly outside of the experience base of the organization.	$0 \leq C_{dev} \leq 0.2$

Besides development and systems engineering capabilities, a metric for manufacturing capabilities is introduced, as shown in Table 5-17. Development and systems engineering and manufacturing capabilities are considered independently, as often, once serial production has started, development and systems engineering capabilities are reduced and reallocated. In such a case, assessing the development and systems engineering capabilities is less important than the manufacturing capabilities. For defining adequate levels of manufacturing capability, the best case is a running production line. A lower level of similarity would be a production line that has been recently shut down. According to Birkler et al., (1993) manufacturing capabilities can usually be easily reconstituted between 1 and 2 years after they have been shut down. After this period, capabilities decay exponentially. Although their sample is taken from military airplanes, I assume that this finding is also valid for other types of systems. Alternatively, if the manufacturing capability is based on state of the art or is an industry standard, the capability can usually be easily acquired or found with other suppliers. For example, the capability of manufacturing on-demand PCBs for electronic components is widespread and various suppliers have this capability. For a production line that has been shut down more than 1-2 years ago, values between 0.5 and 0.2 are assigned. The significantly lower value than the first two captegories reflects the exponential decay. Note that according to Birkler et al., (1993) such production lines can still be reconstituted with less effort than developing a production line from scratch. If no prior experience with producing the technology exists, lower values between 0.2 and 0 are assigned, depending on how far existing manufacturing capabilities can be transferred.

Table 5-17: Manufacturing capability similarity metric

Manufacturing capability categories	Values
- Running production line for technology All of the following conditions must be true: - Data and documentation exists - Skilled key personnel is available and the same as for previous technology - Proven manufacturing processes are available - Proven development methods and tools are available - Required materials are available - Manufacturing equipment, software, and metrology is available - Manufacturing tooling is available - Manufacturing facilities are available	$0.9 < C_{prod} \leq 1.0$
- Production line shut down 1-2 years ago or state of the art / state of experience All of the following conditions must be true: - Skilled key personnel can be reactivated - Data and documentation exists - Proven manufacturing processes are available - Proven development methods and tools are available - Required materials are available - Manufacturing equipment, software, and metrology is available - Manufacturing tooling is available - Manufacturing facilities are available	$0.5 < C_{prod} \leq 0.9$
One of the following conditions is true: - No running production line since several years; - Similar production line for different technology running and can be adapted. All of the following conditions must be true for a similar technology: - Key personnel available or can be reactivated - Data and documentation exists - Proven manufacturing processes exist and can be adapted. - Proven development methods and tools exist and can be adapted. - Required materials are available - Manufacturing equipment, software, and metrology exists - Manufacturing tooling exists - Manufacturing facilities exist	$0.2 < C_{prod} \leq 0.5$
One or more of the following conditions are true: - No experience in producing the technology - Data and documentation does not exists - Key personnel is not available or cannot be easily reactivated - Proven manufacturing processes do not exist or difficult to adapt them. - Proven development methods and tools exist do not exist. - Required materials are not available - Required manufacturing equipment, software, and metrology does not exist - Manufacturing tooling does not exist - Manufacturing facilities do not exist	$0 \leq C_{prod} \leq 0.2$

The supplier relationship capability metric captures the transferability and maturity of the relationship between customer and supplier. Examples for customer – supplier relationships are the relationship between governmental agency and prime contractor, product developer and user, and system developer and component suppliers. Across different industries, managing this relationship is challenging and building up a good working relationship takes lots of efforts, in particular for R&D. For successfully commissioning a product, the acquirer often needs to possess knowledge about formulating proper requirements and how to interact with the supplier. The proposed customer-supplier relationship capability metric is shown in Table 5-18. At the highest level, it is assumed that a customer – supplier relationship has been successfully maintained over several projects. The next category is a relationship where a single project has been successfully conducted between customer and supplier. For the third category, the customer and supplier have worked on a trial project to test the supplier's capabilities. In the forth category, no prior project has been realized between the specific customer and supplier.

The focus is on the relationship between a specific customer and a specific supplier and the effort each side has put into establishing this relationship. In other words, the metric captures how far the relationship between customer and supplier is proven. It does not take the specific capabilities of the supplier into account, such as for development and manufacturing.

Table 5-18: Customer-supplier relationships capability metric

Customer-supplier relationship capability categories	**Value**
Repeatedly successful customer – supplier relationship	$0.9 < C_{sup} \leq 1.0$
Customer and supplier have engaged in a successful relationship	$0.2 < C_{sup} \leq 0.9$
Customer and supplier have engaged in a successful trial relationship, e.g. trial project, trial order.	$0.1 < C_{sup} \leq 0.2$
No prior project has been realized successfully	$C_{sup} = 0$

The supplier relationship capability metric is also agnostic with respect to the nature of the relationship. It is clear that ordering a standard component from a vendor is a much simpler relationship than commissioning a novel technology. In the second case, much more complex interactions between customer and supplier occur. However, what is important with respect to the heritage metric is the confidence in the repeatability of the successful relationship. For example, if a supplier has delivered on time and within budget once and has experienced a schedule overrun the second time, it may be concluded that there is a likelihood that the next project suffers from a schedule overrun. Note that such a judgement needs to be calibrated with respect to the nature of the project. For example, developing a technology that is outside the experience base of the supplier is likely to result in schedule and cost overruns.

Table 5-19 shows the operational capability metric. The resources in each category have been adapted from the AD² levels in Bilbro (2008). Similar to other capability metrics, the capability is represented by the list of resources. The maturity of the capability with respect to the system that is operated is represented by the questions pertaining to the similarity of the system (similar or different) and how far the operations process is formalized and repeatable. The question about the similarity of the system pertains to potentiality. In other words, the resources are enabling factors for the capability, as without them the capability would not exist. Maturity and potentiality can be understood as the performance of the capability. As with previous capability metrics, whenever resources are not available, the lowest capability category is selected.

Table 5-19: Operational capability metric

Operational capability categories	**Value**
Repeatedly successful experience with operating a similar system. Operations process is formalized and is repeatable. All of the following conditions must be true for a similar technology: - Facilities are available - Data and documentation exists - Infrastructure is available, e.g. IT-infrastructure for data storage - Operations systems are available, e.g. antennae, command and control - Skilled key personnel is available	$0.9 < C_{op} \leq 1$
Successful experience with operating a similar system but knowledge is not captured formally. Operations is performed ad-hoc. All of the following conditions must be true for a similar technology: - Facilities are available - Data and documentation exists - Infrastructure is available, e.g. IT-infrastructure for data storage - Operations systems are available, e.g. antennae, command and control - Skilled key personnel is available	$0.2 < C_{op} \leq 0.9$
Successful experience with operating a different system but part of the knowledge can be transferred, e.g. driving a small van versus driving a truck. Knowledge is not captured formally. Operations is performed ad-hoc. All of the following conditions must be true for a similar technology: - Facilities are available - Data and documentation exists - Infrastructure is available, e.g. IT-infrastructure for data storage - Operations systems are available, e.g. antennae, command and control - Skilled key personnel is available	$0.1 < C_{op} \leq 0.2$
No prior experience with operating a similar system or one or more of the following elements is lacking: - Facilities - Data and documentation - Infrastructure, e.g. IT-infrastructure for data storage - Operations systems, e.g. antennae, command and control - Skilled key personnel	$C_{op} = 0$

Technological capability measurement faces the same difficulties as measuring VVTO heritage:

- Aggregation problem: How do individual capabilities contribute to the capability they are part of?
- How to compare capabilities that are orthogonal? For example, technology A has mature manufacturing capabilities associated with it but immature operational capabilities. Technology B by contrast has immature manufacturing capabilities associated with it but mature operational capabilities. Which technology has more mature capabilities?

For aggregating capabilities, the arithmetic mean is used, where C_i is a capability under consideration. The sum is divided by the number of capabilities.

$$C = \frac{1}{n}\sum_{i=1}^{n} C_i \tag{67}$$

I argue that an additive approach captures the degree of existing capabilities with respect to the desired capability level. The desired capability level depends on the assessment context. For example, for assessing if the manufacturing capabilities for a technology still exist, the desired capability level is the previously observed capability level when the production line was running. For assessing the capability for developing a new system, the presence of each component technology's capability is assessed, the prime contractor to supplier relationships etc. and compared to the situation where all capabilities are present for developing the system. For the formal preconditions for using the weighted sum in multi-criteria decision making see Bouyssou et al. (2006, pp.209-214). One criteria of using the weighted sum is the use of an interval scale. This criteria is satisfied, as the capability metric is defined on an interval scale. Note that the capability metric can be aggregated from lower-level capabilities recursively.

It is also clear that capability assessment is associated with a considerable subjective component, as it is not directly observable and what is observable can be interpreted in different ways. For example, the well-established Capability Maturity Metric (CMM) carries a considerable subjective element with it, as many assessment criteria ask for subjective value judgements (Interview I9) (CMMI Product Team, 2006).

Similar to the VVTO assessment and design heritage assessment, capability assessment is concerned with what is inherited (existing capabilities) and how it applies to the new context (new technology development). Hence, the basic underlying logic is similar for all three heritage technology elements.

Application example: ChipSat

Within the context of a space non-profit organization, a capabilitiy analysis was performed for four space systems: a ChipSat, a ChipSat with sail, and a combined PocketQube or CubeSat with a laser and a ChipSat with sail. These space systems form a space program, going from less complex to more complex missions in order to successively develop organizational capabilities. The CubeSat with laser illuminates another spacecraft, the ChipSat with sail, with its laser beam. It thereby generates a thrust force that accelerates the ChipSat with sail. The mission is intended to demonstrate laser sail propulsion in space, as shown in Fig. 5-17. This example not only deals with the elicitation of capabilities, but also with how to aggregate them. Aggregation takes place on a subsystem level for the ChipSat with solar sail and at a system level for the CubeSat and the ChipSat with solar sail.

For eliciting capabilities, the components the systems are composed of and their prospective suppliers are taken into consideration. Data on their prospective capabilities is gathered via interviewing subjects that were either directly in contact with the supplier or were otherwise directly in contact with the products they offer. In cases where products could be bought off-the-shelf, the manufacturing capability is considered. In cases such as the solar sail, where no off-the-shelf components exist, it is hypothesized which organization would most likely develop the technology. Note that at this point no options for organizations are included in the matrix. However, this could be easily done by creating several matrices that represent different combinations of organizations.

The resulting list of capabilities is presented in the capability – system matrix in Table 5-20.The matrix maps capabilities to system concepts. The ChipSat was previously developed by university D and the capability is owned by a former PhD student of the university who is now working for university B. The system has already been developed and the required capabilities are rather in the area of manufacturing the system. For the solar sail ChipSat the situation is different, as the system has not been developed yet. It is assumed that the ChipSat itself can be procured from university B. The solar sail needs to be developed by university A. Furthermore, the system needs to be integrated and tested. It is also assumed that this is done by university A. For the PocketQube, it is assumed that most parts are newly developed. There are only a few providers of components for the PocketQube standard and it is assumed that the relatively low complexity of the components allows for a rather quick development of the components. Only structural parts are procured. Furthermore, once electronic components are developed, they need to be manufactured externally. For the CubeSat the situation is different. Numerous suppliers for CubeSat components exist and the main challenge is rather integrating the components into a functioning system.

Table 5-20: Capability - system matrix for different small space system concepts

Capability	Capability type	Capability owner	ChipSat	ChipSat with solar sail	Laser PocketQube and ChipSat with solar sail	Laser CubeSat and ChipSat with solar sail
Chipsat AIT	Manufacturing	University B	X			
Chipsat VVT	Development	University B	X			
Chipsat parts procurement	Customer – supplier	University B	X			
Solar Chipsat AIT	Manufacturing	University A		X	X	X
Solar Chipsat VVT	Development	University A		X	X	X
Solar Chipsat parts procurement	Customer – supplier	University A		X	X	X
Solar Chipsat development	Development	University A		X	X	X
Solar sail supplier relationship to customer	Customer – supplier	University A, University B		X	X	X
PocketQube AIT	Manufacturing	University A			X	
PocketQube VVT	Development	University A			X	
PocketQube parts procurement	Customer – supplier	University A			X	
PocketQube development	Development	University A			X	
PocketQube Supplier relationship to customer	Customer – supplier	University A, supplier C			X	
Complete system development	Development	University A			X	X
Complete system AIT	Development	University A			X	X
Complete system VVT	Development	University A			X	X
CubeSat AIT	Manufacturing	University A				X
CubeSat VVT	Development	University A				X
CubeSat parts procurement	Manufacturing	University A				X
CubeSat development	Development	University A				X
CubeSat Supplier relationship to customer	Manufacturing	University A, various suppliers				X

Once the capabilities have been identified and mapped to the system concepts, the values for the capability metric are estimated. Table 5-21 shows the metric values for each of capabilities for the respective system. The arithmetic average is taken. It can be seen that the average capability value for the last three systems are similar. Developing a CubeSat with a laser system is more difficult than doing it for a PocketQube as it is assumed that the laser system for the

PocketQube will be limited to the bare minimum. The CubeSat allows for a more sophisticated laser system. However, the higher complexity of the system is counterbalanced by the large number of available component suppliers that are lacking for the PocketQube. The resulting capability value for the CubeSat is therefore similar to the value for the PocketQube.

Table 5-21: Capability - system matrix for different small space system concepts with capability metric value

Capability	**Capability type**	**Capability owner**	**ChipSat**	**ChipSat with solar sail**	**Laser PocketQube and ChipSat with solar sail**	**Laser CubeSat and ChipSat with solar sail**
Chipsat AIT	Manufacturing	University B	0.4			
Chipsat VVT	Development	University B	0.8			
Chipsat parts procurement	Customer – supplier	University B	0.8			
Solar Chipsat AIT	Manufacturing	University A		0.4	0.4	0.4
Solar Chipsat VVT	Development	University A		0.4	0.4	0.4
Solar Chipsat parts procurement	Customer – supplier	University A		0.8	0.8	0.8
Solar Chipsat development	Development	University A		0.4	0.4	0.4
Solar sail supplier relationship to customer	Customer – supplier	University A, University B		0	0	0
PocketQube AIT	Manufacturing	University A			0.4	
PocketQube VVT	Development	University A			0.6	
PocketQube parts procurement	Customer – supplier	University A			0.8	
PocketQube development	Development	University A			0.4	
PocketQube Supplier relationship to customer	Customer – supplier	University A, supplier C			0	
Complete system development	Development	University A			0.3	0.2
Complete system AIT	Development	University A			0.3	0.3
Complete system VVT	Development	University A			0.3	0.3
CubeSat AIT	Manufacturing	University A				0.3
CubeSat VVT	Development	University A				0.3
CubeSat parts procurement	Manufacturing	University A				0.8
CubeSat development	Development	University A				0.4
CubeSat Supplier relationship to customer	Manufacturing	University A, various suppliers				0.5
Sum divided by total number:			**0.67**	**0.4**	**0.39**	**0.39**

5.6 Heritage Metric

In the previous sections, I have developed heritage metrics for VVTO history, design heritage, and capability heritage. I argued that these three elements can be used for representing the heritage of a technology. The remaining question is how the three metrics can be aggregated into a single heritage metric. Four aggregation approaches were presented in Section 2.5.4: Additive, multiplicative, mixed, and the Choquet integral. One of the challenges of using these three heritage elements for constructing a heritage metric is that they are not independent. For example, a modification in the design of a system usually leads to a lower TRL and consequently a lower VVTO history value. Moreover, a change in an organization's capability may have an impact on TRL and the design. In order to treat interactions between variables rigorously, the Choquet integral is selected, as it allows for formally representing these interactions, as shown in equation (69). For capturing the strength of interactions, I rely on common sense and an expert survey presented in Section 5.7.

What are reasonable weightings for the heritage metric elements and subsets of the metric elements? A number of plausibility conditions are used for checking which option makes sense or not. As mentioned in Section 2.5.1 there is no general consensus on how heritage can be aggregated. Hence, the search for a "one fits all" metric is futile until there is a consensus on what empirical relations heritage needs to satisfy. Nevertheless, I perform a first step towards finding a consensus interpretation of heritage technology by conducting two surveys in Section 5.7. In the following, I state some key assumptions I have made for the metric. Other interpretations of "heritage" are likely leading to different metrics.

The first question is if the heritage metric should become 0 if one of the elements is 0.

- <u>Design heritage metric:</u> If two systems have completely different designs, it can still be assumed that the organization developing the system has capabilities that are common to both systems. Hence, it is expected that the heritage metric value is not 0.
- <u>VVTO metric:</u> The heritage metric value can be larger than 0 even if the VVTO history is 0. For example, a component that has been extensively used on Earth is used for a space application. A concrete case would be the use of a smartphone as an element of a CubeSat, called "PhoneSat" (Salas et al., 2014). With respect to the space application, the component has no VVTO history. In practice, the TRL of the technology is not 0, as the smartphone has demonstrated its functionality on Earth. Hence, it should be at least considered TRL 4 (demonstration of full technology in a laboratory environment). The design and organizational capabilities would be inherited but what remains to be done is the qualification program for the space environment.
- <u>Capability metric:</u> A case where the capability is 0 is a design that has been shelved and nobody in the organization has participated in its development or has knowledge related to it. However, it can still be argued that the heritage of this technology is not 0, as the design exists and might even be proven.

As argued, setting one of the elements of the heritage metric to 0 does not necessarily lead to a value of 0 for the heritage metric.

The next question is how these results change if one, two, or all three metric elements are set to 0. These cases commonly do not occur in practice but it helps to explore what happens to the metric when such extreme values are plugged in. For this purpose, the power set of the three heritage variables is generated with their extreme values 0 and 1. The results are shown in Table 5-22, along with the expected value for the heritage metric. For the case where all values are 0, the heritage metric should yield 0. This would be the case where a technology does not exist. If all variables are 1, the metric should yield 1. This would be a full heritage technology. The extreme technology resurrection case would occur when there is a fully proven design of a system but the organization has no experience with the technology. One can argue that in such a case the technology still has heritage. For the case where VVTO is 1 and capability is 1, no corresponding real-world use case could be found. VVTO seems to depend on the existence of a design. A fully proven technology without a design is not possible in practice. Moreover, it is possible to generalize and say that whenever design heritage is 0, VVTO should also be 0. Case E is present when a design is completely unproven. An example is a technology that was used in a completely different environment than the new environment. F is the case when a capability exists for a similar class of technology. This means that the organization can develop a similar technology, although its design is completely different. In such a case, it can be argued that the technological heritage is not 0. G would be the case when, for example, a design is discovered in an archive but the technology is neither proven nor capabilities for its development exist. H is undefined as is D. A technology cannot be proven without a design or a capability.

Table 5-22: Combinations of extreme values for heritage metric elements

Identifier	Use case	VVTO	Design	Capability	Expected heritage metric value
A	No technology	0	0	0	0
B	Full heritage technology	1	1	1	1
C	Technology resurrection	1	1	0	> 0
D	No case identified	1	0	1	Not defined
E	New, untested design or existing design for new context	0	1	1	> 0
F	Experience with same class of system	0	0	1	> 0
G	Unproven design	0	1	0	> 0
H	No case identified	1	0	0	Not defined

A remaining question is, how to assign weightings to the heritage metric. This can be done by defining a preference order for the cases shown in Table 5-22.

$$B \succ E \succ C \succ F \succ G \succ A \tag{68}$$

B and A are the extreme points of the heritage metric. G is considered to have a higher heritage than A but a lower heritage than C, as C is a proven design. The preference order between C and F is controversial. It can well be argued that a proven technology with no capability should have a lower heritage metric value than an existing capability without a proven design. It could be equally argued that C has a higher heritage than F, as by using a proven design, a capability could be developed quicker. It depends on either putting an emphasis on proven design or technological capability. Running trial evaluations yield the result that putting an emphasis on capability leads to situations where modified designs end up with almost the same heritage as developing a new design. For both cases the capability stays constant. Such a situation is considered undesirable, as there should be a strong distinction between a design modification and a new design. Some empirical evidence will be presented in Section 5.7 that supports this ranking.

For determining the coefficients of the Choquet integral, the methods presented in Grabisch et al. (2008) were used, along with the Kappalab R package. The underlying mathematical problem is constraint satisfaction. The constraints are defined by the previously presented heritage preference order. The goal is to find Choquet integral coefficients that result in heritage metric values that satisfy the preference order. As the solution is not unique, additional constraints were introduced, in order to arrive at coefficient values that reflect engineering judgement. Notably, it was assumed that the drop in heritage metric values in the preference order (68) is roughly exponential. This was suggested by one of the experts. The coefficient values were applied to the heritage technology cases in Table 5-22 as a sanity check. Whenever the coefficients violated a sanity check, the coefficients were reiterated. The resulting coefficient values, using the Heuristic Least Mean Squares method, are depicted in Table 5-23.

Table 5-23: Choquet integral coefficients and their values

Symbol	Explanation	Value
μ_1	{VVTO history}	0.20
μ_2	{Design heritage}	0.10
μ_3	{Technological capability}	0.20
μ_{12}	{VVTO history, design heritage }	0.40
μ_{13}	{VVTO history, technological capability}	0.60
μ_{23}	{Design heritage, technological capability }	0.50
I_{12}	Interaction index VVTO history and design heritage	0.10
I_{13}	Interaction index VVTO history and technological capability	0.20
I_{23}	Interaction index design heritage and technological capability	0.20
v_1	Importance index VVTO history	0.35
v_2	Importance index design heritage	0.25
v_3	Importance index technological capability	0.40

The positive values for I_{ij} indicate that significantly different values in x_i result in a penalty on the Choquet integral value. For the interpretation of the Choquet integral, the reader is referred to Section 2.5.4. The resulting Choquet integral for the 2-additive capacity with criteria x_1 (VVTO), x_2 (design), and x_3 (capability) is:

$$C_\mu(x) = v_1 x_1 + v_2 x_2 + v_3 x_3 - \frac{1}{2}(I_{12}|x_1 - x_2| + I_{13}|x_1 - x_3| + I_{23}|x_2 - x_3|) \quad (69)$$

$$= 0.35x_1 + 0.25x_2 + 0.4x_3 - \frac{1}{2}(0.1|x_1 - x_2| + 0.2|x_1 - x_3| + 0.2|x_2 - x_3|) \quad (70)$$

Using these weightings and calculating the heritage metric values for the previously presented extreme cases in Table 5-22 leads to Table 5-24. The calculated values correspond to the ranking for the extreme cases.

Table 5-24: Heritage metric values for extreme cases

Identifier	Use case	Heritage metric value
A	No technology	0
B	Full heritage technology	1.0
C	Technology resurrection	0.40
E	New, untested design or existing design for new context	0.50
F	Experience with same class of system	0.20
G	Unproven design	0.10

Table 5-25 shows the sensitivities for the three variables. The heritage metric is most sensitive to certain TRL values underlying the VVTO metric. The maximum difference of the heritage metric occurs between TRL 6 and 7 with a respective difference of maximally 17%. The values for design heritage and technological capability are lower, with 8% or less difference in the heritage metric for a difference of 20% in design heritage and less than 12% difference in the heritage metric for a difference of 20% in the technological capability metric.

Table 5-25: Sensitivity of heritage metric with respect to variables

Variable	**Sensitivity**
Difference in one TRL	$\leq 17\%$ (maximum between TRL 6 and 7)
20% design heritage difference	$\leq 8\%$
20% technological capability difference	$\leq 12\%$

Furthermore, it is recommended that the value for design heritage is discounted in case the heritage metric is calculated at an early stage of development. The discount harkens back to the notion of "divergence" introduced by Boas (2008). "Divergence" is the difference between planned commonality and actually realized commonality. I argue that unplanned modifications frequently take place when heritage technologies are used. Hence, a sensitivity analysis should be performed. The following rule-of-thumb values are recommended for obtaining conservative values for design heritage. The design heritage is multiplied by the following factors to obtain a conservative value:

- Factor 0.5 for assessments in Phase pre-0, 0, and A;
- Factor 0.7 for assessments in Phase B;
- Factor 0.9 for assessments in Phase C and later.

Example for heritage technology metric calculation

Using the heritage metric, the heritage technology values are calculated for the running example of small spacecraft concepts. The results are shown in Table 5-26. The ChipSat has a drastically higher technology heritage value than the other system concepts. The main reason is that the system has already been developed. It has already been tested in space, although not under operational conditions (Manchester, 2015). Furthermore, the design is unchanged or subject to minor change due to potential electronic component obsolescence. The capability metric value is impacted by the lacking customer – supplier relationship between the non-profit and the university that has developed the ChipSat. The ChipSat with solar sail and the combined ChipSat with solar sail and laser CubeSat have about the same technology heritage value, mainly as they use about the same amount of existing components and are based on the same degree of existing capabilities. The PocketQube with the ChipSat has the lowest heritage value of all system concepts, as not a lot of components are available off-the-shelf for the PocketQube.

Table 5-26: Heritage technology values for small spacecraft concepts

	VVTO metric values	**Design heritage value**	**Capability metric values**	**Heritage metric value**
ChipSat	0.65	1	0.67	0.69
ChipSat with solar sail	0.02	0.25	0.4	0.17
PocketQube with laser sail ChipSat	0.02	0.17	0.39	0.14
CubeSat with laser sail ChipSat	0.02	0.31	0.39	0.18

5.7 Heritage Metric Validation

The heritage metric is validated by three approaches. First, the heritage metric and its elements are validated with respect to a set of heritage metric requirements in the form of empirical relations. Second, the heritage metric is validated with respect to completeness. Completeness means that all relevant factors contributing to heritage are captured by the metric. Third, the heritage metric is applied to historical heritage technology cases, both successful and unsuccessful in order to assess, if the metric returns meaningful results. It is clear that such an a posteriori assessment is subject to the hindsight bias (Christensen-Szalanski and Willham, 1991). Nevertheless, this approach can be used as another way for validating the plausibility of the heritage metric.

Table 5-27 shows the heritage metric empirical relations and how far the heritage metric in its current form satisfies them. Many empirical relations are quite obvious and one would expect that a metric would naturally satisfy them. However, there are many cases where metrics do not satisfy empirical relations, for example complexity metrics (Fenton, 1994). Therefore, verifying the heritage metric against empirical relations is an important step.

Regarding the VVTO empirical relations, it is evident that the TRL-based function satisfies the relation, as the function is monotonically increasing. The context sensitivity of VVTO history is respected by using TRL, as the TRL scale includes various contextual elements. Regarding design modifications, the graph-edit similarity metric returns smaller similarity values when more elements of the design are modified. As a TRL-based function for VVTO history is used that is monotonically increasing, a higher TRL also leads to more heritage.

For modifications, the more a technology is modified, the lower its degree of heritage. The graph-edit similarity metric satisfies this criteria, as the similarity value is calculated on the basis of changed components and relationships. A design that is identical to another system’s design results in the design heritage value of 1. If no component in a design corresponds to the components of another, the design heritage is 0.

Regarding technological capabilities, the manufacturing capability levels assign a higher value to a system in production than a technology out of production.

Regarding composition and aggregation relations, aggregating design heritage from a component to a system level is possible with the design heritage metric. Furthermore, the design heritage can be determined recursively by decomposing the components into parts etc. The design heritage metric also allows for a recursive assessment of design heritage. Changes to a component also lead to a change in the system due to the graph-edit similarity approach, as the similarity value is calculated on the basis of component changes and relationship changes.

Finally, the metric can be used at different levels of the system. For example, the VVTO history metric is always applied to the hierarchical level under consideration. The design heritage and capability metric can be recursively aggregated to different hierarchical levels.

Table 5-27: Heritage metric requirements verification

Requirement	**Satisfied (yes/no)**
VVTO empirical relations	
More successful VVTO history is better than less	Yes
Context-sensitivity of VVTO history	Yes
All other factors being equal, higher maturity / readiness (TRL) means more heritage.	Yes
Design modification empirical relations	
All other factors being equal, the more a design is modified, the lower the technology’s degree of heritage	Yes
All other factors being equal, a technology with the same design as its predecessor has the same heritage as its predecessor.	Yes
A design that does not share any component with another design has no design heritage with respect to this technology.	Yes

Technological capability empirical relations	
A system in production is better than out of production:	Yes
Composition and aggregation empirical relations	
A system can consist of components	Yes
Changes to a component change the system	Yes
The heritage metric can be aggregated	No
General requirements	
The metric can be applied to different hierarchical levels of the system	Yes

One shortcoming of the current metric is that the heritage metric value itself cannot be simply aggregated from lower to higher levels in a system hierarchy. Such an approach would presuppose that a proper aggregation function for the VVTO history metric exists. However, as the specific VVTO history metric used in this thesis is based on TRL, it follows that TRLs need to be aggregated. In the absence of a general TRL aggregation function that satisfies plausibility criteria mentioned in the literature (Kujawski, 2013; Olechowski et al., 2015), there is consequently currently no adequate aggregation function for the heritage metric.

To conclude, the heritage metric satisfies some basic empirical relations regarding heritage technologies. I do not claim that the presented list of empirical relations is complete. Therefore, I propose that future work could aim at eliciting more empirical relations.

Completeness: Expert validation

For assessing completeness and usability of the heritage metric, the metric was validated by experts from industry or a space agency. A short document with the elements of the metric along with an explanation was sent to 10 experts from the space domain. The document can be found in Appendix B.4. 5 experts responded, giving detailed oral or written comments on the metric. The experts' characteristics are shown in Table 5-28. Each of them has worked at least 5 years in the area of space systems development and was regularly involved in heritage technology assessments.

Table 5-28: Characteristics of respondends of heritage metric survey

Expert ID	Current and former positions	Organization in which experience accumlated [industry / governmental agency]	Type of system developed [institutional / commercial]	Experience [years]
1	Technical lead design, manufacture, testing, integration, operation	Industry	Commercial, institutional	22
2	Procurement, subcontractor management, project manager	Industry	Institutional	5
3	Systems engineer	Industry	Institutional	7
4	Deputy department manager, study manager	Governmental agency	Institutional	26
5	Study manager	Industry	Institutional	7

The experts generally agreed that the three metric elements VVTO history, design, and capabilities are necessary and sufficient elements for assessing heritage technologies.

Expert 1 remarked that the aggregation approach of the heritage metric depends on the objective of using the heritage metric. Another area of debate was how static or dynamic heritage should be. For example, if the manufacturing capabilities for a technology are suddenly no longer accessible due to export restrictions between Russia and the USA, is the heritage associated with that technology lost?

Expert 2 remarked that assessing capabilities is likely to be the most challenging part as potential suppliers usually do not provide accurate information about their capabilities. A detailed on-site supplier audit over several days is usually not feasible due to a lack of time. The effective use of the metric in industry would depend on its simplicity of use (clear definition of application steps) and its expressivity (how does the metric aid decision making and is it validated).

To summarize, the completeness of the metric's primary variables was confirmed by all experts.

Preference ordering: Expert validation

To validate the preference ordering, a survey was sent to eight experts of which five responded. The criteria for expert selection are similar to the ones for validating heritage metric completeness. Two of the five experts that responded have also previously validated heritage metric completeness. Three of the returned surveys were accompanied by explanations for the reasoning behind the ranking. The experts were tasked to rank six technologies with respect to their heritage, shown in Table 5-29. The ranks are 1 for the highest heritage and 6 for the lowest.

Table 5-29: Technology options for heritage technology preference ordering survey

Technology option	**Correspondence to heritage extreme cases in Table 5-24**
a) Technology is proven (high TRL), based on an existing design, and the supplier has experience with this technology.	B
b) Technology has a low TRL, is based on a new design, and the supplier has no previous experience with the technology.	A
c) Technology has a low TRL (e.g. was used in a different application before), is based on an existing design, and the supplier has experience with the technology (e.g. COTS component that needs to be qualified for space).	E
d) Technology is proven (high TRL), based on an existing design, but the supplier has lost his competency in developing / producing it.	C
e) Technology has a low TRL, based on an existing design, and the supplier has lost its competency in developing / producing it.	G
f) The supplier has experience with the same class of or a similar technology but needs to develop the new technology (develop a design and do all the verification, validation, and testing).	F

The results from the survey are shown in Table 5-30, where the entries indicate the number of times a rank for a technology option was selected. One respondent assigned two alternative rankings. Both were taken into consideration, although this double-counts the rankings of the respondent. It is clear that option a) and b) are the best and worse. These two options also serve as a sanity check of the results. All respondend ranked a) first and b) last. Technology e) is ranked 5th. f) is ranked 4th. However, for technologies c), d) the results are not robust. Comments from a respondent indicate that supplier experience seems to be a very important factor. This is also confirmed by the low rank of e). Therefore, before more extensive data is collected, d) is ranked 3rd and c) 2nd.

Table 5-30: Survey results for technology preference ordering: Technology option vs. rank

Technology option \ rank	1	2	3	4	5	6
a)	5	0	0	0	0	0
b)	0	0	0	0	0	5
c)	0	2	2	1	0	0
d)	0	1	3	1	0	0
e)	0	0	0	2	3	0
f)	0	1	2	1	1	0

The resulting ranking corresponds to the ranking presented in Equation (68):

$$a) \succ c) \succ d) \succ f) \succ e) \succ b) \qquad (71)$$

It is clear that the small number of respondents reduces the value of the results. However, one of the conclusions is that the previously hypothesized higher importance of organizational capabilities compared to the importance of design and VVTO history seems to be confirmed.

Application to existing heritage technologies

The heritage metric was applied to two well-known cases where heritage technologies were wrongly used. The first case is the Ariane 5 Flight 501 case. The results are shown in Table 5-31. To the author's knowledge, the inertial guidance system has been used without any design modifications. Neither the hardware nor the software was modified. Hence, the value for the design heritage metric is set to 1. Furthermore, the investigation report does not mention any lost capabilities on the side of the supplier. Therefore, the value for the capabilities was also set to 1. As the system into which the component was integrated significantly differed from the Ariane 4, the applicability of the VVTO history needs to be significantly reduced. A priori, the component is assigned a TRL of 5. As a result, the heritage metric yields 0.55, which indicates that the heritage is rather low and extensive VVT activities need to be envisaged. According to the investigation report, a lack of VVT activities has lead to the failure of the Ariane 5 Flight 501 (Lions, 1996).

Table 5-31: Case 1 - Ariane 5 Flight 501 inertial guidance system

Heritage aspect	**Ariane 5 inertial guidance system**	**Comment**
VVTO	0.1	Flown on Ariane 4 but changed environment / system: TRL 5
Design	1	No noted changes
Systems engineering capability	1	No noted changes
Tech. Capability components	1	No noted changes
Heritage metric value	***0.55***	

The second case is the Mars Observer bus system. The results are shown in Table 5-32. The bus design was previously used for LEO spacecraft. Hence, its VVTO history is only partly applicable to a mission to Mars. Furthermore, the spacecraft architecture has significantly changed. As a result, a TRL of 5 is selected. Moreover, the spacecraft bus was subject to design modifications that significantly reduced its design heritage. However, I take the perspective from the beginning of the development program, where it was probably expected that the bus can be used as-is. Hence, I classify the bus according to Table 5-13 into design heritage category 3 and assign its mean value of 0.61 to it. As a result, the Mars Observer bus has a heritage value of 0.43, which is fairly low, compared to a proven technology that is used off-the-shelf.

Table 5-32: Case 2 - Mars Observer bus

Heritage aspect	Mars Observer	Comment
VVTO	0.1	Flown on LEO missions but integrated into different system and different environment: TRL 5
Design	0.61	Reuse of bus system design
Capability	1	No changes assumed
Heritage metric value	***0.43***	

It is clear that one of the limitations of a retrospective analysis is hindsight bias (Christensen-Szalanski and Willham, 1991; Kamin and Rachlinski, 1995). As it is known that these systems failed due to heritage-related problems, I know what to look for a posteriori. If I would not know about the later source of failure, analysis would probably lead to different results. Nevertheless, the metric returns a low heritage value compared to a value of 1 for flight-proven technology that is operated in the same environment and context.

5.8 Summary and Conclusions

A methodology for assessing heritage technologies has been presented, comprising an assessment process, tools, and a metric for quantifying heritage. The metric is verified against its requirements, validated by experts, and applied to historical cases of heritage technologies. Although the development of a metric is impeded by the lack of a general consensus on what heritage technologies are, a first step towards such a definition has been made by conducting two surveys for validating the metric. In the next chapter, the methodology will be validated by applying it to a wide range of space systems.

6 Case Studies

The case study methodology is used for validating the heritage assessment methodology. The main purpose of the case studies is to validate the heritage assessment methodology internally and externally. Yin (2013) served as a basis for conducting case study research. The issue of validating design theories and methodologies in general has been considered in (Blessing and Chakrabarti, 2009; Frey and Dym, 2006; Olewnik and Lewis, 2005, 2003; Pedersen and Emblemsvag, 2000).

The validation approach for design methods was adopted from Pedersen and Emblemsvag (2000). Internal validation seeks to validate the internal logic of the methodology, for example, the logical order of assessment steps. External validation seeks to validate the usability of the methodology with respect to a purpose. Note that this is a pragmatic definition of validity, which is also a criterion for the validity of decision making methods in general (Keeney and Winterfeldt, 2007). From a pragmatist point of view, a theoretically perfect but practically useless methodology would not be considered valid. Frey and Dym (2006) emphasize the importance of practical, real-world impact of design methods in contrast to consistent logical and mathematical foundations of a method. A similar point was made by the architect Christopher Alexander in his seminal book "Notes on the Synthesis of Form", where he stresses the practical applicability and usefulness of design methods (Alexander, 1964).

However, if real-world impact is the measure, Blessing and Chakrabarti (2009) note that in most cases validation by real-world applications is not within the scope of a PhD thesis, as such a validation is often only possible after years of application and diffusion of the methodology in industry. Notable examples for validation using a large sample of industrial applications are Hannay et al. (2009) and Mohagheghi et al. (2013) for the software engineering methods of pair programming and model-driven engineering. Within the product development domain, Kuppuraju et al., (1985) demonstrated that Quality Function Deployment (QFD) seems to have positive results on design practice. For most forms of design methodology research, validation stays at the level of individual case studies that show that the methodology can actually be applied to a design problem. The case studies presented here are no exception. All three case studies are based on available data from existing space system development programs. However, the methodology was not used within the programs. The assessment was conducted independently.

The case studies were selected with respect to the following criteria:

- *Diversity of technologies and systems:* For a methodology to be generic, it is crucial to demonstrate its applicability to various types of technologies and systems.
- *Diversity of objectives:* The methodology should support a variety of heritage-related assessment situations.

Three case studies were selected. Table 6-1 shows their classification with respect to the criteria. The CubeSat component case is a case where a decision needs to be made if an existing technology is going to be used in a new system. The technology issues to be addressed are the changes in the supporting systems, context, and environment. Further issues are obsolescence and the loss of development capability. In the case of the Ariane 5 hydraulic tank, the decision is to either *modify* an existing tank to fit a new application or to develop a new tank. The impact of the modifications on the heritage of the technology needs to be assessed. In the case of the Saturn V / SLS case study, a retired but proven system (Saturn V) is compared to a system under development that heavily relies on heritage components.

Table 6-1: Case study classification with respect to system type and complexity

System and technology type \ Objective	**Technology reuse (integration in new system, obsolescence, capability loss)**	**Technology modification vs. new technology (modification impact on heritage)**	**Technology resurrection vs. new technology (obsolescence, capability loss)**
Satellite component	CubeSat component		
Rocket launcher component		Ariane 5 hydraulic tank	
Rocket launcher			Saturn V / SLS

6.1 Small Satellite Component

The heritage assessment methodology is applied to a component of a small satellite, developed at a university department. The department plans to reuse the component in a successor satellite. The assessment focuses on modifications induced by obsolescence and comparing the component with alternatives. Furthermore, the technological capabilities related to the component are assessed.

6.1.1 Motivation and Objectives

The small satellite component under consideration is the Hard Commanding Unit (HCU) of the pico-satellite First-MOVE, depicted in Fig. 6-1. First-MOVE was developed at the Institute of Astronautics of the Technical University of Munich (TUM) between 2006 and 2013. The satellite was launched into LEO in 2013 by a Russian Dnepr launcher. End of 2013 the satellite ceased to operate, possibly due to a failure on the On-Board Data Handling (OBDH) Board. The satellite adhered to the CubeSat Standard. Among other requirements, this means that the total mass of the satellite needs to be equal to or less than 1.33kg and needs to fit into a volume of 100mm x 100mm x 113.5mm (Lee et al., 2009). The satellite was exclusively developed by graduate students of TUM.

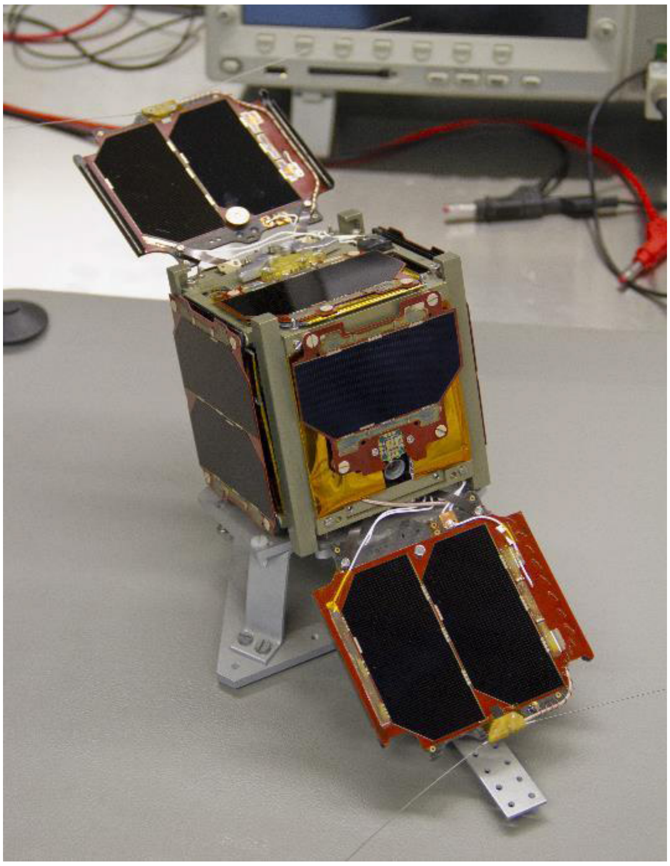


Fig. 6-1: First-MOVE satellite with deployed solar panels (Langer et al., 2015)

The HCU is mounted on the First-MOVE On-Board Data Handling (OBDH) board, shown in Fig. 6-2. The HCU is called HPC in this diagram. The HCU's main function is to reset the OBDH in case of an error, for example in case the OBDH needs a reboot. This reset is called "MC reset". Such reboots may be necessary in order to correct software errors or errors induced by the space radiation environment such as single event upsets. The reset command is sent up from a ground station, decoded by the HCU into a reset signal that is sent to the OBDH. Decoding takes place via an analogous circuit with a number of shift registers. The analog implementation of the circuit was intended to avoid the use of software and achieve a higher reliability. The HCU was developed between 2007 and 2013 in-house by graduate students, among them the author of this thesis. All parts were procured from external suppliers. The HCU was assembled, along with the OBDH at a workshop within TUM by professional printed circuit board (PCB) makers.

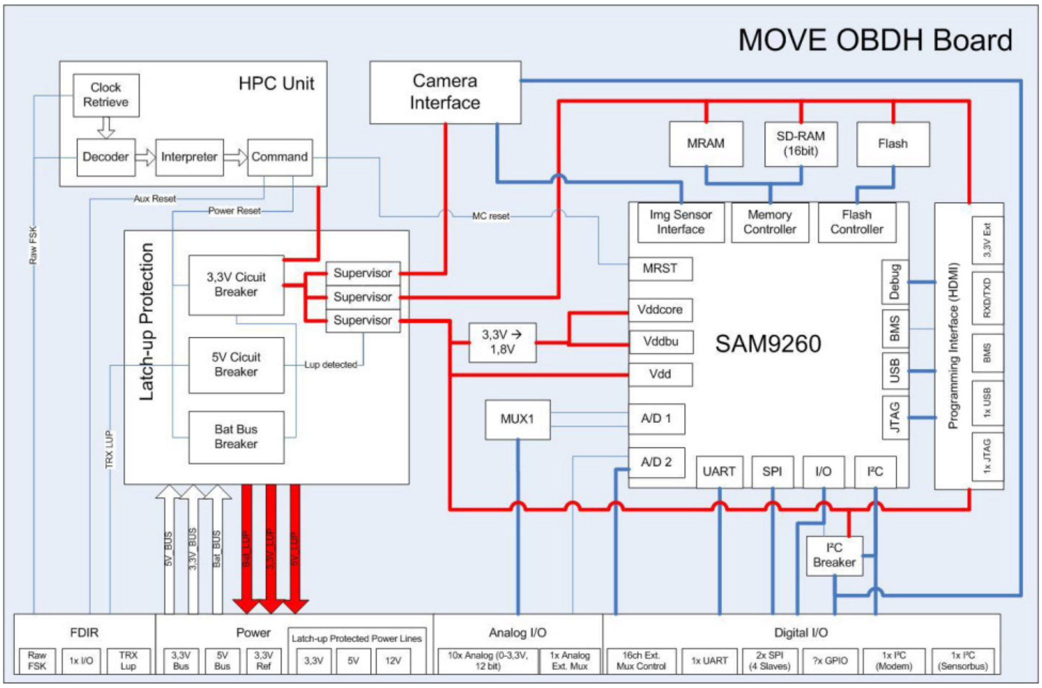


Fig. 6-2: First-MOVE OBDH Board (Institute of Astronautics, 2012)

Fig. 6-3 shows the circuit diagram for the HCU. The HCU consists of a number of shift registers that are depicted as rectangular boxes in the upper half of the figure. Connecting the shift registers in specific patterns allows for translating a raw input signal into a digital output signal. The output signal is either a soft reset or a master reset, which results in an interruption of the power supply to the OBDH.

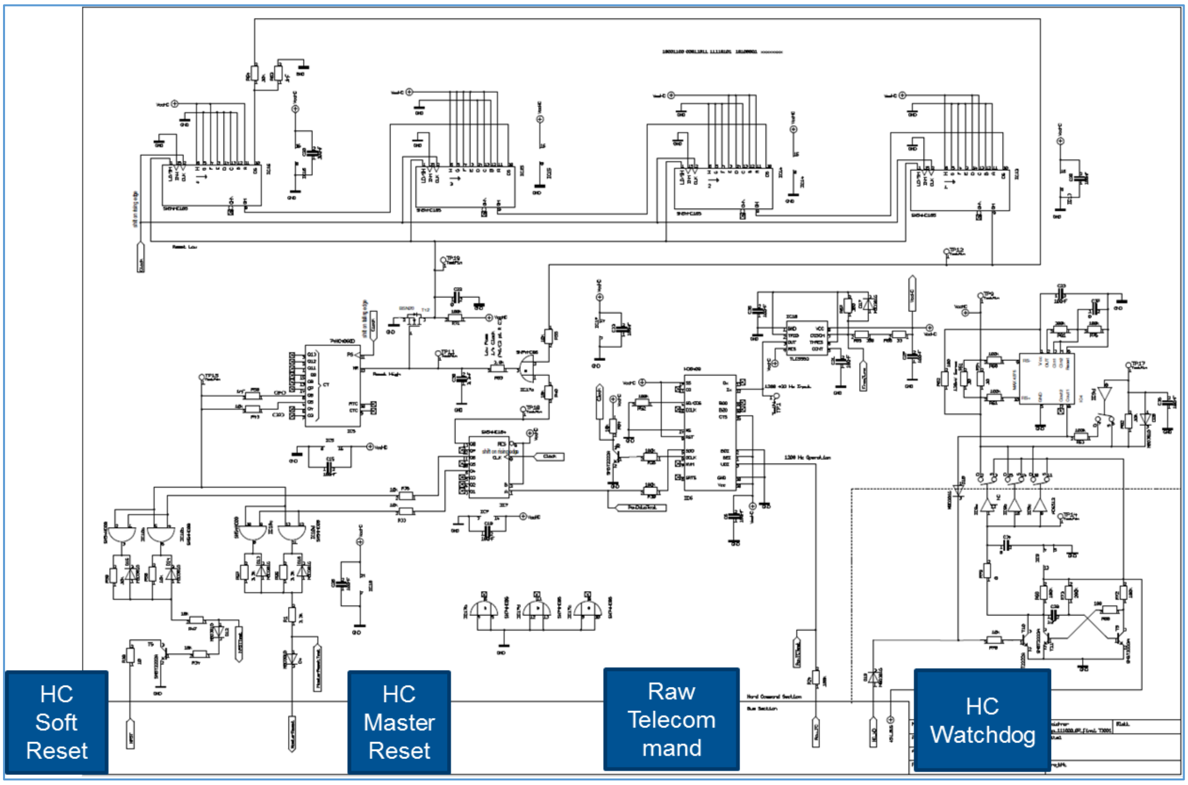


Fig. 6-3: HCU circuit diagram (Institute of Astronautics, 2012)

In 2012, the successor project to First-MOVE, MOVE 2 WARP was initiated. MOVE 2 WARP at that point was conceived as a so-called triple-unit CubeSat. It is approximately three times larger than a single-unit CubeSat such as First-MOVE. The objective of the satellite is to measure the antiproton flux in LEO (WARR, 2012). Antiprotons are a form of antimatter. The antiprotons are generated by interactions of high-energy cosmic rays with the upper layers of the atmosphere (Casolino et al., 2008; Picozza et al., 2007). Fig. 6-4 shows the MOVE 2 WARP concept in 2012. The scientific payload is deployed via a deployable boom mechanism. The purpose of the boom is to generate a wide field of view for the antiproton detectors. The OBDH along with the HCU is located in the section indicated in blue in the middle of the satellite.

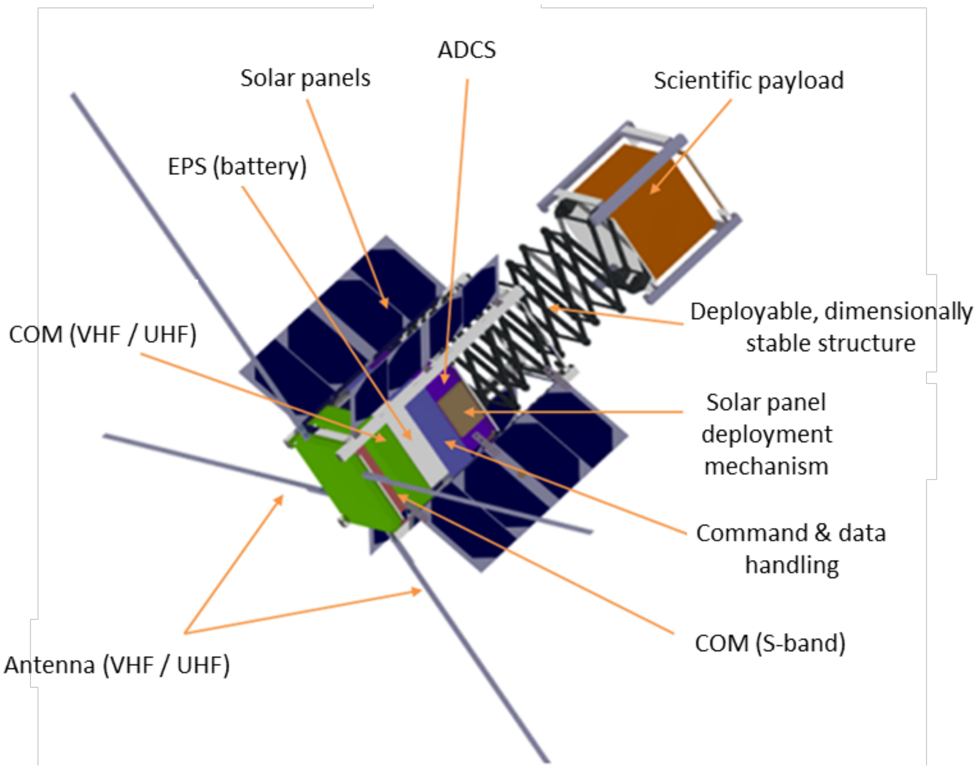


Fig. 6-4: MOVE 2 WARP concept in 2012, adapted from WARR (2012)

In this case, the main objective of using the heritage assessment methodology is to assess how far the HCU matches the requirements for MOVE 2 WARP and to assess the impact of modifications on the HCU. In parallel, alternatives for using the HCU were considered. The assessment was conducted at a point in time when the MOVE 2 WARP team prepared for the Mission Concept Review. Hence, the project was at a stage where the feasibility of the mission was assessed and different technology options were considered.

6.1.2 Defining System Functions and Performance

The HCU's value-related function is to reset the OBDH, when reset commands are received. Fig. 6-5 shows a graphical representation of the function. The HCU performs the "reset OBDH" function when the reset command is received. The OBDH's state is changed from its initial, possibly malfunctioning state into a reset state.

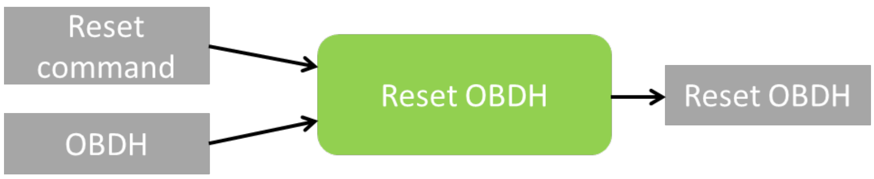


Fig. 6-5: HCU value-related function

The HCU can perform two types of resets:

- Soft reset
- Hard reset

The soft reset shuts down all running applications and clears all data from the random access memory (RAM) of the OBDH. It is similar to restarting a personal computer. Hard reset by contrast shuts down the OBDH and restores it, using the initial configurations and settings. A hard reset may address software issues, such as errors caused by updates. A hard reset is similar to formatting a personal computer.

6.1.3 Systems Under Consideration and Compliance Assessment

A compliance assessment is performed with respect to supporting systems and the changed context, in order to identify potential issues for reusing the HCU in the MOVE 2 WARP mission. In a first step, it is assessed whether the value-related function of the HCU would still deliver value in the MOVE 2 WARP spacecraft. As the main value-related operand of the function is the OBDH, any change of the OBDH may have an effect on the utility of the HCU. Indeed, one of the questions addressed by the MOVE 2 WARP team is whether or not the OBDH board should be reused. At the time when the OBDH board was developed, it was unique in its processing power and no commercially available board for CubeSats with similar performance values were available. However, in 2012, further alternative boards were available. The main factor that may render the HCU obsolete is the choice of an OBDH board other than the heritage OBDH. The HCU is integrated into the OBDH board and significant integration problems may occur in case it needs to be combined with a commercially available OBDH board. Furthermore, several OBDH boards have been developed in recent years with similar performance. Some of them are commercially available. For example, Botma (2011), Delaporte et al. (2010), Laizans et al. (2014), and Manyak (2011) present fault-tolerant on-board computers and software for CubeSats. Fault-tolerance is based on hardware, software, or FPGA. An overview of potential changes to inputs to the value-related function are shown in Table 6-2.

Table 6-2: Changes to inputs to the HCU and potential changes

Inputs to value-related function	Potential changes
Raw reset telecommand (UHF / VHF)	No changes expected
OBDH	Alternative OBDH boards with fault-tolerant architecture may render HCU obsolete.

The supporting systems that are needed for operating the OBDH are listed in Table 6-3. A potential change of the on-board power supply from 5V to, for example, 3.3V can have an impact on the on-board electronics of the HCU, leading to the relplacement of components that are no longer compatible. The raw telecommand that is sent up from a ground station needs to be within a certain data rate in order to be decodable by the HCU. A change in the data rate may render the HCU useless. As the HCU is mounted on the OBDH, a change in the OBDH structure can lead to a redesign of the HCU in order to fit on the OBDH. This could become problematic, as the space on the OBDH is in general tightly constrained.

Table 6-3: Supporting systems and their potential impact on the HCU

Interfaces with supporting systems	Potential changes
5V power supply	Different on-board power supply voltage
Raw telecommand	Uplink with a different data rate results in a change of the HCU clock.
OBDH board structure	Potentially different layout to fit changed structure.

Changes to the contextual sytems and environment are also expected, as shown in Table 6-4. First, the thermal environment of the MOVE 2 WARP satellite could be different, as the satellite uses 3-axis stabilization to point the anti-proton experiment payload. A possible implication is that the thermal environment might not be as even as in the case of the First-MOVE satellite that had no 3-axis stabilization and tumbled around one axis. Another change is expected from the flight path over the South Atlantic Anomaly, as a high rate of anti-proton flux is expected in this area. As a result, the HCU would be subject to significantly higher radiation doses than First-MOVE. This could lead to the use of specifically radiation-hardenend components. One of the problems with this approach is that the casings for the radiation-hardened integrated circuits (ICs) are larger than in the original HCU version, leading to a larger required space. As space is in general tightly constrainted on the satellite and in particular on the OBDH board, this will likely lead to a separation of the HCU from the OBDH and mounting it on the OBDH. In case radiation should indeed render the current version of the HCU obsolete, a software or FPGA-based solution is preferred.

Table 6-4: Contextual systems and environmental factors and their potential impact on the HCU

Interfaces with and constraints from contextual system / environment	**Potential changes**
MOVE 2 WARP thermal environment	No significant change expected.
Flight through South Atlantic Anomaly and resulting higher radiation dose	Use of radiation-hardened components that would increase the size of the board.

6.1.4 HCU Verification, Validation, Testing, and Operations History

Table 6-5 shows notable VVTO events for First-MOVE. The HCU has been ground tested, along with the OBDH board before being launched into space. In space, the HCU operated as intended. However, it is unclear if the HCU contributed to the OBDH error that lead to the failure of the First-MOVE mission. One hypothesis relates the mission failure to an error of one of the HCU components, due to exceeding its operational temperature range. Such an error may have lead to sending repeated reset commands to the OBDH. In such a case the OBDH would no longer be rebooted. Hence, the VVTO history of the HCU is considered only partly successful. Ground testing in the thermal-vacuum chamber confirmed its correct functionality under simulated space conditions. Furthermore, the HCU was able to perform its functionality under simulated space conditions while integrated into the satellite system.

Table 6-5: First-MOVE VVTO events

VVTO events	**Result**
Testing in First-MOVE system under simulated space environment	Successful
Operation in space in First-MOVE system	Ambiguous

Subsequent assessment of the HCU concluded that a design error cannot be excluded and additional temperature shift simulations for the HCU are necessary.

Due to these issues, the HCU needs to be requalified and is considered to be at TRL 5, leading to a VVTO history value of 0.1 with respect to the First-MOVE and MOVE 2 WARP OBDH context.

6.1.5 Design Heritage Assessment

The HCU is subject to two types of modifications. First, modifications induced by changed requirements and second, modifications induced by the obsolescence of some of its components.

Modifications from changed requirements

The main change consists in an addition of commands to the original system's specification, as listed in Table 6-6.

Table 6-6: Added functionality for modified HCU

Original set of commands	Extended set of commands
Master reset	Master reset
Latchup bridge reset	Latchup bridge reset
Microcontroller reset	Microcontroller reset
	COM reset
	Payload reset

The requested additional two commands imply that two additional code sequences need to be analogously decoded. This would lead to a reconfiguration of the circuit logic and an addition of further components. At this point, it is unclear how profound these modifications would be.

Modifications resulting from component technology obsolescence

An analysis of the HCU components showed that about 17% of the original components were no longer available, as shown in Table 6-7. Furthermore, stocks of these components were not created at the institute. Frequent obsolescence is a common phenomenon for electronic parts (Sandborn et al., 2007; Singh and Sandborn, 2006; Solomon, 2000; Stogdill, 1999).

Table 6-7: List of HCU components and their availability

HCU component type	Availability (in 2014)
74HC4060	Yes
ADG511	Yes
ADG512	Yes
ADG513	Yes
fn2951	No
MAX4373	Yes
MAX4375	Yes
SN54HC08	Yes
SN54HC165	No
SN74HC86	Yes
SN74HC164	Yes
TLC555	Yes

A rough estimate of the design change was performed (Zöllner, 2014). It is estimated that 30% of the HCU needs to be modified due to the two obsolescent components, as they play an important role on the HCU. Furthermore, further cases of obsolescence can be expected during the period from 2012 to the point where the actual flight hardware is built, leading to additional not anticipated design changes. For taking these unexpected changes into account, an additional 50% is added to the design modification value. This leads to a conservative estimate of 80% changes to the HCU, only due to obsolescence.

As a result, a design heritage value of 0.7 is selected for the nominal case, taking existing obsolescence into account, and 0.2 for the pessimistic case, taking potential future obsolescence into account.

6.1.6 Technological Capability Assessment

The technological capability assessment for the HCU is two-fold. The first is an assessment of maturity and the second the availability of knowledge and resources. Regarding maturity, the Institute of Astronautics has experience in developing the HCU throughout its whole lifecycle. However, in a university context, knowledge is often difficult to retain due to a high level of turnover among graduate students. Table 6-8 shows the resources, their status, and potential redundancies in the resources. The original designer of the HCU is still available in 2012. However, it is not clear how long this would be the case. Therefore, a back-up option should be developed with a designer who is made familiar with the HCU. Such efforts are underway. Other resources consist of the data files on which the HCU design is stored as well as additional documentation. The files are available, along with the software for executing the files. However, a proper documentation of the HCU is not available and needs to be written. The OBDH specifications that are needed for properly interfacing the HCU are also available.

Table 6-8: Availability of resources for developing a modified HCU

	Status	**Option 1**	**Option 2**
Original HCU designer	Available	Original HCU designer	Successor HCU designer
HCU board Target files	Available	Use existing files	
HCU board documentation	Does not exist	Recreate documentation via interviews	
Target software	New version	Use new version	
OBDH specs	Available		

At this stage, the capability of modifying the HCU are still retained at the Institute of Astronautics. Therefore the capability value is 1. However, this value might be impacted by the departure of the original designer of the HCU. The training of a back-up HCU designer and creating some design documentation should safeguard against a detoriation of the capability.

6.1.7 Technology Heritage Assessment

The heritage metric values for three cases are determined. The first is the nominal value for the situation as-is. The second value is the case where further obsolescence occurs until the flight hardware is developed. In the third case, further obsolescence occurs and the HCU designer departs without a proper replacement.

Table 6-9 shows the heritage metric element values and the resulting value for the heritage metric. The value is relatively low, compared to the flight-ready case of ~0.9. This is mainly due to the low VVTO value, as the HCU might not have functioned correctly in orbit.

Table 6-9: HCU heritage metric elements and heritage metric value (nominal case)

Metric	**Value**
VVTO	0.1
Design	0.7
Capability	1
Heritage metric	***0.46***

With potential future obsolescence, the value for design decreases. As a side-effect, the VVTO also decreases, as the functioning of the substituting components is no longer guaranteed. Therefore, the TRL is reduced from 5 to 4. The heritage metric of 0.27 is significantly lower than for the nominal case of 0.46.

Table 6-10: HCU heritage metric elements and heritage metric value (futher obsolescence)

Metric	**Value**
VVTO	0.02
Design	0.2
Capability	1
Heritage metric	***0.27***

In the worst case where the HCU designer departs without a successor and without leaving proper documentation, HCU development results in a new development, which is indicated by the low heritage metric value of 0.03. In such a case, no significant benefits from using the heritage component can be expected.

Table 6-11: HCU heritage metric elements and heritage metric value (further obsolescence and staff loss)

Metric	**Value**
VVTO	0.02
Design	0.2
Capability	0
Heritage metric	***0.03***

6.1.8 Conclusions

To summarize, the heritage assessment for the First-MOVE HCU showed that there are several risk factors related to the HCU. The first element of risk is a change in the OBDH design or the use of a commercially available OBDH. These changes to the OBDH could induce significant changes to the HCU and can even render it obsolete. The second risk area is the increased radiation level of the Move 2 WARP mission that could induce significant design changes. Another area of considerable risk of heritage loss due to obsolete parts and the departure of the original HCU designer. As a risk mitigation strategy, a successor has been recruited and it is planned to create a design documentation.

Applying the heritage assessment methodology to this case study demonstrated that several risk areas regarding the HCU were identified systematically. The heritage metric supported the analysis by quantifying the impact of obsolescence and loss of capabilities.

6.2 Launcher Hydraulic Tank

The heritage assessment methodology is applied to the case of a rocket launcher component. This case study demonstrates the applicability of the methodology to a technology that is modified. Data for the case study was collected by Scharringhausen (2013). Further data from Radtke (2006) and Wächter (1997) was used. The rocket launcher is the European Ariane 5 and the component the Groupe d'Activation Moteur (GAM) pressure vessel, which is a modified version of the Groupe d'Activation Tuyère (GAT) pressure vessel. Both vessels are shown in Fig. 6-6. GAM is a hydraulic liquid tank, pressurized by Helium. The hydraulic liquid is used by the actuators steering the Vulcain engine of the Ariane 5 first stage, as shown in Fig. 6-7. GAT is a high-pressure vessel. Several of these vessels are mounted on the solid rocket boosters. They supply hydraulic liquid to the actuators of the solid rocket booster nozzles. Both pressure vessels were developed and qualified by MAN Technologie AG, today MT Aerospace AG in Augsburg. They are currently producing the vessels in series. GAT is being manufactured for Airbus (formerly EADS, responsible for the boosters) in Bordeaux and GAM for Airbus in Paris (responsible for the core stage). Both vessels were developed during the 1980s, as were other components of the Ariane 5.

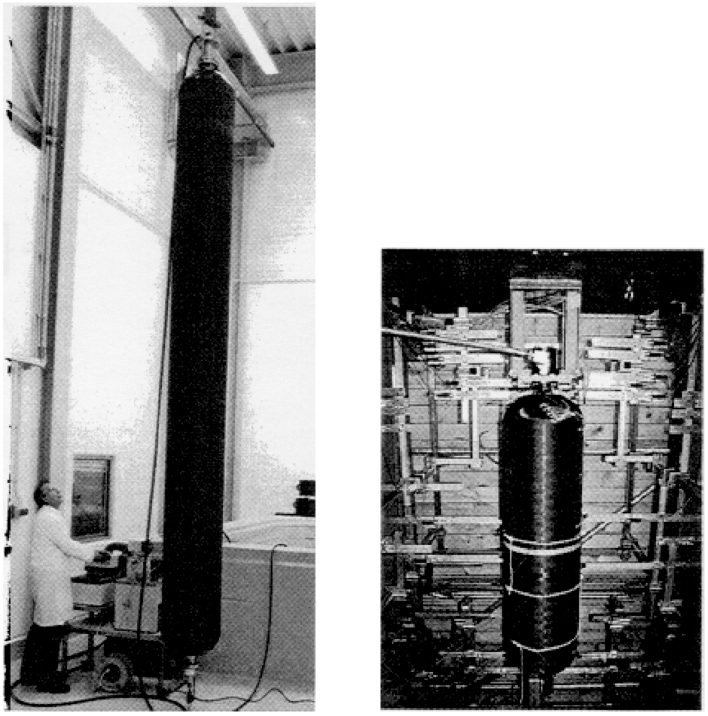


Fig. 6-6: GAT tank during acceptance testing and GAM tank during pressure test (Wächter, 1997)

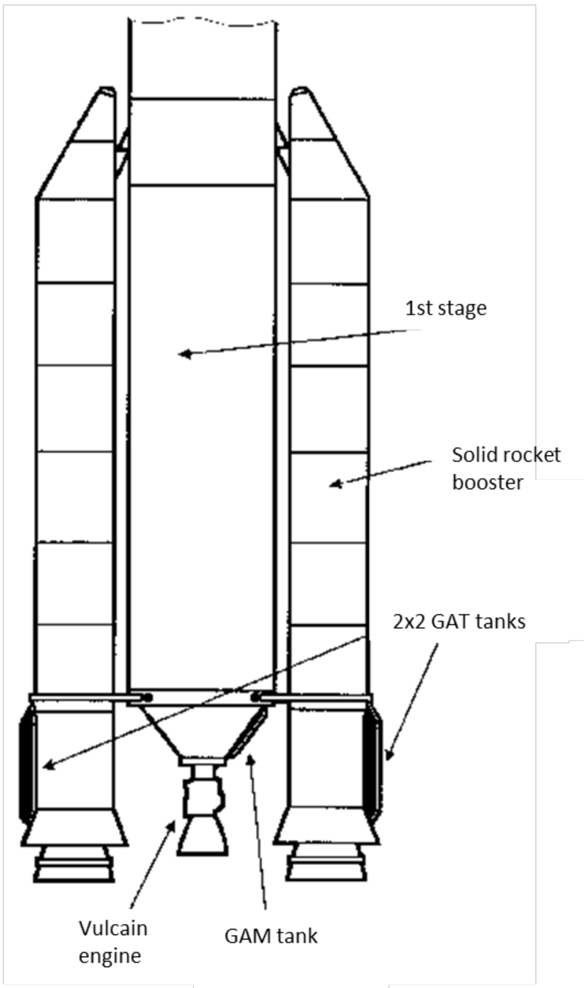


Fig. 6-7: GAM and GAT tanks on the Ariane 5 launcher (Wächter, 1997)

6.2.1 Motivation and Objectives

During the original GAM development process, no systematic heritage assessment was performed. Here, the heritage assessment is conducted as if the decision to modify the GAT has yet to be made. The main purpose of the assessment is to compare the use of a modified GAT pressure vessel and compare it with a new development. The GAT pressure vessel was designed for much higher pressures than the GAM vessel. Moreover, the GAT tank is significantly longer than the GAM tank.

6.2.2 Defining System Functions and Performance

The value-related functions of GAM and GAT are similar, as shown in Table 6-12. They both supply hydraulic liquid to the actuators.

Table 6-12: Value-related function of GAM and GAT

System	Value-related function
GAM	Supply hydraulic liquid to actuators
GAT	Supply hydraulic liquid to actuators

However, the performance requirements, shown in Table 6-13, differ significantly. First, the required volume of the GAM tank is significantly smaller than for GAT (183 l versus 520 l). Furthermore, the maximum operating pressure is about half the pressure of GAT (23 MPa versus 45 MPa). Identical durability, leakage rates, and load cycle demonstrations are required for both systems.

Table 6-13: Requirements for GAT and GAM (Wächter, 1997)

	Dim.	**GAT**	**GAM**
Required volume	l	520	183
Maximum operating pressure		45.0	23.0
Test pressure	MPa	67.5	34.5
Required minimum bursting pressure		90.0	46.0
Leakage rate	Ncm^3/s	$< 2 \times 10^{-3}$	
Quality factor (nominal)	km	25	15,4
Durability (Storage and operation)	Years	6	
Load cycles to be demonstrated		116x max. operating pressure + 4x test pressure + 4x max. operating pressure + 10^5 dynamic load cycles	

6.2.3 Systems under Consideration and Compliance Assessment

Three systems are considered. The first is the GAT tank, the second GAM. The third system under consideration is a hypothetical newly developed tank that serves as a benchmark. In terms of compliance, the GAT tank has a too large volume and it is designed for a much higher pressure, as shown in Table 6-13. Thus, it cannot be used directly and needs to be modified.

Furthermore, as Fig. 6-8 and Fig. 6-9 show, the supporting systems and the system context are different for the GAT and GAM tanks. Whereas the GAT tanks are mounted on the Ariane 5 solid rocket boosters, the GAM tank is mounted on the Ariane 5 first stage. Hence, the location of the tank mounts need to be changed. Other supporting systems are the helium tanks for supplying the tank with pressure. The interface compatibility between the helium tanks and GAM needs to be checked.

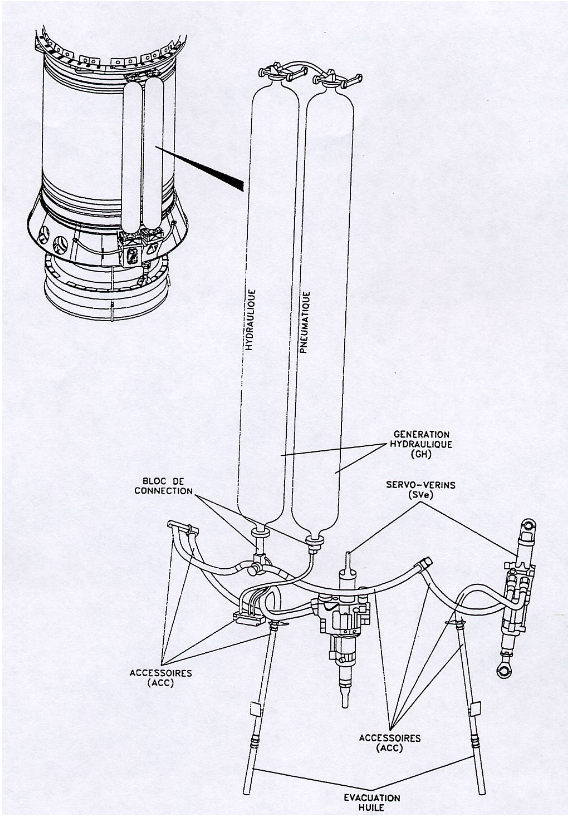


Fig. 6-8: GAT tanks mounted on the Ariane 5 solid rocket booster (Wächter, 1997)

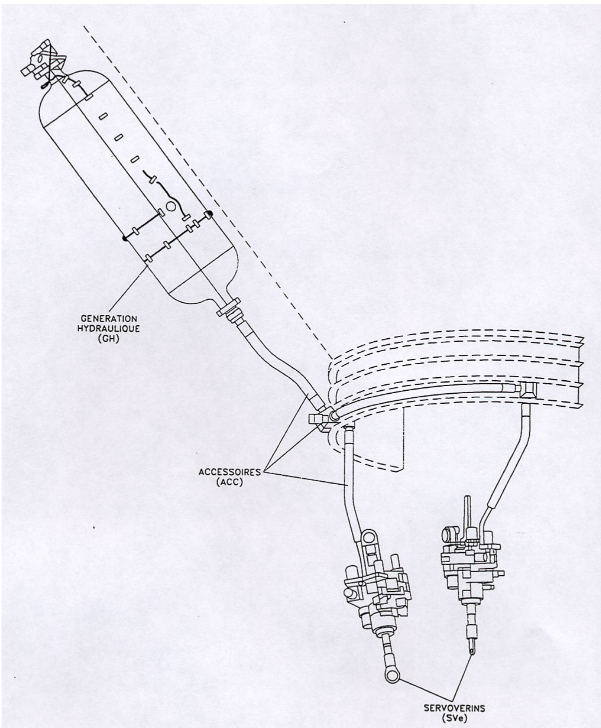


Fig. 6-9: GAM tank integrated with the Vulcain 2 hydraulic system (Wächter, 1997)

6.2.4 Create Modified System / Technology

The characteristics of the modified GAT tank are shown in Table 6-14. As the length of the GAT tank needs to be changed, the length of the cylindrical section of the tank is shortened. Furthermore, the carbon composite winding needs to be modified. As the winding is continuous over the whole tank, shortening the metal liner means that the whole winding has to be modified.

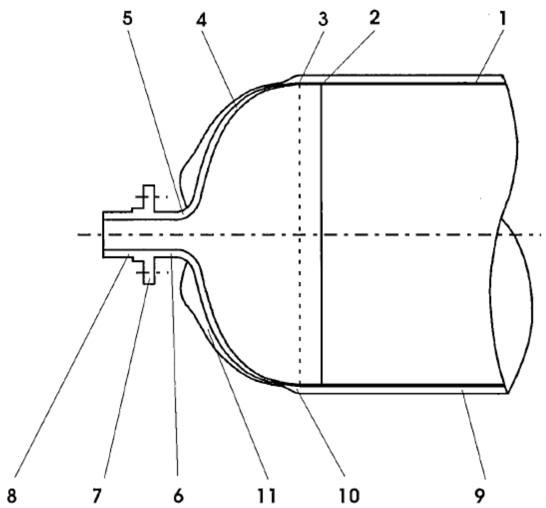


Fig. 6-10: Schematics of the GAT / GAM tank (Wächter, 1997)

Table 6-14: Parts of the GAT / GAM tank

Metalic liner shell		**Changed?**
1	Cylindrical part	Yes
2	Welding zone	No
3	Intersection between cylindrical part to dome	No
4	Dome	No
5	Intersection between dome and connecting piece	No
	Connecting piece	
6	Cylindrical part of connecting piece	No
7	Connecting flange	No
8	Line connection	No
	Composite material winding	
9	Cylindrical part, criss-crossed winding and circumferal windings	Yes
10	Intersection between cylindrical part and dome	Yes
11	Dome, criss-crossed winding	Yes

6.2.5 Design Heritage Assessment

For conducting the design heritage assessment, a design structure matrix of the system was created, shown in Fig. 6-11. Only physical connections are represented.

	Welding zone	Intersection between cylindrical part to dome	Dome	Intersection between dome and connecting piece	Cylindrical part of connecting piece	Connecting flange	Line connection	Cylindrical part, criss-crossed winding and circumferal windings	Intersection between cylindrical part and dom	Dome, criss-crossed winding
Welding zone		X	X							X
Intersection between cylindrical part to dome	X		X							X
Dome	X	X		X					X	X
Intersection between dome and connecting piece			X		X					X
Cylindrical part of connecting piece				X		X	X			
Connecting flange					X		X			
Line connection						X				
Cylindrical part, criss-crossed winding and circumferal windings						X	X		X	X
Intersection between cylindrical part and dome			X					X		X
Dome, criss-crossed winding	X	X	X	X				X	X	

Fig. 6-11: DSM of the GAT tank

Taking the modifications shown in Table 6-14 into account results in the change DSM, shown in Fig. 6-12. It can be seen that changing the carbon composite binding has an impact on several components of the tank. As a consequence, numerous relationships between components are changed.

	Welding zone	Intersection between cylindrical part to dome	Dome	Intersection between dome and connecting piece	Cylindrical part of connecting piece	Connecting flange	Line connection	Cylindrical part, criss-crossed winding and circumferal windin	Intersection between cylindrical part and dome	Dome, criss-crossed winding
Welding zone		X	X							X
Intersection between cylindrical part to dome	X									X
Dome	X								X	X
Intersection between dome and connecting piece										X
Cylindrical part of connecting piece										
Connecting flange										
Line connection										
Cylindrical part, criss-crossed winding and circumferal windings									X	X
Intersection between cylindrical part and dome			X					X		X
Dome, criss-crossed winding	X	X	X	X				X	X	

Fig. 6-12: Necessary modifications for the GAM tank

Calculating the change metric for components and relationships using the graph-edit similarity algorithm results in a change value of 0.5.

6.2.6 Verification, Validation, Testing, and Operations History

It is assumed that at the point where the decision to build the GAM tank as a derivative of the GAT is made, GAT development has already passed all qualification tests. Hence, the GAT tank is expected to have a TRL of 7. However, as GAM is a modification of GAT and used in a different context, its TRL is reduced by default to TRL 5. Conversations with an engineer who participated in the development program confirmed the TRL of 5, as the change in the environment of the tank was considered to be significant. Therefore, the VVTO history value for TRL 5 of 0.1 is selected.

6.2.7 Technological Capability Assessment

The main technological capability of interest is the development capability of a tank with a metal liner and a carbon composite winding. With the development of the GAT tank, this capability is considered to be present at MAN Technologie AG. The GAM tank is different from GAT in terms of performance but is within the experience base of the organization. Furthermore, all equipment that is needed for development is present. As a result, a capability value of 0.9 is selected.

6.2.8 Technology Heritage Assessment

With the three heritage element values calculated, it is now possible to calculate the heritage metric value. The individual metrics along with their values are shown in Table 6-15.

Table 6-15: GAM heritage metric elements and heritage metric value

Metric	Value
VVTO	0.1
Design	0.5
Capability	0.9
Heritage metric	***0.38***

Calculating the heritage metric for a newly developed tank results in the values shown in Table 6-16. It is expected that the tank is based on a similar technology as the GAT tank but with a completely different design. Furthermore, Titan as an alternative material for the metal liner is selected, due to its superior material strength and weight characteristics. However, despite the use of Titan, it is expected that the TRL of the tank is 4, as it is based on existing technologies. A development capability value of 0.8 is selected in order to reflect that the company does have previous experience with developing tanks for space launchers. The capability is discounted by 0.1 from 0.9 to 0.8, as the tank is nevertheless a new development.

Table 6-16: Newly developed tank heritage metric elements and heritage metric value

Metric	Value
VVTO	0.02
Design	0
Capability	0.8
Heritage metric	***0.17***

Using these heritage values, the approximate savings on development duration and specific development cost can be estimated using the estimation relationships from Section 4.3.7. The estimated savings in development duration for the GAM tank are about 19%. A newly developed tank at MAN Technologie AG would however still result in some savings as the organization has already developed space launcher tanks. This would result in savings of 9% for the newly developed tank. For specific development cost, the savings are about 33% for GAM. For a new development the specific development cost would be 15% lower than for an organization with no prior experience. Hence, the relative difference between the GAM and the newly developed tank is about 18%. Compared to the estimates for the real development program, the development duration was about 25% shorter than developing a new tank within the organization. Hence, the estimate using the heritage metric was roughly in the same range as the real development duration with an error of 7%.

Note that this result does not mean that any organization without experience can develop a tank that is just 9% more expensive than MAN Technologie. An organization is usually only selected for such a development if it can somehow justify that they are able to develop a tank. Hence, the comparison is between an organization that has the *potentiality* to develop a tank but does not yet have the *ability* and an organization that does have the ability.

6.2.9 Conclusions

The heritage assessment methodology was applied to a space launcher tank. By calculating the heritage metric, reasonable schedule and cost saving estimates could be made. However, the application of the estimation relationships from Section 4.3.7 have to be taken with care, as they were derived from a sample that does not contain tanks. Hence, more reliable values can be obtained by performing a similar statistical analysis for a tank sample and then estimate the impact of heritage on development duration and specific development cost.

6.3 Launch Vehicles: Saturn V versus Space Launch System

The heritage assessment methodology is applied to a case where a retired heavy lift launch vehicle (Saturn V) is compared to a launch vehicle that is currently under development (Space Launch System). The purpose of the case study is to demonstrate how the heritage assessment methodology can be applied to a retired technology and a technology based on currently active technologies. Finally, it is demonstrated that the methodology can be applied to a case where heritage exists on different hierarchical levels: In the first case (Saturn V), heritage exists on the launch vehicle level with a proven system architecture and components. In the second case (Space Launch System) the launch vehicle is newly developed and has a novel system architecture. However, it heavily relies on heritage technologies at the component level.

6.3.1 Motivation and Objectives

The heritage assessment methodology is applied to the proposed designs of NASA's Space Launch System (SLS) and the Saturn V launcher, depicted in Fig. 6-13.

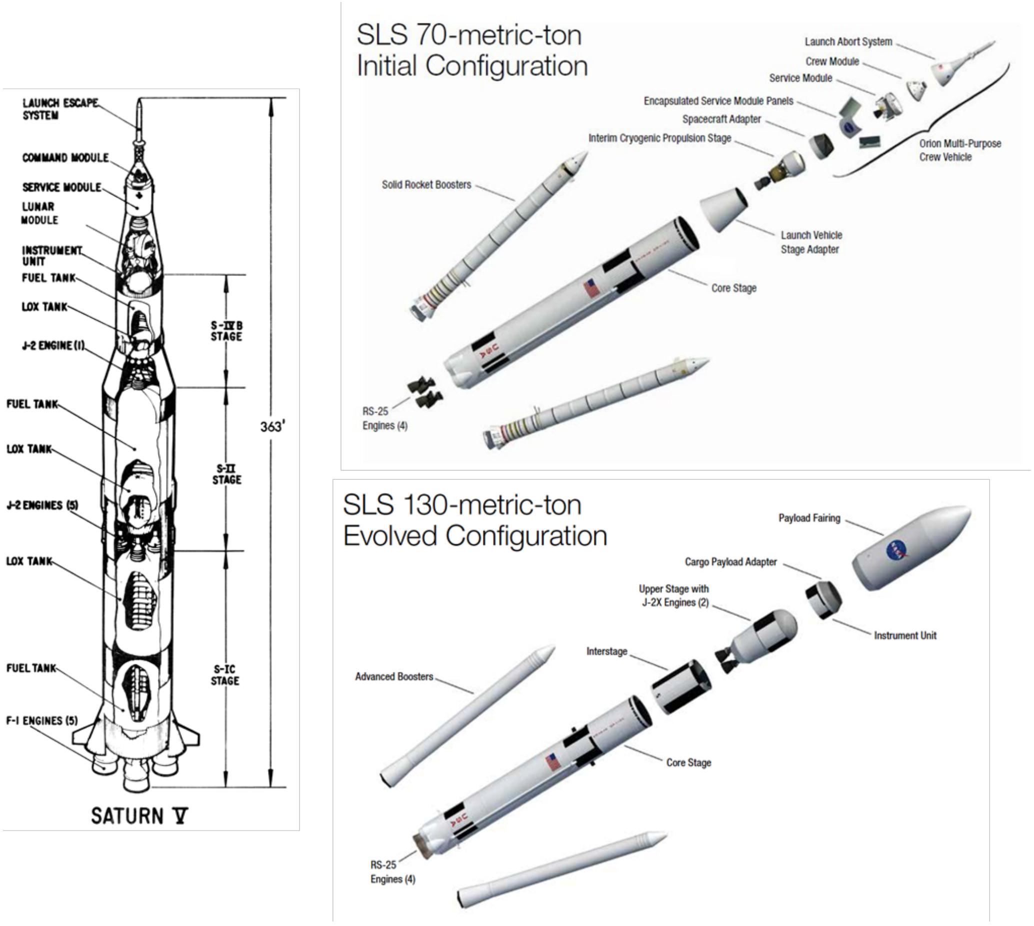


Fig. 6-13: Saturn V (left), SLS standard configuration with ICPS upper stage (upper right), SLS with advanced boosters and Earth Departure Stage (EDS) (lower right) (Jetzer, 2016; NASA, 2012a)

The Saturn V launcher is a heritage technology where the original context and technological capabilities no longer or only partly exist. However, the Saturn V is one of the few heavy lift launch vehicles with an extensive operational history. Furthermore, parts of the Saturn V were subject to recent resurrection activities, such as the F-1 engine (F-1b) and the J-2 engine (J-2X), which shows that the Saturn V can still serve as a source of proven designs (Betts, 2013; Snoddy, 2006). By contrast, SLS makes extensive use of heritage component technologies but has not yet been proven on a system-level. It would be expected that SLS has a higher heritage than Saturn V with respect to existing technological capabilities and Saturn V a higher heritage than SLS with respect to VVTO. Table 6-17 summarizes the heritage-related characteristics of the Saturn V and SLS.

Table 6-17: A priori comparison of Saturn V and SLS in terms of heritage

Heritage aspects	Saturn V	SLS
VVTO history	System level	Component level
Design heritage	System level	Component level
Technological capabilities	Only partly existing	Existing

For the sake of this analysis, the SLS is considered to be at a stage of conceptual development (Phase 0/A). By contrast, the Saturn V has been an operational system. Therefore, both systems are at very different stages in their life cycle. However, in terms of existing technological capabilities, the SLS is based on existing technological capabilities whereas for the Saturn V, capabilities are expected to be resurrected. In short, a retired technology (Saturn V) is compared to a new development based on active technologies (SLS). By applying the systematic heritage assessment methodology, a more extensive picture of the existing heritage for both systems / technologies is developed.

Assessment objectives:

Two heritage assessment objectives have been defined:

- Assess if resurrecting the Saturn V system would make sense in terms of performance and existing heritage.
- Assess the various proposed concepts for the SLS in terms of used heritage and performance.

Determine adequate depth of assessment

The depth of assessment is at the level of individual rocket stages and their respective engines, as the SLS is in its initial stages of development.

6.3.2 Defining System Functions and Performance

As a first step, the value-related function of the system is defined. For a rocket launcher, the value-related function is commonly to transport a payload into space. Typical performance requirements for the value-related function are the payload mass and the orbit or trajectory into which the payload is inserted. For this case study, the value-related function is defined as:

Value-related function: Transport cargo payload (>100t) into LEO

The value of >100t to LEO is rather arbitrarily defined but a typical value for a heavy lift launch vehicle.

6.3.3 Systems under Consideration and Compliance Assessment

Different versions of the Saturn V and the SLS are assessed in this case study. The SLS variants have already been presented in the existing literature (Cook et al., 2012; Crocker et al., 2013; GAO, 2014b). As the resurrection of the Saturn V is hypothetical, I present a few potential modifications, mainly based on recent rocket engine development efforts.

A necessary modification is the exchange of the instrument unit by a current equivalent. Due to the rapid increase of computational power and memory size, the original instrument unit became obsolete.

By contrast, the F-1 and J-2 engine are technologies that are still competitive with contemporary alternatives from a performance point of view. Hence, resurrecting these technologies might be a legitimate option. However, an alternative would be to use rocket engines that were recently proposed, are under development, or are in production. In the following, two engines are selected.

- *F-1b:* The F-1b is a proposed upgraded version of the F-1 engine for the SLS Pyrios boosters. The engine was proposed by Dynetics in 2012 and is based on a reverse engineered F-1. Nevertheless, significant modifications to the original design have been proposed. For example, the parts count of the original engine has been drastically reduced, enabled by the use of advanced manufacturing approaches such as additive manufacturing. Although the Isp is expected to be roughly the same as for the F-1, the thrust level is expected to be significantly higher.

- *J-2X:* The J-2X was intended to be a resurrected J-2 engine, intended for its use in the Ares V heavy lift launch vehicle. However, due to requirements changes, the engine design moved away from the J-2 design. The final J-2X design can be considered a new engine. Compared to the J-2, the engine has a significantly higher thrust and Isp.

As a result, the following Saturn V and SLS variants are considered:

Saturn V versions

- Original Saturn V
- Saturn V with modified instrument unit
- Saturn V with modified instrument unit and F-1b engines
- Saturn V with modified instrument unit and J-2X engines
- Saturn V with modified instrument unit, F-1b engines, and J-2X engines

SLS versions

- SLS standard configuration with ICPS upper stage
- SLS standard configuration with EUS upper stage
- SLS with Pyrios boosters, ICPS upper stage
- SLS with Pyrios boosters, EUS upper stage

For each of the Saturn V and SLS versions, payload to LEO capabilities are estimated using a launcher analysis tool from Bühler (2012). The accuracy of the tool was validated by comparing the results of the analysis for the Saturn V with original flight data presented in Braeunig (2013). The error of the calculated payload to LEO for the given velocity requirement of 9.2 km/s was less than 10%. The accuracy was considered to be sufficient for this case study.

Note that both the Saturn V and SLS use a third stage for achieving orbital velocity but reuse the stage for escaping Earth after its insertion into LEO. The payload to LEO, therefore, includes the inert mass and remaining propellant of the third stage.

Table 6-18 gives an overview of the estimated payload capacity to LEO for the systems under consideration. The SLS standard configuration with ICPS upper stage is close to the cut-off criteria for payload capacity. All other systems surpass the minimum payload requirement by a wide margin, which is within the 10% error of the tool. The primary value-related function is satisfied by all systems under consideration.

In the following, it is assumed that the Saturn V variants have the same gross mass at launch as the Saturn V. This assumption seems reasonable in light of the rather insignificant change of the rocket engine mass from the F-1 to the F-1b and from the J-2 to the J-2X engine. Furthermore the change in mass of the instrument unit is also assumed to be insignificant; 1953kg for the original Saturn V instrument unit, according to Allday (2000, p.49).

A reduction in instrument unit mass may lead to a slight increase in payload mass, as the instrument unit is mounted on the third stage. However, even a drastic reduction in instrument unit mass is estimated to lead to an increase of only one ton in payload mass.

A more relevant increase in payload mass of about 9t can be achieved by using F-1b engines instead of F-1 engines. With the higher thrust of the F-1b engine, gravitational losses of the Saturn V are reduced, which results in a higher Δv for the first stage engine. Thrust throttling during the early stages of ascent to reduce aerodynamic losses were not included in the analysis.

A large increase of 19t in payload mass can be achieved by using the J-2X engines in the second and third stage. The payload increase is larger than the increase achieved by the F-1b engines. The J-2X has a higher thrust and specific impulse compared to the J-2 engine. At the point when the second and third stage engines are ignited, gravity losses are already significantly lower than during first stage operations, which means that the higher Isp of the J-2X has a larger impact on launcher performance than its higher thrust.

Combining the F-1b with the J-2X leads to an increase in payload mass which is about the sum of the individual increases. An increase of almost 29t compared to the Saturn V baseline seems to be possible.

Table 6-18: Compliance check for Saturn V and SLS variants using the compliance matrix

System	>100 t payload to LEO
Saturn V	126
Saturn V with modified instrument unit	126
Saturn V with modified instrument unit and F-1b engines	135
Saturn V with modified instrument unit and J-2X engines	145
Saturn V with modified instrument unit, F-1b engines, and J-2X engines	155
SLS standard configuration with ICPS upper stage	101
SLS standard configuration with EUS upper stage	139
SLS with Pyrios boosters, ICPS upper stage	118
SLS with Pyrios boosters, EUS upper stage	158

In the next step, sub-functions of the launcher are assessed for compliance. In this step, only compliance issues in terms of function, performance, and constraints are assessed that have their origin in stakeholder needs. Potential issues of availability of the technology are not considered in this step but in the "capability assessment" step.

Table 6-19: Subsystem level compliance for the Saturn V

Sub-function	Subsystem	Potential compliance issues
Provide guidance and control	*Avionics*	Processing power and memory of the original system are way below current standards.
Propel launcher	*Propulsion systems*	Potential compliance issues in terms of today's human-rating requirements
Contain fuel	*Propellant tanks*	No compliance issues detected.

For the SLS standard configuration, one compliance issue related to the solid rocket boosters (SRBs) is detected, as shown in Table 6-20. The Shuttle boosters contain asbestos as an insulating material and a non-asbestos material is planned to be integrated (GAO, 2014b). The integration of the new material is expected to cause changes in the manufacturing process and has proven to be difficult (GAO, 2014b, p.16).

Table 6-20: Subsystem level compliance for the SLS

Sub-function	Subsystem	Potential compliance issues
Propel launcher	*SRBs*	Replacement of asbestos by a non-asbestos insulating material. (GAO, 2014b)

In the next step, the value-related function is further decomposed into an operational sequence that performs the value-related function. In particular, the launch vehicle fires the engines of the first, second, and third stage in order to leave the Earth's atmosphere (Earth ascent) and to reach orbital velocity (in-space). Besides this operational sequence, some preparatory steps are required before beginning operations: the vehicle needs to be assembled, transported, and prepared for launch. Furthermore, after the stages are burnt out, they either descend into the Earth's atmosphere (entry and landing) or are discarded in space.

Table 6-21 maps the different mission phase (mode) environments to the components of the Saturn V that are subject to the environment. The mission phases and their relationships are often called concept of operations (ConOps). The mission phases are similar for the SLS. The natural environment has not changed significantly, except the space debris environment in LEO. The S-IVB stage remains in LEO until the trans-lunar injection burn is performed between the second and third orbit. The risk from an increased space debris density should be negligible. However, the situation might change, in case docking operations for more elaborate missions require a longer stay in LEO.

Table 6-21: Saturn V system elements subject to mission phase environments

Mission phase environments \ system elements	**F-1 engines**	**J-2 engines**	**Launch Escape System**	**Payload**	**S-IC stage**	**S-II stage**	**S-IVB stage**
Prelaunch - ground processing	X	X	X	X	X	X	X
Launch countdown	X	X	X	X	X	X	X
Earth ascent	X	X	X	X	X	X	X
In-space		X		X			X
Entry and landing	X	X			X	X	

This high-level analysis indicates that the operational environment for the system has not changed significantly. Hence, existing VVTO history is still applicable to the current setting.

Interfaces with supporting systems

In this step, potential compatibility issues of the Saturn V with supporting systems are identified. The SLS is not considered, as it is expected that its design adheres to requirements and constraints imposed by the supporting systems from the beginning.

For launching the Saturn V, the launch infrastructure at the Kennedy Space Center is vital. Most of the infrastructure at the Kennedy Space Center still exists. However, the launch complex LC-39A and LC-39B, used for the original Saturn V launches, have been significantly modified. LC-39B is currently prepared for the future launch of the SLS. It is assumed that the ongoing modifications of the launch complex for SLS launches is compatible with a Saturn V launch, without significant modifications. The crawler-transporter which was used for transporting the Saturn V and Space Shuttle still exists. Upgrading for transporting the SLS recently started. The transportation capacity of the crawler is going to be increased to 8,200t (Peddie, 2012). The interface between the guidance and control system and ground systems seems to be compatible with today's ground systems. A S-band link is used for sending commands to the launch vehicle. Phase shift keying is used for modulating the baseband. There does not seem to be a reason why existing ground systems could not communicate with the vehicle.

The infrastructure for transporting the Saturn V components to the Kennedy Space Center can still be used in principle. For example, the ships that transported the Saturn V components from the Michoud Assembly Facility to the Kennedy Space Center were also used for transporting the Space Shuttle external tank (Heppenheimer, 2014). Table 6-22 summarizes the Saturn V subsystems along with their interfaces to supporting systems and potential compliance issues.

For transporting the stages via waterway, the existing barges that were used to transport Shuttle components would have to be modified. However, the modifications are probably not very costly. Furthermore, the interfaces of the launcher with the servicing tower can be used as interfacing requirements for designing the new servicing tower. The original Saturn V servicing tower no longer exists.

Table 6-22: Compliance matrix supporting systems interface compliance and potential modifications

Subsystem	Interface to supporting system	Potential compliance issues
Guidance & control - Command communications system	S-band link, phase shift keying for modulation	No issues identified
First stage	Attachment and interfaces to ground support systems	Derive interface requirements for servicing tower from launcher servicing interfaces
	Transportation via waterway	Modification of transportation barge
2nd and 3rd stage	Interfaces to service tower	Derive interface requirements for servicing tower from launcher servicing interfaces
	Transportation via waterway	Modification of transportation barge

Interactions with context systems

Potential issues related to context systems are shown in Table 6-23. The requirements for human-rating have changed considerably since Apollo and are much stricter today. It is therefore likely that the original Saturn V vehicle does not comply with them (Klaus et al., 2014; O'Connor and Chief, 2011; Zupp, 1995). A detailed assessment of the human-rating requirements was not possible, as current requirements are mostly written in a generic form and need to be tailored to the system under study. Such a detailed analysis would be out of the scope of this case study.

Another potential issue is that important stakeholders will probably only support a Saturn V resurrection program if its technologies are current state of the art. Adapting the system to the current state of the art would likely significantly alter its design. The F-1b proposal by Dynetics for the advanced booster of the SLS is such an example. The engine is based on the Saturn V F-1 engine but significantly different manufacturing technologies are planned to be used, resulting in a drastic reduction in parts count (Cook et al., 2012; Crocker et al., 2013).

Table 6-23: Saturn V context systems and potential issues related to them

Context system	Potential issues
Standards: Human-rating requirements	Missing redundancies and potential mission abort options
Stakeholders: Potential contractors, NASA	Resistance to resurrection

In the next step, the VVTO heritage for the systems under consideration is determined.

6.3.4 Verification, Validation, Testing, and Operations History

As the Saturn V and all its variants are capable of performing the value-related function, the next step deals with how much VVTO history the Saturn V has, with respect to the value-related function.

Functions: environments and modes

The value-related function of the Saturn V is to transport heavy payloads into Low Earth Orbit (LEO) and beyond. This function has been proven by the Apollo and Skylab missions.

Table 6-24: Saturn V mission types and number of missions

Mission type	**Number of missions**	**Successes / failures**
Lunar missions and precursors	13	13 (2 anomalies) / 0
Skylab mission	1	1 / 0

Table 6-24 shows that the Saturn V has an extensive operational history and an almost flawless success record. However, of 13 launches, two launches (Apollo 6 and Apollo 13) suffered from anomalies. During Apollo 6, a fuel line leak on the second stage S-II caused a premature shutdown of the engine. Further engines were shutdown and only one engine operated nominally until stage cutoff. As a result, the trajectory was significantly altered and only 6 out of 16 mission goals were accomplished. During Apollo 13, the central J-2 engine in the second stage S-II was damaged by pogo oscillations and shut down too early. The on-board guidance system was able to compensate the error by burning the remaining engines in the second and third stage longer (Teitel, 2012). Despite these anomalies, none of the Saturn V launches is considered a failure.

Determining the TRL of the Saturn V is putting the TRL to a test. Taking the ESA TRL Handbook (ESA, 2008) it is clear that the Saturn V has reached TRL 9. However, the question is, how the missing capability of manufacturing a Saturn V should be taken into account. If the TRL is penalized for the missing capability, I could argue for a TRL 3, as I would first need to develop components and prove their proper functioning. As the context for for Saturn V has significantly changed, it has a TRL 5 at most. As a compromise, a TRL of 4 is selected for all Saturn V variants which results in a VVTO metric value of 0.02.

For the SLS, I assume that the TRL is also at TRL 4, as validation in a relevant environment has yet to occur. However, component TRLs are considerably higher and have already entered the testing stage such as the solid rocket boosters.

The resulting values for the VVTO metric are shown in Table 6-25.

Table 6-25: VVTO metric values for Saturn V and SLS variants

	VVTO
Saturn V	0.02
Saturn V with modified instrument unit	0.02
Saturn V with modified instrument unit and F-1b engines	0.02
Saturn V with modified instrument unit and J-2X engines	0.02
Saturn V with modified instrument unit, F-1b engines, and J-2X engines	0.02
SLS standard configuration with ICPS upper stage	0.02
SLS standard configuration with EUS upper stage	0.02
SLS with Pyrios boosters, ICPS upper stage	0.02
SLS with Pyrios boosters, EUS upper stage	0.02

6.3.5 Design Heritage Assessment

The design heritage assessment analyses the impact of the modifications on the system architecture. Fig. 6-14 depicts a DSM for the original Saturn V system architecture, based on historical data from Bilstein (1996) and Crawley et al. (2015, pp.317-319). Energy, material, information, and structural relationships are modelled separately. It can be seen that the instrument unit exchanges information with most of the system's components. The rocket stages have a strong structural and material exchange relationship with their engines. The payload is considered external to the system and not represented in the DSM. It would be connected to the launcher via the payload adapter.

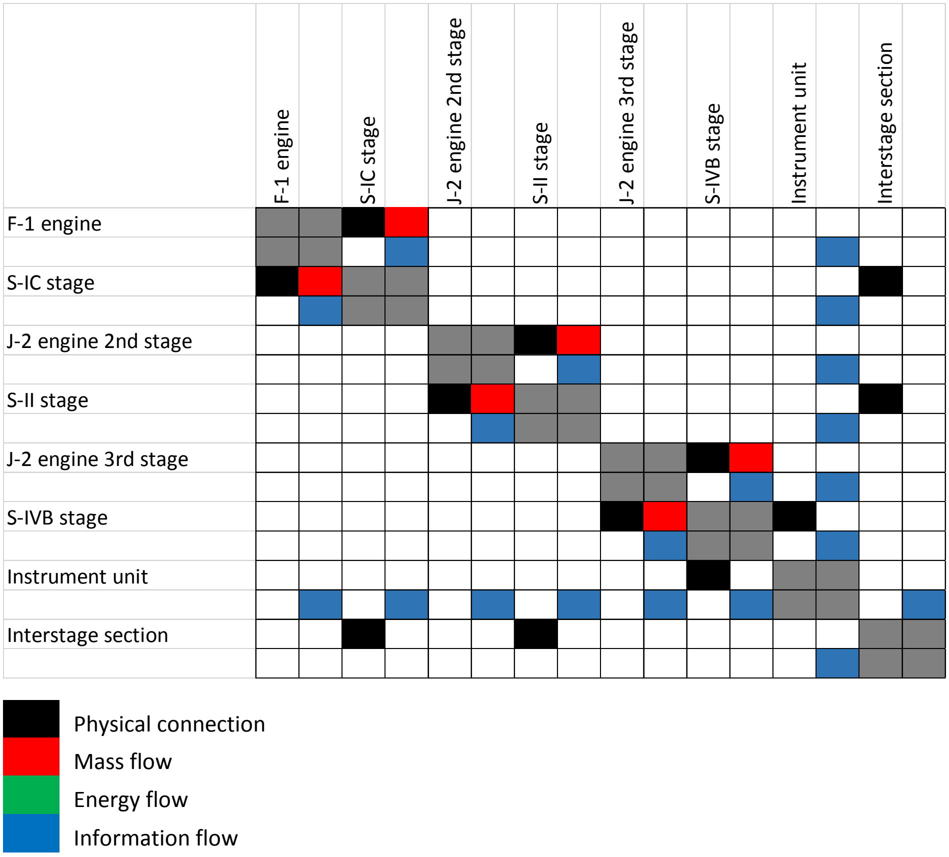


Fig. 6-14: DSM representation of Saturn V launcher

One of the general challenges with DSM modeling and analyses based on it is to choose an adequate granularity for the system components. Fig. 6-14 shows that due to its relationships with all represented components, the instrument unit has a disproportionally large impact on the change metric. However, at least for launcher development, rocket engines are considered much more challenging to develop than the instrument unit. Hence, it can be argued that the importance of the instrument unit is exaggerad by the model. As the instrument unit is nevertheless considered vital for the functioning of the launcher, I decide to keep it in the DSM. For example, the well-known failure of the Ariane 5 Flight 501 was due to the malfunctioning of the launcher's instrument unit.

Modification effects on system architecture

In this step, the relative component and relationship changes between the original Saturn V and its modified versions are calculated by using the graph-edit similarity algorithm presented in Section 5.4. Table 6-26 lists the calculated values. For calculating the combined change values, a weighting of 0.5 was a priori selected for component and relationship changes.

Table 6-26: Relative change values between the original Saturn V and its modified versions

	Relative component changes	**Relative relationship changes**	**Combined change**	**Design heritage metric**
Instrument unit	0.13	0.42	0.28	0.73
Instrument unit and F-1b	0.19	0.58	0.39	0.62
Instrument unit, and J-2X	0.38	0.79	0.59	0.42
Instrument unit, F-1b and J-2X	0.43	0.95	0.69	0.31

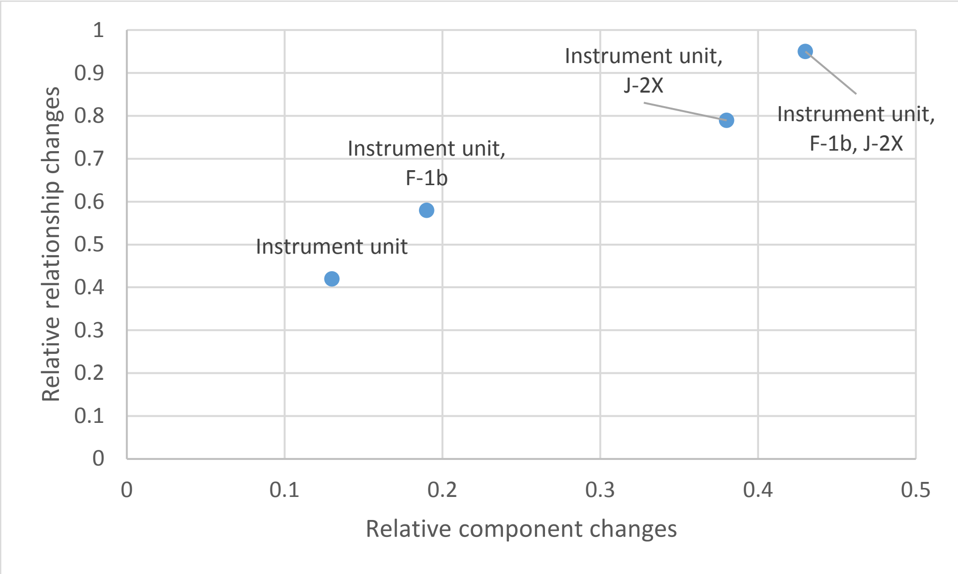


Fig. 6-15: Relative component and relationship changes for Saturn V variants

Fig. 6-15 shows the changes in relationships and components with respect to the original Saturn V architecture. The ratio of components changed remains below 0.43, whereas the relationships are heavily impacted by the component changes (up to 0.95). The main reason is the large number of interactions between the instrument unit and all other components of the system. If the impact of the modifications of the instrument unit on other components are considered to be rather minor, the weighting factor for these relationships can be reduced to reflect this.

Table 6-27 shows the relative component and relationship changes without taking the instrument unit into consideration.

Table 6-27: Relative component and relationship changes between the Saturn V and its variants without instrument unit

	Relative component changes	**Relative relationship changes**	**Relative total change**	**Design heritage metric**
F-1b	0.07	0.27	0.17	0.83
J-2X	0.29	0.54	0.42	0.58
F-1b and J-2X	0.36	0.81	0.59	0.41

Fig. 6-16 depicts the relative component and relationship changes with and without taking the instrument unit into account. It can be seen that the instrument unit has a significant impact on the relationship change metric. Hence, the question whether or not to consider the instrument unit within the scope of the assessment is an important question.

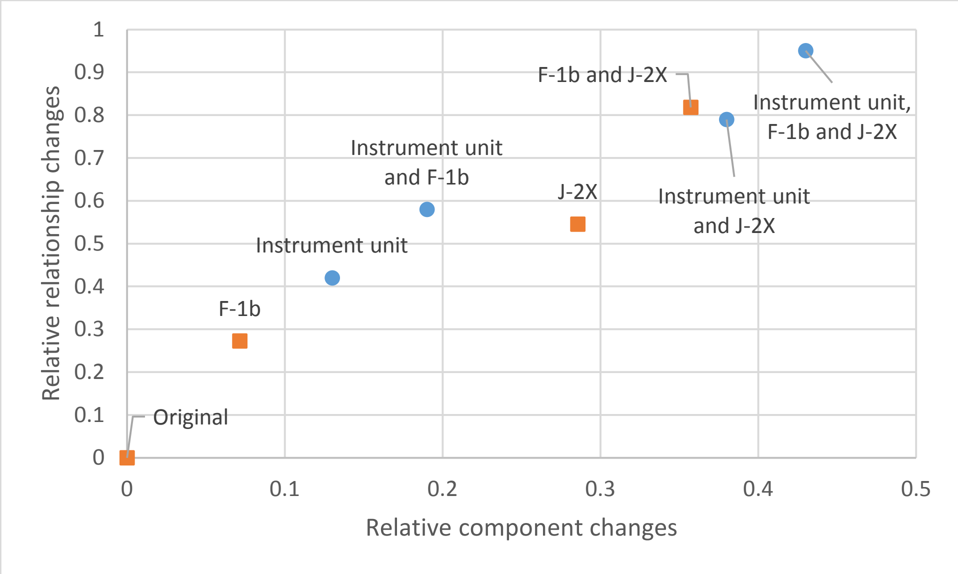


Fig. 6-16: Sensitivity analysis of relative component and relationship changes with respect to the instrument unit for Saturn V variants

Design heritage-based comparison

In the following, it is assessed how much performance increase can be achieved by the different sets of modifications: {instrument unit}, {instrument unit, F-1b}, {instrument unit, J-2X}, {instrument unit, F-1b, J-2X}. The purpose of the assessment is to identify modification – payload increase trade-offs and Pareto-optimal designs. In general, a modification should lead to achieving compliance, added functionality, or to an increase in performance. Modifications without these benefits might not be further taken into consideration.

Payload mass was selected as the performance parameter. An alternative would be the growth factor, which is the ratio of gross mass at launch divided by the payload mass. The growth factor would be suitable in case the gross mass at launch and the payload mass change between launcher designs. As previously mentioned, it is assumed that the gross mass at launch stays *constant*. In this case, using the payload mass is sufficient to compare the different designs.

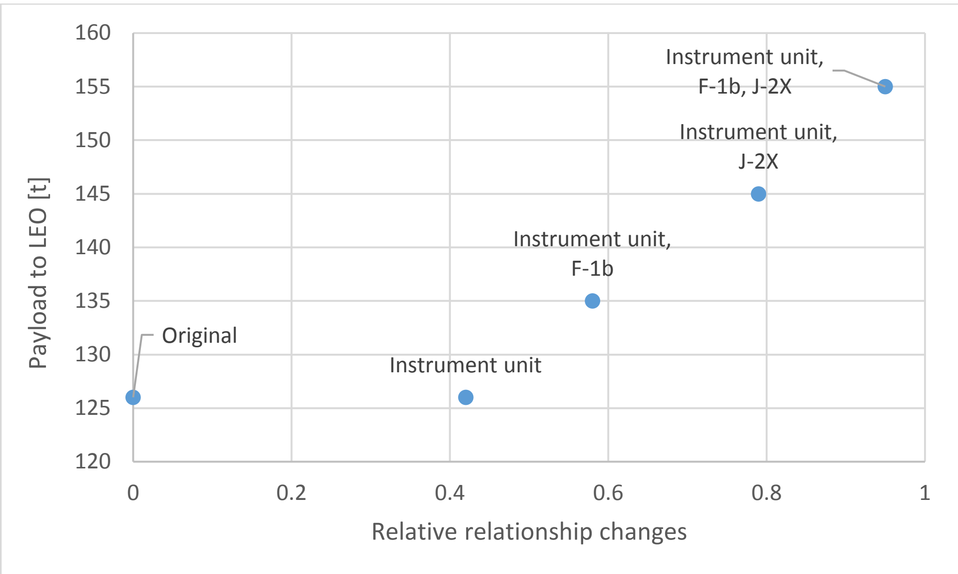


Fig. 6-17: LEO payload capacity versus relative relationship changes for Saturn V and its variants

Fig. 6-17 shows the payload mass to LEO versus the relative changes in relationships for the original and modified Saturn Vs. Again, the large jump in relative relationship change between the original Saturn V and the Saturn V with modified instrument unit can be seen.

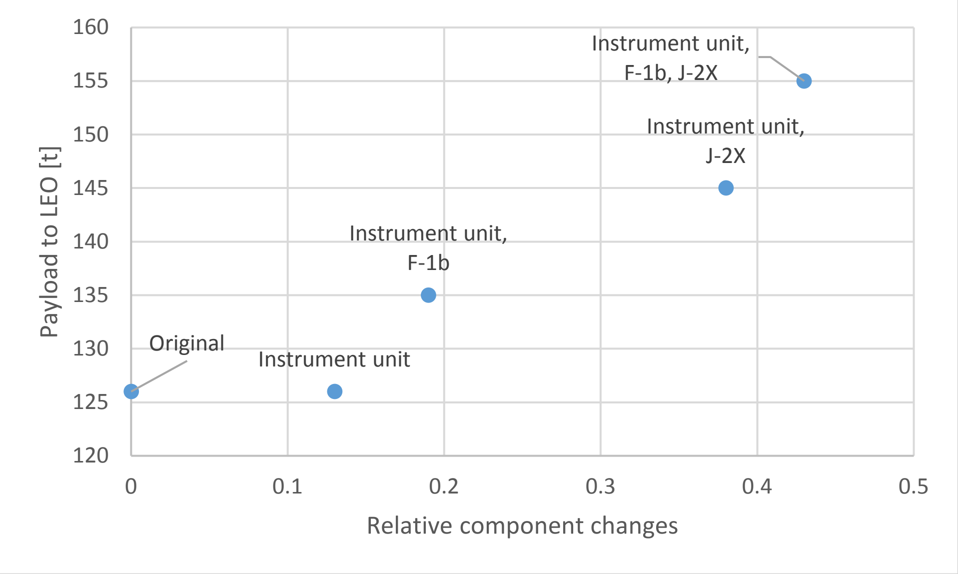


Fig. 6-18: LEO payload capacity versus relative component change for Saturn V and its variants

Fig. 6-18 and Fig. 6-19 show the payload to LEO with respect to relative component change and the design heritage metric. An interesting observation in Fig. 6-18 is the relatively modest increase in component changes from the J-2X version to the combined J-2X and F-1b version. Similarly, the increase in relative component changes from the Saturn V with changed instrument unit to the Saturn V with changed instrument unit and F-1b is rather modest.

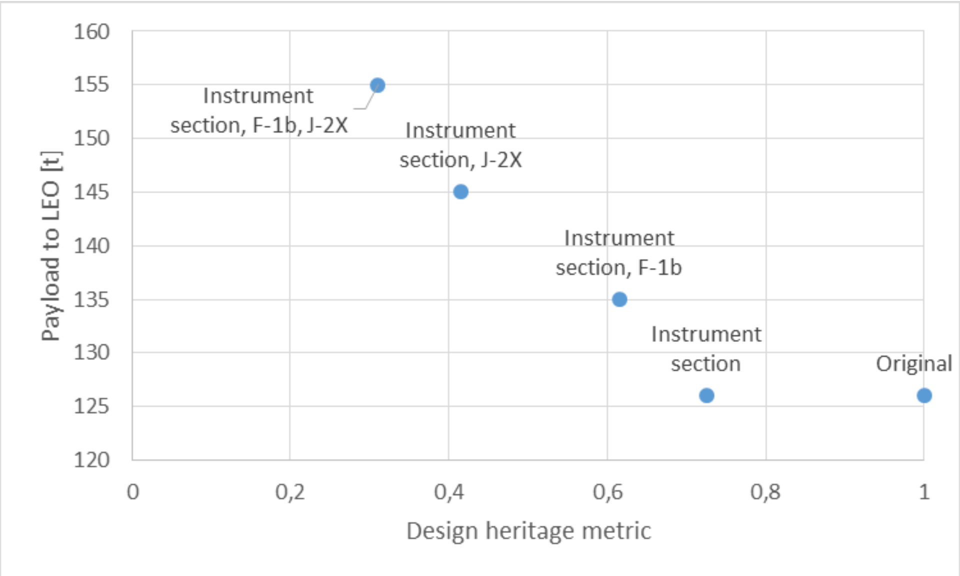


Fig. 6-19: LEO payload capacity versus design heritage metric for Saturn V and its variants

An interesting result of this analysis is that all modified Saturn V versions are on or close to the Pareto frontier. The first trade for a modified Saturn V seems to be between a Saturn V with the F-1b engine and a Saturn V with J-2X engine. For the F-1b variant, a rather small decrease in design heritage is accepted which results in a modest increase in payload mass compared to the J-2X variant. For the J-2X variant, a large loss in design heritage needs to be accepted but the corresponding increase in payload mass is large. Finally, besides these two options, one can opt for the combined F-1b and J-2X variant with a further loss in design heritage but a further increase in payload mass.

6.3.6 Technological Capability Assessment

In order to determine the integrated heritage metric, the existing technological capabilities have to be estimated. More specifically, the combined development and manufacturing capability for each technology is estimated. For the sake of simplicity, customer – supplier relationships are omitted at this point. The Saturn V case is extraordinary, as it is to a large extent a case of technology resurrection. With respect to existing capabilities, the following question is asked: Is the Saturn V technology still state of the art or within current state of experience?

For example, large cryogenic tanks for rocket launchers are currently still within the experience base of suppliers. Resurrecting the Saturn V stages therefore does not require the buildup of a fundamentally different capability. Note that the notion "state of the art" and "state of experience" always depend on the possibility to acquire the capability or getting access to it. A capability which is not accessible should be considered as not existing and the technology is excluded at the first "systems / technologies under consideration" step as described in Section 5.1.

Table 6-28 shows the evaluation of existing technological capabilities with respect to the Saturn V. The F-1 engine is out of production since the end of the Apollo program. Large LOX / Kerosene engines are currently produced for example for the Delta launch vehicle family by Rocketdyne (RS-27A). As the thrust levels for these engines is significantly lower than for the F-1, experience with these engines is only partly useful for developing the F-1 or a F-1 derivative. Hence, the value 0.4 was assigned to the F-1 capability. The F-1b is assigned a slightly higher capability value of 0.5, as the engine is planned to be based on existing technological capabilities. However, the difficulties of developing the engine are probably similar to resurrecting the F-1. Similarly, for the J-2 engine, a low value of 0.5 was selected, as existing LOX/liquid hydrogen engines have a much lower thrust level compared to the J-2, for example the RL10. The J-2X engine is currently under development, undergoing extensive testing. As the engine has not yet entered production for operational vehicles, the value 0.8 was assigned. For the S-IC, S-II, and S-IVB stages, the rather high value of 0.7 was selected, as large stages with cryogenic (LOX and liquid hydrogen) as well as conventional fuel (kerosene) are part of current state of the art. Examples are the Atlas and Delta launch vehicle family. The instrument unit and interstage section are also well within current technological capabilities.

Table 6-28: Existing technological capabilities with respect to Saturn V component technologies

Saturn V technology portfolio	**Capability estimate**
F-1 engine	0.4
F-1b engine	0.5
S-IC stage	0.7
J-2 engine 2nd/3rd stage	0.5
J-2X engine	0.8
S-II stage	0.7
S-IVB stage	0.7
Instrument unit	0.7
Interstage section	0.7

Using these values, the capability values for the Saturn V variants in Table 6-29 are calculated. It can be seen that due to the relatively high capability values for stages, the overall capability values are relatively high. However, it can also be seen that the capability values for the Saturn V variants with the F-1b and J-2X engines are higher than for the original Saturn V.

Table 6-29: Saturn V technological capability estimates

System	Capability estimate
Saturn V	0.62
Saturn V with modified instrument unit	0.62
Saturn V with modified instrument unit and F-1b engines	0.63
Saturn V with modified instrument unit and J-2X engines	0.67
Saturn V with modified instrument unit, F-1b engines, and J-2X engines	0.68

SLS technological capabilities

A similar capability assessment for the SLS technologies is performed. The results for the individual technological capabilities is shown in Table 6-30. The 5 Segment SRB was already developed for the Ares I. However, to the author's knowledge, the booster has not been in production 1-2 years after the cancellation of the Constellation Program.

Table 6-30: SLS component technology capability estimates

SLS technology portfolio	Capability estimate
F-1b	0.5
5 Segment SRB	0.7
Modified Shuttle external tank	0.7
J-2X	0.7
RS-25 / RS-25D	0.7
Pyrios	0.4
RL10	1
Avionics	0.7
Delta Cryogenic Second Stage (DCSS)	0.9

Using the weighted sum for the set of technologies used in each SLS variant, the capability values are calculated. The results are depicted in Table 6-31.

Table 6-31: SLS variant technological capability estimates

System	Capability estimate
SLS standard configuration with ICPS upper stage	0.78
SLS standard configuration with EUS upper stage	0.78
SLS with Pyrios boosters, ICPS upper stage	0.70
SLS with Pyrios boosters, EUS upper stage	0.70

6.3.7 Technology Heritage Assessment

Based on the results for the heritage elements, the heritage metric can now be calculated. The results are listed in Table 6-32, along with the values for the individual heritage metric elements. As expected, the capability values for the SLS variants are slightly higher than for the Saturn V and its variants. However, the design heritage of the SLS variants is considerably lower than for the Saturn V and its variants. This is rather surprising, as one would have rather expected high design heritage values for the SLS. The main reason for these low values is that the relationships between components need to be yet developed.

Table 6-32: Heritage metric values for Saturn V and SLS variants

	VVTO	Design	Capability	Heritage metric value
Saturn V	0.02	1	0.62	0.36
Saturn V with modified instrument unit	0.02	0.73	0.62	0.33
Saturn V with modified instrument unit and F-1b engines	0.02	0.62	0.63	0.32
Saturn V with modified instrument unit and J-2X engines	0.02	0.42	0.67	0.27
Saturn V with modified instrument unit, F-1b engines, and J-2X engines	0.02	0.31	0.68	0.24
SLS standard configuration with ICPS upper stage	0.02	0.33	0.78	0.26
SLS standard configuration with EUS upper stage	0.02	0.33	0.78	0.26
SLS with Pyrios boosters, ICPS upper stage	0.02	0.22	0.70	0.22
SLS with Pyrios boosters, EUS upper stage	0.02	0.22	0.70	0.22

Fig. 6-20 shows the heritage metric values for the systems under consideration. The heritage metric values for the SLS variants are significantly lower than some of the Saturn V variants. Overall, the heritage metric values are rather low and none of the systems reaches a value of 0.40. Recall that for a fully developed and proven system, the heritage metric value should be close to 1.

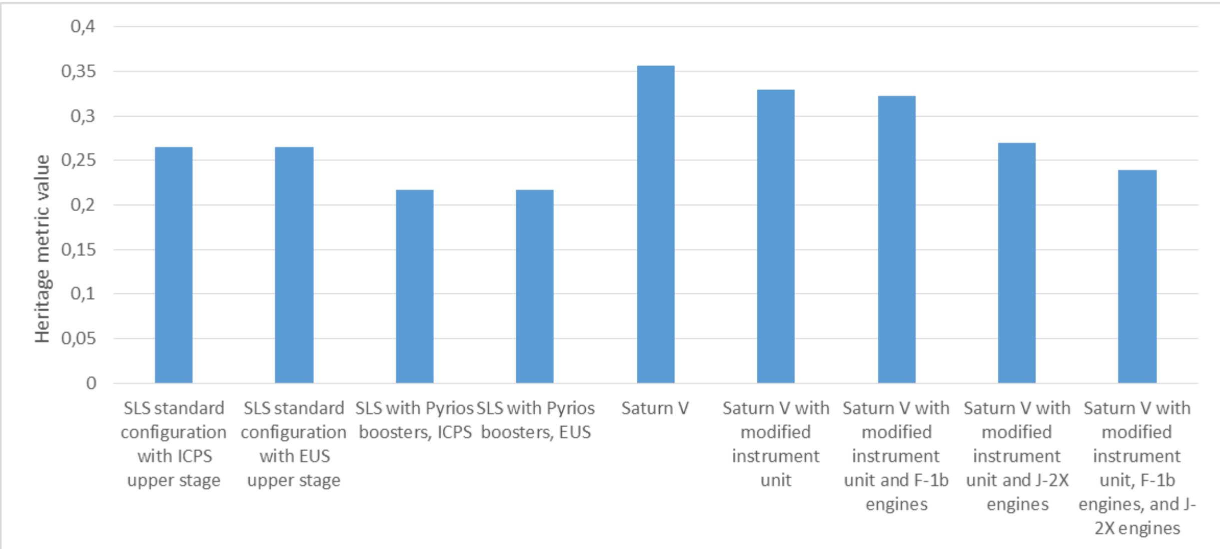


Fig. 6-20: Heritage metric values for the systems under consideration

Fig. 6-21 shows the heritage metric values for the case where the SLS standard configuration has passed the CDR. In that case the TRL of the system is expected to be at either 5 or 6. At CDR it is expected that most of the design drawings are finished. Hence, the design heritage at that point should be higher than at the beginning of the development program. Furthermore, the development capability should also have increased. I am interested in seeing how increasing the heritage of the SLS standard configuration affects the heritage of the other SLS variants. Taking these changes in design heritage and capability heritage into account leads to the heritage values shown in Fig. 6-21 for the SLS in its standard configuration (at TRL 6). It can also be seen that the heritage of the other SLS variants have increased, as parts of these systems are commonal to the SLS standard configuration. The heritage of the SLS standard configuration with EUS upper stage has increased more than the other SLS variants, as this variant has more technologies in common with the SLS standard configuration with the ICPS upper stage. The TRL of the three SLS variants remains low, as it is assumed that their development has not yet progressed beyond the preliminary design phase.

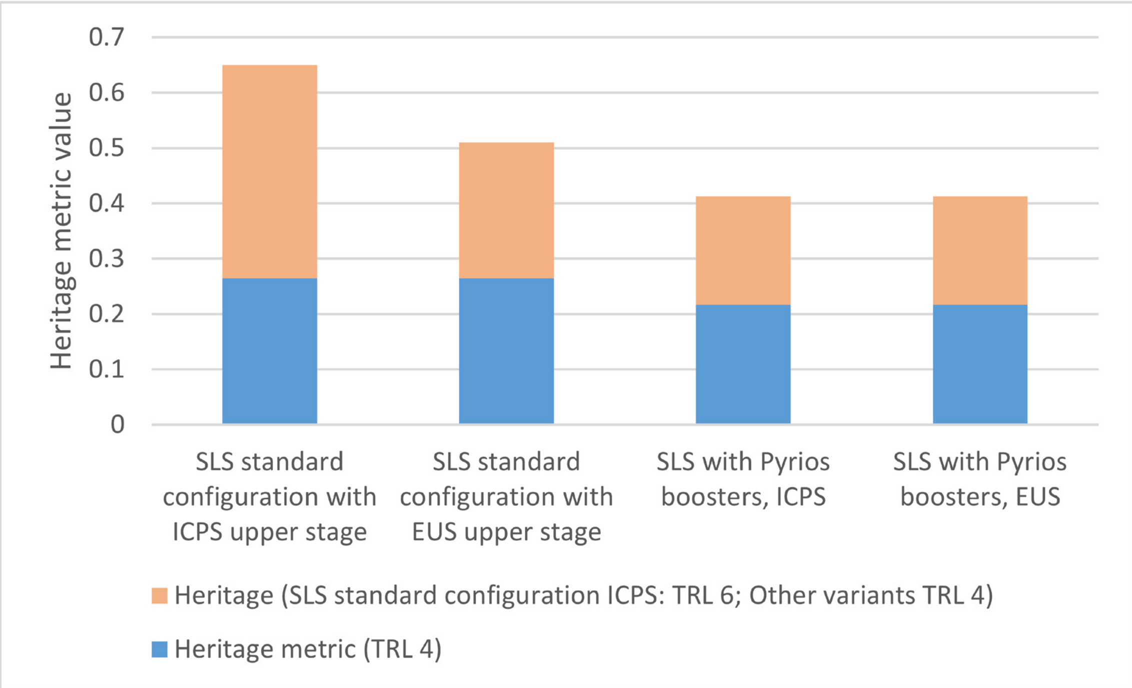


Fig. 6-21: Heritage values for SLS variants once the SLS standard configuration has passed CDR

The result of the heritage assessment shows that the SLS and its variants had less heritage than the Saturn V when development started. However, once the SLS in its standard configuration passes CDR, all variants will have a higher heritage than the Saturn V.

Looking at the heritage – performance trade, Fig. 6-22 depicts the heritage metric values and the payload to LEO values for the systems under consideration. The points in grey are the systems with heritage values at the beginning of the SLS development program. The black points are points for the SLS variants when the standard configuration has passed CDR. The systems on the Pareto frontier when development started are the original Saturn V and its variants, along with the SLS with Pyrios boosters and EUS upper stage. When the SLS standard configuration passes CDR, the situation changes and the SLS in standard configuration with ICPS upper stage, the SLS in standard configuration with EUS upper stage, and the SLS with Pyrios boosters and EUS upper stage are on the Pareto frontier. The SLS with Pyrios boosters and EUS upper stage is on the Pareto frontier in both cases.

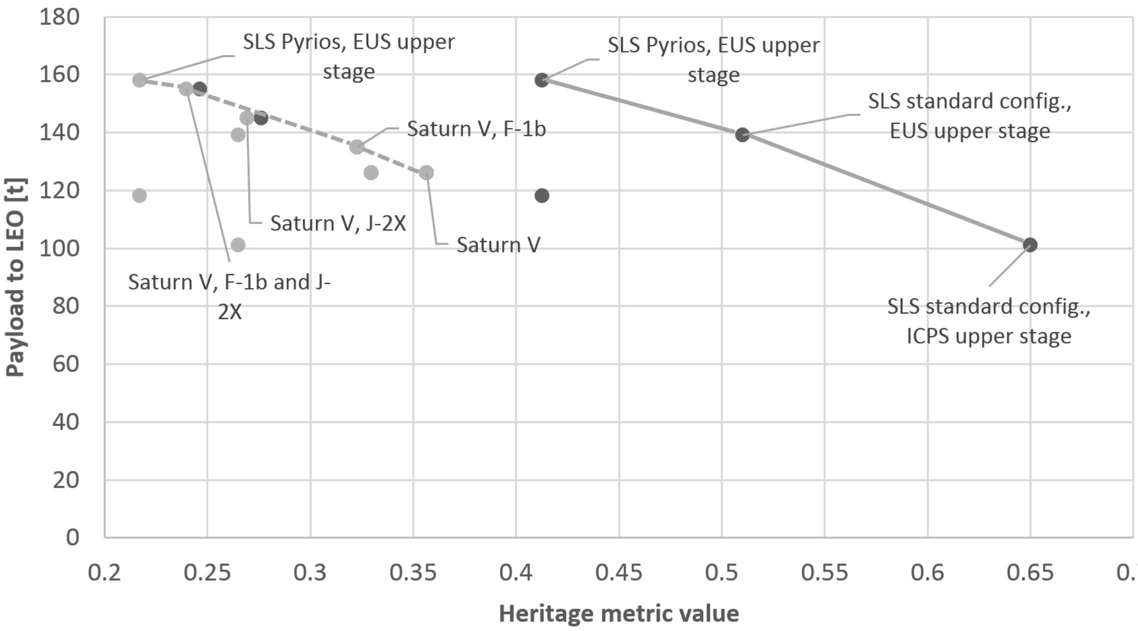


Fig. 6-22: Heritage versus payload to LEO for systems under consideration, different maturity stages for SLS

Assuming a performance and heritage drop of 10% from the calculated values, it can be easily seen that the SLS variants on the Pareto frontier would still be superior to all Saturn V variants when the SLS standard configuration passes CDR.

Using the estimation relationships (42) for development cost and development duration (44), the savings from using heritage technologies at the beginning of development can be estimated. The resulting values are depicted in Table 6-33. It can be seen that the savings for all variants are between 19 to 31% for specific development cost and between 11 to 18% for relative development duration. Considering the uncertainties associated with these estimates, the difference between the SLS and Saturn V variants seems rather insignificant. Differences within the group of Saturn V and SLS variants is also rather insignificant.

Table 6-33: Estimated savings in relative specific development cost and relative development duration for Saturn V and SLS variants

	Relative specific development cost savings	**Relative development duration savings**
SLS standard configuration with ICPS upper stage	0.23	0.13
SLS standard configuration with EUS upper stage	0.23	0.13
SLS with Pyrios boosters, ICPS	0.19	0.11
SLS with Pyrios boosters, EUS	0.19	0.11
Saturn V	0.31	0.18
Saturn V with modified instrument unit	0.29	0.17
Saturn V with modified instrument unit and F-1b engines	0.28	0.16
Saturn V with modified instrument unit and J-2X engines	0.23	0.14
Saturn V with modified instrument unit, F-1b engines, and J-2X engines	0.21	0.12

Taking divergence into account, the savings from using heritage technologies could significantly decrease. The savings for a divergence of 20% are shown in Table 6-34.

Table 6-34: Estimated relative specific development cost and relative development duration with 20% divergence

	Relative specific development cost savings (20% divergence)	**Relative development duration savings (20% divergence)**
SLS standard configuration with ICPS upper stage	0.18	0.11
SLS standard configuration with EUS upper stage	0.18	0.11
SLS with Pyrios boosters, ICPS	0.15	0.088
SLS with Pyrios boosters, EUS	0.15	0.088
Saturn V	0.25	0.14
Saturn V with modified instrument unit	0.23	0.13
Saturn V with modified instrument unit and F-1b engines	0.22	0.13
Saturn V with modified instrument unit and J-2X engines	0.19	0.11
Saturn V with modified instrument unit, F-1b engines, and J-2X engines	0.17	0.097

Taking the uncertainties associated with these estimates into consideration, it seems that no drastical savings from using heritage technologies can be expected for the SLS and Saturn V variants.

6.3.8 Conclusions

This case study demonstrated how the heritage assessment methodology can be used for comparing a retired system with limited available technological capabilities with a newly developed system that uses a considerable number of heritage components. Moreover, a set of variants for each of the systems was taken into consideration. The case study also demonstrated how heritage changes when technologies mature. The SLS and its variants have significantly less heritage than the Saturn V at the beginning of development but this situation changes once the SLS in its standard configuration passes CDR. The heritage metric was also used for showing how maturing one technology can help maturing its variants by exploiting different forms of commonality. In this case, commonality was based on design and capability commonality. However, other cases can be imagined, where capability commonality alone could support the development of technologies that have a different design.

7 Conclusions

7.1 Summary

This thesis presented an assessment methodology and a statistical analysis for heritage technologies in space programs. Heritage technologies are proven technologies, based on a proven design, consisting of capabilities to develop, manufacture, and operate a system or other artifacts. The focus of the assessment methodology is on the early stages of system development, in which heritage technology-related decisions are already made, although detailed information about the system is still lacking.

Table 7-1 shows the thesis objectives presented in Section 1.7, how they have been addressed, and how the results were validated.

Table 7-1: Thesis objectives and how these were addressed, along with validation approaches

Thesis objective	Addressed by	Validation approach
1. Provide a general **definition** of heritage technologies	Heritage technology definition in Section 1.3, general technolog definition in Section 2.1.4, and general technology framework in Section 3.2.	Validation via heritage metric survey in Section 5.7.
2. Provide a **conceptual framework** for heritage technologies within a general technology framework.	Three-part conceptual framework in Chapter 3: System architecture framework, technology frame-work, VVTO framework.	Application to historical techno-logies.
3. Provide **statistical evidence** for heritage benefits.	Statistical analysis in Chapter 4 provided evidence for reduced specific development cost and development duration.	Statistical significance tests of results. Two different design heritage metrics used in order to check for robustness of results.
4. Enable the **assessment** of heritage technologies with respect to a new set of requirements, constraints, and environments	Compliance assessment in Section 5.2 enables for the identification of potential compliance issues between the heritage technology and external systems and factors. VVTO assessment in Section 5.3 enables assessing how far past successful VVTO history is relevant for the new application.	Case studies in Chapter 6 and small application example in Section 5.2 and 5.3.
5. Enable evaluating the effects of **modifications** on heritage technologies	Design heritage assessment in Section 5.4 allows for assessing similarities between designs.	Case studies in Chapter 6 and small application example in Section 5.4.
6. Enable assessing **capabilities** related to the development, manufacturing, and operation of a heritage technology.	Technological capability assess-ment in Section 5.5 enables assessing capabilities relevant for a technology.	Case studies in Chapter 6 and small application example in Section 5.5.
7. Enable the **measurement** of heritage in order to compare technology options.	A heritage metric based on three heritage elements was presented in Section 5.6. The elements are	The metric was validated via expert reviews, extreme values for the

	aggregated via the Choquet integral.	heritage metric variables, and historical cases in Section 5.7.
8. **Validate** the methodology by application to case studies.	The methodology was applied to three case studies: Small satellite component, launcher high-pressure tank, and two heavy-lift launcher families in Chapter 6.	Case study methodology presented in Chapter 6.

I have provided a definition of "heritage technology" in Section 1.3 and developed an understanding for its essential and supplementary elements.

Three conceptual frameworks provide the theoretical underpinnings for the heritage assessment methodology and the statistical analysis. First, the systems architecting framework adopted from Crawley et al. (2015) provides notions of system, function, and furthermore supporting and context systems that are external to the system under consideration. Second, the technology framework extends the systems architecture framework to technologies by adding technological capabilities, verification, validation, testing, and operations history, and its design. Finally, the verification, validation, testing, and operations framework provides the conceptual underpinnings of what makes a technology proven.

Based on the conceptual frameworks, the statistical analysis aims at confirming hypotheses regarding heritage technology benefits. Specifically, the effect of using heritage technologies on specific development cost, development duration, cost overruns, and schedule overruns is investigated. For the analysis, heritage technology is represented by two variables. The first variable represents design heritage, the degree to which the design of the system was inherited. The second variable represents technological capabilities by asking the question whether or not the prime contractor has previous experience with developing a system in the same class. I use the multiple regression approach and control for other variables that have been confirmed to have a relationship with the programmatic variables. The results show that the more heritage technologies are used, the lower the specific development cost and development duration. For cost overrun and schedule overrun no statistically significant relationship was discovered, potentially due to the small sample size. Taking design heritage and technological capability together, the results indicate **savings of 87% for specific development cost** and **51% for development duration** assuming full heritage.

Informed by the results from the statistical analysis, the heritage assessment methodology is introduced. In the first step, the objectives of the assessment and the required depth of analysis are defined. In the second step, a set of technologies under consideration is defined. In the third step, the compliance of these technologies with the new application is assessed, taking supporting systems, context systems, and other contextual elements into consideration. Technologies that are considered to be non-compliant remain under consideration in case modifications can be proposed that would make them compliant. In three parallel steps, heritage-related characteristics of the technologies are assessed. First, the successful verification, validation, testing, and operations history; second, the degree of changes to which the design of the system has been subject to; and third, the technological capabilities associated with the system. Using the results from this step, the heritage metric can be calculated that quantifies the degree of heritage of a technology. The heritage metric is based on the Choquet integral which enables calculating the heritage metric by aggregating variables that are not mutually independent. Mutual independence of variables is a precondition for common aggregation functions. The heritage metric is validated for completeness and applicability. Nine experts from the space domain with at least five years of experience and who have been regularly involved in heritage technology assessments reviewed the metric and provided feedback on its completeness and usefulness. According to the reviewers, the metric seems to capture key heritage-related aspects. Furthermore, applicability was validated by testing the metric by using extreme values for its elements and two historical heritage technology examples. Testing the metric with the extreme values and historical cases showed that the specific weighting assigned to the heritage variables depends on specific interpretations of heritage. It is concluded that at the current stage, no general consensus on these weightings exist and they ideally need to be calibrated from case to case. However, a first step towards such a consensus has been made.

Three case studies are used for validating the applicability of the heritage assessment methodology. The case studies are selected in order to cover a wide range of space systems and components. The first case study is a Hard Commanding Unit (HCU) component of a CubeSat that was developed at the Institute of Astronautics of the Technical University of Munich. The objective of the assessment is to evaluate if the component should be used in the successor CubeSat that is under development at the same institute. The heritage assessment shows that reusing the component may introduce significant risks. First, changes in a supporting system, the on-board data handling subsystem, may significantly impact the component. Regarding technological capabilities, capturing knowledge in the form of documentation and developing competent personnel is a necessary condition for retaining the technology. To conclude, the methodology provides useful insights into key uncertainties and risks that need to be considered in order to reuse the component.

The second case study deals with a high-pressure tank for the Ariane 5 launcher. The objective is to make a decision between modifying an existing tank for this purpose or to develop a new tank. One of the results of the assessment methodology is that the modified tank has less heritage than anticipated by the participating engineers, resulting in a longer than expected development duration. This result is confirmed by the schedule overrun of the actual project. Using the heritage metric shows that the actual difference in development duration between the modified tank and the newly developed tank is smaller than expected. This case study demonstrates that the heritage assessment methodology can be applied to cases where modification decisions have to be made.

The third case study deals with variants of the future Space Launch System (SLS) and hypothetical variants of the Saturn V. The objective is to compare the heritage of the SLS variants and variants of the Saturn V to answer the hypothetical question if a resurrection of either the original Saturn V or its modified versions makes sense. Identified major obstacles to a Saturn V resurrection are the lack of original technological capabilities, willingness of stakeholders to invest in a resurrection program, and changed human-rating requirements. Comparing the payload mass and heritage of the SLS and Saturn V yields that at the current stage the Saturn V has a higher heritage than the SLS, mainly due to the existence of a proven design. However, once the SLS standard configuration reaches a TRL of 6, it will surpass the Saturn V in its heritage and furthermore improve the heritage of other SLS variants due to commonality. The case study demonstrates that the methodology can be used for projecting future heritage evolution and the impact of developing a baseline system (SLS standard configuration) and its effects on its variants in a system family.

7.2 Key Findings and Contributions

The thesis has the goal of improving the understanding of heritage technologies by developing a conceptual framework, performing a statistical analysis, and developing a systematic methodology for identifying potential risk areas when heritage technologies are used. In the following, I will present conclusions and limitations of the findings.

Regarding the theoretical understanding of heritage technologies, I report the following contributions:

- The proposed definition of "heritage technology" improves on shortcomings in existing definitions and can serve as a baseline for future research in this area.
- The notion of "technological capability" has been considered by major guidelines such as the ESA TRL Handbook and the NASA Systems Engineering Handbook. The framework for describing technological capabilities presented in this thesis can contribute to how capabilities can be represented and systematically assessed.
- The technology framework presented is at least able to accommodate various forms of technology change such as different types of innovation and obsolescence. It allows for an integrated perspective on system, system design, and capabilities. The framework can serve as a theoretical basis for future research on an integrated assessment of system design and organizational capabilities.
- The VVTO framework has attempted to provide a theoretical understanding of what "proven" in a systems engineering context means.

The following findings from the statistical analysis are compiled:

- For the space program sample, the **heritage technology-related variables** (design heritage and technological capabilities of prime contractor) were **among the best predictors for specific development cost and development duration** of all independent variables considered.
- Using **design heritage can have a significant effect on development cost and development duration**; about 85% if the complete system design is reused, and about 60% reduction in development duration.
- **Technological capabilities**, as an element of heritage technology, also have a significant effect on development cost and development duration. An organization that has developed a type of space system before is likely to develop another system of the same type more than **50% cheaper and faster**, independently of the amount of design heritage used in the system.

- Taking design heritage and technological capabilities together into a single **heritage technology variable results in significant savings in specific development cost and development duration** in the same range as for the design heritage and technological capability variables. The reason is that the variables for design heritage and technological capability interact which means that they absorb part of the effect of the other variable.
- Even using very **crude categories** for the degree of design heritage used in a system **can predict cost savings**.
- The **effect of technological capabilities on development cost and schedule savings can also be predicted** by asking the simple question if the prime contractor has already developed a system within the same class. The effect of technological capabilities on specific development cost and development cost is statistically significant.
- The effect on cost overrun and schedule overrun remains to be demonstrated. From this follows that either heritage has or has no statistically significant effect on cost and schedule overrun. Two conclusions can be drawn: If the former is the case, only a larger sample is needed. If the latter is the case, one can hypothesize that, in general, using heritage technologies provides benefits without increasing programmatic risk.
- One of the limitations of using heritage technologies for reducing development cost and development duration is that **divergence can significantly impact an early-stage prediction**, as heritage can be considerably reduced during the course of a space program due to unanticipated modifications. Divergence coefficients are proposed for taking this uncertainty into account.
- A serendipitous finding is that **cost and schedule overruns seem to decrease over time** during the period between 1959 and 2015 from which the sample was taken, and it was shown that this result is statistically significant. One can only speculate about the reasons. One possible explanation is that space programs have been improving on project management and systems engineering.

Two limitations for the statistical analysis are important. First, sampling is performed using convenience sampling, which means that the sample could be subject to sampling bias. Second, the available data on design heritage is compiled using publicly available sources. Hence, the estimates for design heritage might be subject to considerable errors. I tried to limit the effect of errors by using a second, simple design heritage metric. Nevertheless, the possibility of considerable errors in the data cannot be excluded.

The following findings and conclusions are reported from applying the methodology to the case studies:

- Compliance assessment is able to **systematically guide the identification of potential risk areas** for using heritage technologies. However, it cannot replace detailed domain-specific knowledge about the technologies under assessment.
- The VVTO assessment has been conducted by using a TRL-based metric. As the use of TRL in general is not a rigorous approach, there remains considerable leeway in what TRL to choose. However, the approach proved to be easily usable for decision-makers familiar with TRL. One limitation of the proposed TRL-based VVTO metric is that the shape of the curve is likely different for other types of technologies such as rocket launchers.
- It has been demonstrated that the heritage metric can be used for **comparing the heritage of different technologies**. Nevertheless, there remains work to be done on developing a consensus on the empirical relations pertaining to heritage technologies. Similar findings have been reported in Olechowski et al. (2015) in the context of TRL, where questions remain about how to treat changes in the system design and context in which the technology is used. If a consensus on these issues can be developed, it would greatly contribute not only to the management of heritage technologies but to technology management in general.

One of the limitations of the heritage metric is the lack of a general consensus on the importance of the elements of heritage. The weightings used in this thesis put an emphasis on technological capabilities. However, depending on the technology under assessment, weightings might differ considerably. Only the result of a larger survey can identify general tendencies and its variance that needs to be accounted for.

It is concluded that a few parameters that are relatively easy to obtain seem to have a strong predictive power for the effect of using heritage technologies in a space program. Looking at which proven technologies are going to be used in the space system and asking the question “Have they done it before?” enables to predict savings in budget and schedule with a certain variance. However, changes between the planned and actual degree of heritage technologies have to be taken into account.

7.3 Future Work

Promising future research can be found in the area of statistical analysis of space programs and other system development programs. One important aspect is the further analysis of the impact of heritage technologies on cost and schedule overruns using a larger sample to obtain statistically significant results. Further research on the decrease of cost and schedule overruns over time also seems to be promising. Is this a phenomenon of space programs or is it a general phenomenon? This research can have a major impact on current project management and systems engineering research, as it might show that there is a general effect of using these methods in system development programs.

Regarding technological capabilities, a major challenge remains the modeling of organizational capabilities and gathering adequate data. A promising area of research could be the identification of indicators for organizational capabilities. The key challenge is to find indicators for which gathering data is easy. Finding such indicators could have a major impact on supplier auditing.

An aspect of heritage technology use that has not been considered in this thesis is the relationship between heritage technology and mission risk. Does the risk of mission failure increase or decrease with the degree of heritage technologies used in a space system? To give two examples, the Mars Observer and Genesis mission failures had their origin in improper management of heritage technologies. However, it is unclear if *in general* such failures occur more frequently with heritage technologies than with newly developed technologies. This would be a promising area of performing a statistical analysis, which was not conducted in this thesis, due to the low number of mission failures in the used sample.

Another area that merits more in-depth study is the effect of change propagation on heritage. In this thesis, only the direct effects of change is accounted for. The risk from change propagation is indirectly taken into consideration via a divergence factor. However, existing approaches for predicting change propagation could be used for identifying risk areas at an early stage.

Further work on developing a consensus view on heritage technology seems to be promising. A first step would be a larger survey for determining the importance of different heritage technology elements (verification, validation, testing and operations (VVTO), design heritage, technological capabilities). Furthermore, the quantitative relationship between Technology Readiness Levels (TRLs) and VVTO seems to merit further exploration. How does the relationship change for different technologies and different groups of survey participants? A set of quantitative measures could increase the objectivity and repeatability of technology maturity assessments.

As a general area of future work, extending the concept of heritage technology to other domains could be promising. The most attractive domains would be domains that have already developed synonymous terms such as “carryover component”, such as the automotive and aeronautical industry. As a starting point, the conceptual framework can be used for capturing domain-specific notions in these industries. After sufficient conceptual underpinnings have been developed, the methodology and the metric could be adapted and validated by respective case studies.

Finally, applying the presented heritage assessment methodology within real-world projects would validate its practical usefulness and increase its maturity.

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Appendix A

A.1) List of Figures

A.2) List of Tables

A.3) List of Definitions

Capability

The attribute of an agent which can perform an action.

Design

A set of attributes of an artifact such as its geometric dimensions, materials, parts, etc. that can be used for manufacturing an artifact.

General ability

A general ability is an ability that does not depend on external circumstances to exist.

General technology

A technology in general can be a method, artifact, process, and knowledge or a combination of these. It uses resources for the purpose or intended purpose of realizing a function, solving a problem or performing a task.

Heritage

Heritage refers to something transmitted by or acquired from a predecessor that is considered increasing its quality.

Heritage technology

A heritage technology is a technology that has inherited a successful verification, validation, testing, and operation history, technological capabilities, its design, and optional artifacts based on the design.

Process

A process can be defined as a sequence of activities or tasks to achieve an objective or function (Eppinger & Browning, 2012, p.130; Estefan, 2008, p.2)

Organizational capability

An organizational capability is a capability of an organization

Obsolescence

The status given to a technology that is no longer available from its original manufacturer.

Potentiality[18]

“Potentiality” is the ability of an agent to acquire an ability.

[18] This definition of potentiality is similar to the notion of “iterated ability” from (Vetter, 2015, p.81).

Proven

A system is called “proven”, if it has a *successful* history of verification, validation, testing, and operational history.

System

An “integrated set of elements, subsystems, or assemblies that accomplish a defined objective.” (Hamelin, 2010, p.5)

Systems architecting

“SA (systems architecting) is a subset of [systems engineering], focusing on the top-level structure (or top-level design) of the system;” (Emes et al., 2012, p.389)

System architecture

A system architecture is “the embodiment of concept, and the allocation of physical / informational function to elements of form, and definition of relationships among the elements and with the surrounding context.” (Crawley and Simmons, 2006)

Systems engineering

“Systems Engineering” is “an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem: operations, cost and schedule, performance, training and support, test, manufacturing, and disposal. SE considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs.” (Haskins et al., 2007)

Technological capability

A technological capability is a capability that is related to the lifecycle phases of a technology.

Technology

A technology is a set of technological capabilities, an artefact’s design, and optionally artifacts based on the design.

Specific ability

A specific ability is an ability that is bound to specific external circumstances to exist.

Uninvention

The status given to a technology that is in general no longer available.

A.4) List of Interviews

Table 8-1: List of interviews

Interview ID	Person ID	Interview Details	Length (minutes)	Organizational Affiliation	Role	Date	Domain
I1	A	In person	120	Industry	Study systems engineer	3.8.2012	Rocket laucnhers
I2	B	Remote	45	Space Agency	Mission study manager	26.11.2012	Space science mission
I3	C	Remote	60	Space Agency	Mission study scientist	29.11.2012	Space science mission
I4	D	In person	80	University	Scientist	18.4.2013	Space science mission
I5	E	In person	45	University	Science manager	26.4.2013	Space science mission
I6	F	In person	20	Space Agency	Study manager	17.8.2013	Space science / manned mission
I7	L	In person	120	Industry	Consultant	12.3.2014	Defense
I8	K	Remote	22	Industry	Systems study engineer	31.3.2014	Manned space missions
I9	M	In person	115	Industry	R&D manager	2.4.2014	Automotive
I10	P	Remote	58	Industry	AIT engineer	8.5.2014	Navigation
I11	G	In person	30	University	Former test engineer / Engineering manager	15.4.2014	Space science mission / Earth observation
I12	G	In person	5	University	Former test engineer / Engineering manager	17.4.2014	Space science mission / Earth observation
I13	N	In person	30	Industry	R&D / integration manager	12.5.2015	Aeronautics

I14	Q	Remote	99	Industry	Procurement / supply chain manager	14.5.2014	Agency / commercial space missions
I15	G	In person	10	University	Former test engineer / Engineering manager	15.5.2014	Space science mission / Earth observation
I16	O	In person	15	University	Thermal engineer	15.5.2014	Earth observation
I17	H	Remote	106	University	Student	7.9.2014	Defense
I18	J	In person	30	University	Engineering manager	16.9.2014	Rocket engines
I19	I	Remote	27	Industry	Development systems engineer	9.11.2014	Space science missions

A.5) List of Supervised Semester and Diploma Theses

1. Rössner, A., (2014) Implementation of Short Term Life Support Systems that Generate Oxygen and Consume Carbon Dioxide, Diploma Thesis, Institute of Astronautics, Technical University of Munich.
2. Zöllner, B., (2014) Technology Resurrection – Validation of a Methodology with Case Studies, Semester Thesis, Institute of Astronautics, Technical University of Munich.
3. Zöllner, B., (2014) A Methodology for Reverse and Reengineering in Systems Engineering, Semester Thesis, Institute of Astronautics, Technical University of Munich.
4. Manhardt, H., (2013), A Methodology to deal with Heritage Technology in Preliminary Design, Diploma Thesis, Institute of Astronautics, Technical University of Munich.
5. Scharringhausen, J., (2013) A Methodology for Heritage Modifications in Preliminary Design, Diploma Thesis, Institute of Astronautics, Technical University of Munich.
6. Hennig, C., (2012) A Methodology for Reusing Legacy Components in Spacecraft Systems Engineering, Semester Thesis, Institute of Astronautics, Technical University of Munich.
7. Springinklee, A., (2012) Preliminary Design of a Personal Life Support System for Extravehicular Activities on Planetary Surfaces, Institute of Astronautics, Technical University of Munich.
8. Bühler, C., (2012) Tradespace Exploration for a Future European Launcher Family (in cooperation with MT-Aerospace), Institute of Astronautics, Technical University of Munich.
9. Condat, H., (2011) Model-based Automatic Generation and Selection of Safe Architectures (in cooperation with EADS Innovation Works), Institute of Astronautics, Technical University of Munich.

Appendix B

B.1) Statistical Analysis Sample Data

Table B-1 to Table B-12 shows the data used for the statistical analyses in Chapter 4. For better readability the data is divided into data for interplanetary spacecraft in Table B-1 to Table B-4, LEO to GEO spacecraft in Table B-5 to Table B-8, and launchers in Table B-9 to Table B-12. Note that all control variables represent categories, except for the year of launch. The categories are represented by different numerical values such as 0, 1, 2, 3.

Table B-1: Values for interplanetary spacecraft design heritage

	PAYLOAD	STRUCTURE	THERMAL	EPS	TT&C	C&DH	ADCS	PROPULSION	MECHANISMS	SOFTWARE	*AVERAGE VALUE WITH WEIGHTING*
WEIGHTING FACTOR	*0.4*	*0.183*	*0.02*	*0.233*	*0.126*	*0.171*	*0.184*	*0.084*			
VIKING ORBITER	0.5	0.5	0.5		0.75	0.25	0.5	0.5			*0.49*
VIKING LANDER	0	0	0	0.25	0	0	0	0	0		*0.042*
PHOENIX CRUISE STAGE	0.5	0.5	1	0.25	1	1	1	1	1		*0.67*
PHOENIX LANDER		1	1	0.9	1		0.75		1		*0.91*
PHOENIX AEROSHELL	0	0.75							1		*0.24*
MARS PATHFINDER LANDER	0.5	0.25									*0.42*
MARS PATHFINDER ROVER	0.5	0	0.5	0.25					0		*0.32*
MARS CLIMATE ORBITER	1	0.25	0	0.5	0.5	0.5	0.25	0.75		1	*0.59*
MARS GLOBAL SURVEYOR	1	0	0	0.25	0.75	0	0	0	0	1	*0.39*
MARS OBSERVER	0	0.25		0.25	0.5	0.5	0.75	1	0.25	0.25	*0.34*
MAVEN	0.5	0.5				0.75	0.5	0.75	0.5		*0.56*
JUNO						0.75					*0.75*
MSL		0		0.5			0.25	0.25			*0.27*
CASSINI	0.25	0		0.25			0	0	0		*0.15*
DAWN	0.25			0.5		0.5	1	0.75			*0.51*
KEPLER	0.25	0	0.25	0.25	0.25	0.25	0.25	0.25			*0.22*
MER LANDER		0.25	0.25								*0.25*
MER ROVER		0.25	0.25								
VOYAGER	0	0	0	0	0	0.75	0	0			*0.092*
PIONEER 11				0.75							
MAGELLAN		0.5			0.5	0.5					*0.5*
NEAR	0.25			0.5		0.5	0.5	0.5			*0.41*
LRO	0.54	0			0.5	0.5		0.5			*0.42*

GRAIL	0.75	0.5	0.75	0.25	0.25	0.5	***0.57***
LADEE	0.75				0.75		***0.75***
MESSENGER	0.6		0.25				***0.47***

Table B-2: Values for interplanetary spacecraft programmatic variables

	DEVELOPMENT COST [K$]	DEV COST WITH INFLATION [2005 K$]	DRY MASS [KG]	SPECIFIC DEVELOPMENT COST [K$/KG]	SPECIFIC DEVELOPMENT COST W. INFLATION [2005 K$/KG]]	DEVELOPMENT DURATION [MONTHS]	DEVELOPMENT COST OVERRUN	SCHEDULE OVERRUN
VIKING ORBITER	240500	1075035	883	272.37	1217.48	40	0.191	1.50
VIKING LANDER	545000	2436150	572	952.80	4259.0	40	0.741	1.50
PHOENIX CRUISE STAGE	283000	283000	597	646.57	646.57	30	0.148	0
PHOENIX LANDER								
PHOENIX AEROSHELL								
MARS PATHFINDER LANDER	200000	260000	451.5	332.23	431.89	27	-0.04	0
MARS PATHFINDER ROVER			11.5	2173.91	4936.96			
MARS CLIMATE ORBITER	80000	98400	354	925.42	1138.27		-0.218	0.01
MARS GLOBAL SURVEYOR	154000	200200	1030.5	387.19	503.35	25	0.292	0
MARS OBSERVER	479000	718500	1018	798.62	1197.94	46	1.5	1.091
MAVEN	553300	475838	809	829.42	713.30	37	0	0
JUNO	581000	522900	1600	687.5	618.75	36	0	0
MSL	1781400	1567632	3354	745.38	655.93	50	0.84	0.923
CASSINI	1422000	3229646.4	3354	971.97	2207.55	54	-0.16	
DAWN	376000	376000	1240	359.68	359.68	47	0.247	0.424
KEPLER	390300	366882	1052.4	522.61	491.26	53	0.215	0.205
MER LANDER	625000	668750	828	809.48	1059.66	28	0.253	0.01
MER ROVER			185				0.26	0.01
VOYAGER	716000	2620560	721.9	1324.28	4846.88		0	0
PIONEER 11	342000	1634760	259	1351.35	6459.46	26		

MAGELLAN	367000	631240	1035			60	0.301	0.277
NEAR	113000	151420	468	500.85	671.15	27	-0.108	0
LRO	473100	444714	809	622.99	585.61	40	0.093	0.25
GRAIL	427000	384300	201	2468.66	2221.79104	33	-0.067	0
LADEE	191400	166518	248.2	1134.17	986.72	35	0.138	-0.0540
MESSENGER	337700	361339	485.2	919.21	983.55	40	0.384	0.1

Table B-3: Values for interplanetary spacecraft capability variables and control variables

	PROJECT MANAGER EXPERIENCE	TEAM TRANSFER [0: NO TRANSFER; 1: TRANSFER]	ORGANIZATIONALS FIRST [0: NO; 1: YES]	GENERATE (POWER TYPE): 0: NONE; 1: SI; 2: GAAS; 3: FUEL CELLS; 4:RTG	CONTROL (ADCS): 0: NONE; 1: SPUN; 2: DESPUN; 3: GG; 4: 3AXIS	REACTION: NONE: 0; 1: MONO; 2: BIPROP; 3: BOTH	YEAR OF LAUNCH	NUMBER OF UNITS PRODUCED [ONE: 0; TWO: 1; PRODUCTION LINE: 2]
VIKING ORBITER		0	0	1	4	2	1975	1
VIKING LANDER		0	1	4	4	1	1975	1
PHOENIX CRUISE STAGE	1	1	0	2	4	1	2007	0
PHOENIX LANDER	1		0	2	4	1	2007	0
PHOENIX AEROSHELL	1		0	0	0	0	2007	0
MARS PATHFINDER LANDER	1	0	1	2	4	1	1996	0
MARS PATHFINDER ROVER	1		1	2	0	0	1996	0
MARS CLIMATE ORBITER	1	1	0	2	4	3	1998	0
MARS GLOBAL SURVEYOR	0	1	0	2	4	3	1996	0
MARS OBSERVER	1	0	0	2	4	3	1992	0
MAVEN	0	1	0	2	4	1	2013	0
JUNO	1	0	0	2	4	3	2011	0
MSL	1	0	0	4	0	1	2011	0
CASSINI	0	0	0	4	4	3	1997	0
DAWN	1	1	0	2	4	1	2007	0
KEPLER		0	0	2	4	1	2009	0
MER LANDER	1	0	0	2	4	1	2003	1

MER ROVER	1		0	2	0	0	2003	1
VOYAGER	1	1	1	4	4	1	1977	1
PIONEER 11	1	1	1	4	1	1	1973	1
MAGELLAN		1	0	1	4	1	1989	0
NEAR		1	0	2	4	3	1996	0
LRO		1	0	2	4	1	2009	0
GRAIL		1	0	2	4	1	2011	1
LADEE		0	0	2	4	2	2013	0
MESSENGER			0	2	4	3	2004	0

Table B-4: Values for interplanetary spacecraft control variables

	SPACE SYSTEM CLASS [LAUNCHER: 3; PLANETARY: 2; OTHER: 1]	HERITAGE CATEGORY	MISSION CLASS	EXTERNAL REASON OF SIGNIFICANT COST INCREASE	HERITAGE-RELATED COST OVERRUN	NEW TECHNOLOGY-RELATED COST OVERRUN
VIKING ORBITER	2	2	3	1	0	0
VIKING LANDER	2	1	3	1	0	0
PHOENIX CRUISE STAGE	2	2	2	0	0	0
PHOENIX LANDER	2	2	2	0	0	0
PHOENIX AEROSHELL	2	2	2	0	0	1
MARS PATHFINDER LANDER	2	0	1	0	0	0
MARS PATHFINDER ROVER	2	0	1	0	0	0
MARS CLIMATE ORBITER	2	2	2	0	0	0
MARS GLOBAL SURVEYOR	2	2	2	0		
MARS OBSERVER	2	3	2	1	0	0
MAVEN	2	2	2	0	0	0
JUNO	2	2	3	0	0	0
MSL	2	0	3	0	1	1
CASSINI	2	0	3	1	0	0

DAWN	2	3	2	0	1	0
KEPLER	2	3	2	0	1	0
MER LANDER	2	0	2	0	0	0
MER ROVER	2	0	2	0	0	0
VOYAGER	2	0	3	0	0	0
PIONEER 11	2	0	2	0	0	0
MAGELLAN	2	3	2	1	0	1
NEAR	2	1	2	0		
LRO	2	1	2	1	1	0
GRAIL	2	3	2	1	1	0
LADEE	2	1	2	0	0	1
MESSENGER	2	1	2	0		

Table B-5: Values for LEO to GEO spacecraft design heritage

	PAYLOAD	STRUCTURE	THERMAL	EPS	TT&C	C&DH	ADCS	PROPULSION	MECHANISMS	SOFTWARE	*AVERAGE VALUE WITH WEIGHTING*
WEIGHTING FACTOR	***0.4***	***0.183***	***0.02***	***0.233***	***0.126***	***0.171***	***0.184***	***0.084***			
TDRS K	0.25	0.75	0.75	0.75	0.75	0.75	0.75	0.75			***0.61***
LDCM	0.25	1	1	1	1	1	1	1			***0.79***
MMS	0.2										
NPP	0.05	0.75	0.75	0.75	0.75	0.75	0.75	0.75			***0.55***
SMAP											***0.50***
GLAST	0	1	1	1	1	1	1	1			***0.71***
GLORY	0.44	1	1	1	1	0.5	1	1			***0.78***
GPM	0.5	0.75	0.75	0.75	0.75	0.75	0.75	0.75			***0.68***
WISE	0	0.5	1	1	0.25	0.5	1				***0.49***
SDO											
OCO-1											***0.71***
OCO-2											***0.84***
HETE 1											***0.50***
HETE 2											***1.0***
QUICKBIRD 1											***0.75***
QUICKBIRD 2											***1.0***

Table B-6: Values of LEO to GEO spacecraft programmatic variables

	DEVELOPMENT COST [K$]	DEV COST WITH INFLATION [2005 K$]	DRY MASS [KG]	SPECIFIC DEVELOPMENT COST [K$/KG]	SPECIFIC DEVELOPMENT COST W. INFLATION [2005 K$/KG]]	DEVELOPMENT DURATION [MONTHS]	DEVELOPMENT COST OVERRUN	SCHEDULE OVERRUN
TDRS K	184600	160232.8	1600	115.34	100.15	46	-0.248	0.0222
LDCM	577200	501009.6	1512	381.75	331.36	43	-0.01	0
MMS	876800	734758.4	1000	876.8	734.76	70	0.0226	0
NPP	767900	698789	2200	349.05	317.63	87	0.295	0.933
SMAP	479000	401402	1042	459.69	385.22	39	0.0142	-0.0488
GLAST	423000	423000	4099	103.20	103.20	59	0.049	0.18
GLORY	337600	307216	545	619.45	563.70	66	0.53	0.1
GPM	509900	433924.9	3850	132.44	112.71	63	-0.082	0.125
WISE	194900	183595.8	645	302.17	284.64	52	0.015	0.0196
SDO	682600	619118	1700	401.53	364.19	71		
OCO-1	235079	221444	315	746.28	703.0	63	0.179	0.0862
OCO-2	249000	211899	409	608.80	518.09	52	0.286	0.486
HETE 1	23326	30743.668	128	182.23	240.18	71		
HETE 2	9000	10782	124	72.58	86.95	31	0.7	0.33
QUICKBIRD 1	354171	424297	995	355.95	359.68	31		
QUICKBIRD 2	230000	269560	951	241.85	491.26	11		
AQUARIUS	225900	205569			1059.66	76	0.172	0.433

Table B-7: Values of LEO to GEO spacecraft capability variables and control variables

	PROJECT MANAGER EXPERIENCE	TEAM TRANSFER [0: NO TRANSFER; 1: TRANSFER]	ORGANIZATIONALS FIRST [0: NO; 1: YES]	GENERATE (POWER TYPE): 0: NONE; 1: SI; 2: GAAS; 3: FUEL CELLS; 4:RTG	CONTROL (ADCS): 0: NONE; 1: SPUN; 2: DESPUN; 3: GG; 4: 3AXIS	REACTION: NONE: 0; 1: MONO; 2: BIPROP; 3: BOTH	YEAR OF LAUNCH	NUMBER OF UNITS PRODUCED [ONE: 0; TWO: 1; PRODUCTION LINE: 2]
TDRS K			0	2	4	2	2013	0
LDCM			0	2	4	1	2013	0
MMS			0	2	4	1	2015	0
NPP			0	2	4	1	2011	0
SMAP			0	2	4	1	2015	0
GLAST			0	2	4	1	2008	0

GLORY			0	2	4	1	2011	0
GPM			0	2	4	1	2014	0
WISE			0	2	4	0	2009	0
SDO							2010	
OCO-1			0	2	4	1	2009	0
OCO-2			0	2	4	1	2014	0
HETE 1			1	2	4	0	1996	0
HETE 2			0	2	4	0	2000	0
QUICKBIRD 1			0	2	4	1	2000	0
QUICKBIRD 2			0	2	4	1	2001	0
AQUARIUS							2011	

Table B-8: Values of LEO to GEO spacecraft control variables

	SPACE SYSTEM CLASS [LAUNCHER: 3; PLANETARY: 2; OTHER: 1]	HERITAGE CATEGORY	MISSION CLASS	EXTERNAL REASON OF SIGNIFICANT COST INCREASE	HERITAGE-RELATED COST OVERRUN	NEW TECHNOLOGY-RELATED COST OVERRUN
TDRS K	1	3	2	1	0	0
LDCM	1	3	2	1	0	1
MMS	1	1	2	1	0	1
NPP	1	3	2	1	1	0
SMAP	1		2	0	0	1
GLAST	1	3	2	1	1	1
GLORY	1	3	2	0	1	1
GPM	1	3	2	0	0	0
WISE	1	3	2	1	0	0
SDO						
OCO-1	1	3	2	1	0	1
OCO-2	1	4	2	1	0	0
HETE 1	1	1	1	0	1	1
HETE 2	1	4	1	0	0	0
QUICKBIRD 1	1	3	2	0	1	0
QUICKBIRD 2	1	4	2	0	1	0
AQUARIUS					0	0

Table B-9: Values for launcher design heritage

	1. STAGE ENGINES	1. STAGE STRUCTURE	BOOSTERS	2. STAGE ENGINES	2. STAGE STRUCTURE	3. STAGE ENGINES	3. STAGE STRUCTURE	*AVERAGE VALUE WITH WEIGHTING*
WEIGHTING FACTOR	***0.3***	***0.05***	***0.25***	***0.3***	***0.05***	***0.25***	***0.05***	
L3S EUROPA	1	1		0	0	0	0	***0.35***
ARIANE 1	0	0		0.75		0.5		***0.38888889***
ARIANE 2	1		0	1		1		***0.77272727***
ARIANE 3	0.75			0.75		0.75		***0.75***
ARIANE 4	0.75	0.25	1	1	0.5	1	0.5	***0.88541667***
ARIANE 5	0	0	0	0	0			***0***
TITAN I	0	0		0	0			***0***
TITAN II	1	0.5		0.5	0.5			***0.71428571***
TITAN III	0.75	0.5	0	0.75	0.5			***0.52631579***
TITAN IV	0	0.5	1	0.5	0.5			***0.47368421***
FALCON 1	0.25	0		0.25	0			***0.21428571***
FALCON 9	1	0		0.75	0			***0.75***
SATURN IB	1	0.5		1	1			***0.96428571***
SATURN V	1	0		1	0	1	1	***0.9***
SATURN I	0.5	0.5		1	0			***0.67857143***
SPACE SHUTTLE	0	0	0	0	0			***0***

Table B-10: Values for launcher programmatic variables

	DEVELOPMENT COST [K$]	DEV COST WITH INFLATION [2005 K$]	DRY MASS [KG]	SPECIFIC DEVELOPMENT COST [K$/KG]	SPECIFIC DEVELOPMENT COST W. INFLATION [2005 K$/KG]]	DEVELOPMENT DURATION [MONTHS]	DEVELOPMENT COST OVERRUN	SCHEDULE OVERRUN
L3S EUROPA	150000	3272727	9706	15.45	337.19	108		
ARIANE 1	2000000	2600000	18866	106.01	137.81	96		
ARIANE 2	129600	225647	19015	6.816	11.87	21		
ARIANE 3			20171.5	0	0	44		
ARIANE 4	428400	745887	23095	18.55	32.30	44		
ARIANE 5		8000000	46400	0	172.41	96		
TITAN I	1643300	10632151	5725	287.04	1857.14	49		
TITAN II	400000	2144000	9140	43.76	234.57	21		

TITAN III	955000	5710900	43844	17.29	103.39	38	
TITAN IV	13600000	4121212	66505	204.50	61.97	52	
FALCON 1	90000	90000	1855	48.52	48.52	72	
FALCON 9	300000	300000	27000	11.11	11.11	60	
SATURN IB	1002200	6113420	54494	18.39	112.19	44	
SATURN V	7439600	43000888	187566	39.66	229.26	71	
SATURN I	838100	5238125	52480	15.97	99.81	56	
SPACE SHUTTLE	6744000	32236320	172535	39.09	186.84	105	

Table B-11: Values for launcher capabiliy variables and control variables

	PROJECT MANAGER EXPERIENCE	TEAM TRANSFER [0: NO TRANSFER; 1: TRANSFER]	ORGANIZATIONS FIRST [0: NO; 1: YES]	GENERATE (POWER TYPE): 0: NONE; 1: SI; 2: GAAS; 3: FUEL CELLS; 4:RTG	CONTROL (ADCS): 0: NONE; 1: SPUN; 2: DESPUN; 3: GG; 4: 3AXIS	REACTION: NONE: 0; 1: MONO; 2: BIPROP; 3: BOTH	YEAR OF LAUNCH	NUMBER OF UNITS PRODUCED [ONE: 0; TWO: 1; PRODUCTION LINE: 2]
L3S EUROPA			1	0	0	0	1968	2
ARIANE 1			1	0	0	0	1979	2
ARIANE 2			0	0	0	0	1986	2
ARIANE 3			0	0	0	0	1984	2
ARIANE 4			0	0	0	0	1988	2
ARIANE 5			1	0	0	0	1998	2
TITAN I			1	0	0	0	1959	2
TITAN II			0	0	0	0	1962	2
TITAN III			0	0	0	0	1964	2
TITAN IV			0	0	0	0	1989	2
FALCON 1			1	0	0	0	2008	2
FALCON 9			0	0	0	0	2010	2
SATURN IB			0	0	0	0	1966	2
SATURN V			0	0	0	0	1967	2
SATURN I			0	0	0	0	1961	2
SPACE SHUTTLE			1	0	0	0	1981	2

Table B-12: Values for launcher control variables

	SPACE SYSTEM CLASS [LAUNCHER: 3; PLANETARY: 2; OTHER: 1]	HERITAGE CATEGORY	MISSION CLASS	EXTERNAL REASON OF SIGNIFICANT COST INCREASE	HERITAGE-RELATED COST OVERRUN	NEW TECHNOLOGY-RELATED COST OVERRUN
L3S EUROPA	3	2	0	0		
ARIANE 1	3	0	0	0		
ARIANE 2	3	3	0	0		
ARIANE 3	3	3	0	0		
ARIANE 4	3	1	0	0		
ARIANE 5	3	0	0	0		
TITAN I	3	0	0	0		
TITAN II	3	1	0	0		
TITAN III	3	2	0	0		
TITAN IV	3	3	0	0		
FALCON 1	3	0	0	0		
FALCON 9	3	1	2	1	0	0
SATURN IB	3	3	1	0	1	1
SATURN V	3	2	1	0	0	0
SATURN I	3	1	2	0	1	0
SPACE SHUTTLE	3	0	2	0	1	0

B.2) Sample Data Sources

All data in Table B-1 to Table B-12 has been collected from publicly available data sources. The various sources are listed in Table B-13.

Table B-13: Data sources for space system sample

Space program	References
Viking Orbiter	(Ezell and Ezell, 2009)
Viking Lander	(Morrisey, 1992) (Teledyne Company, 1969)
Mars Phoenix	(NASA, n.d.) (NASA, 2006) (NASA, 2008)
Mars Pathfinder	(Nicholas, 2004, p.354) (NASA, n.d.) (US Department of Energy, 2009)
Mars Climate Orbiter	(NASA, n.d.) (NASA, 1999b) (NRC, 2010)
Mars Global Surveyor	(Taylor et al., 2001) (Clark, 1998) (NRC, 2010)
Mars Observer	(Investigation Board, 1993) (NASA, 1999c) (Lambright, 2014, pp.101-102) (Arlington Economics, 2016)
MAVEN	(NASA, 2013a) (Spaceflight 101, 2016a)
Juno	(Spaceflight 101, 2016b) (NASA, 2012b)
MSL	(Butts, 2011) (NASA, 2011a)
Cassini	(Russell, 2005, p.112) (Russell, 2004, p.149) (Meltzer, 2015, p.6) (Meltzer, 2015, p.55) (CBO, 2004, p.10) (Johnson and Cockfield, 2005)
Dawn	(Russell and Raymond, 2012, p.180, 181, 195, 200, 218, 221, 235, 258, 390) (GAO, 2009) (Groshong, 2006)
Kepler	(Koch et al., 2004) (GAO, 2009)
MER	(NASA, n.d.) (NRC, 2010) (Rayl, 2012) (Tsuyuki et al., 2004)
Voyager	(Muirhead et al., 2004, p.46) (Tomayko, 1988)

	(Ward, 1979) (Staehle et al., 1993)
Pioneer 11	(Wikipedia, 2016c) (Sulf, 2014) (Staehle et al., 1993)
Magellan	(GAO, 1988) (Doody, 2010, p.146)
NEAR	(Wiley et al., 1995) (Wikipedia, 2016d) (Cheng, 2002) (Aerospace Technology, 2016) (NRC, 2010)
LRO	(Tooley, 2006) (Wikipedia, 2016e) (GAO, 2010)
GRAIL	(Zuber and Russell, 2014, p.4, 8, 13, 43) (NASA, 2011b) (Zuber et al., 2013) (MIT, 2016)
LADEE	(Elphic et al., 2012) (GAO, 2014a) (GAO, 2013) (Spaceflight 101, 2016c)
Messenger	(Dakermanji and Jenkins, 2006) (Lilly et al., 2005) (Dommer and Wiley, 2006) (NRC, 2006, p.55)
TDRS K	(Directorate, 2012) (GAO, 2013)
LDCM	(NASA, 2013c) (GAO, 2013, 2012, 2011) (eoPortal Directory, 2015b)
MMS	(Jackson et al., 2007) (ABSL, 2010) (Spaceflight 101, 2016d)
NPP	(GAO, 2012)
SMAP	(GAO, 2015, 2014b, 2013)
GLAST	(Orbital ATK, 2014a) (GAO, 2009)
Glory	(Gunter's Space Page, 2016) (Parkinson et al., 2006) (eoPortal Directory, 2016a) (Orbital ATK, 2014b) (GAO, 2009)
GPM	(eoPortal Directory, 2016b) (Spaceflight 101, 2016e)
WISE	(Liu et al., 2008) (Wikipedia, 2016f)
SDO	
OCO-1	(Spaceflight 101, 2016f) (GAO, 2009)
OCO-2	(Spaceflight 101, 2016f) (GAO, 2015, 2014b, 2013, 2012, 2011)
HETE 1	(Wikipedia, 2016g)
HETE 2	(Wikipedia, 2016g) (NRC, 2010)

QuickBird 1	(Astronautix, 2016a) (Coonce et al., 2009)
QuickBird 2	(Astronautix, 2016a) (Coonce et al., 2009)
Aquarius	(GAO, 2012, 2011, 2009)
L3S Europa	(Secret Projects, 2008)
Ariane 1	(Astronautix, 2016b)
Ariane 2	(Astronautix, 2016c) (Astronautix, 2016d)
Ariane 3	(Astronautix, 2016d)
Ariane 4	(Astronautix, 2016e)
Ariane 5	(Astronautix, 2016f)
Titan I	(Wikipedia, 2016h)
Titan II	(Wikipedia, 2016i)
Titan III	(Heuston Consulting, 2009) (Astronautix, 2016g)
Titan IV	(FAS Space Policy Project, 1998) (FAS Space Policy Project, 1997) (Bolten et al., 2008) (Wikipedia, 2016j)
Falcon 1	(Wikipedia, 2016k)
Falcon 9	(Wikipedia, 2016l) (NASA, 2011c)
Saturn IB	(Astronautix, 2016h) (Wikipedia, 2016m)
Saturn V	(Heuston Consulting, 2009)
Saturn I	(Astronautix, 2016i)
Space Shuttle	(Butts, 2010)

B.3) Saturn V / SLS DSMs

In the following, Delta-DSMs and DSMs used for the Saturn V / SLS case study in Section 6.3 are presented. The Delta-DSMs in Fig. B-1 to Fig. B-4 show the elements that are changed between the original Saturn V version in Fig. 6-14 and one of its hypothetical variants. Fig. B-5 and Fig. B-6 depict the DSMs for the SLS variants. Table B-14 and Table B-15 show the color codes used for relationship and component changes.

Table B-14: Color code for changed relationships

Color code for relationships	Description
	Changed physical connection
	Changed mass flow
	Changed energy flow
	Changed information flow

Table B-15: Color code for component changes

Color code for components	Description
	Replaced component design
	Significant change
	No significant change

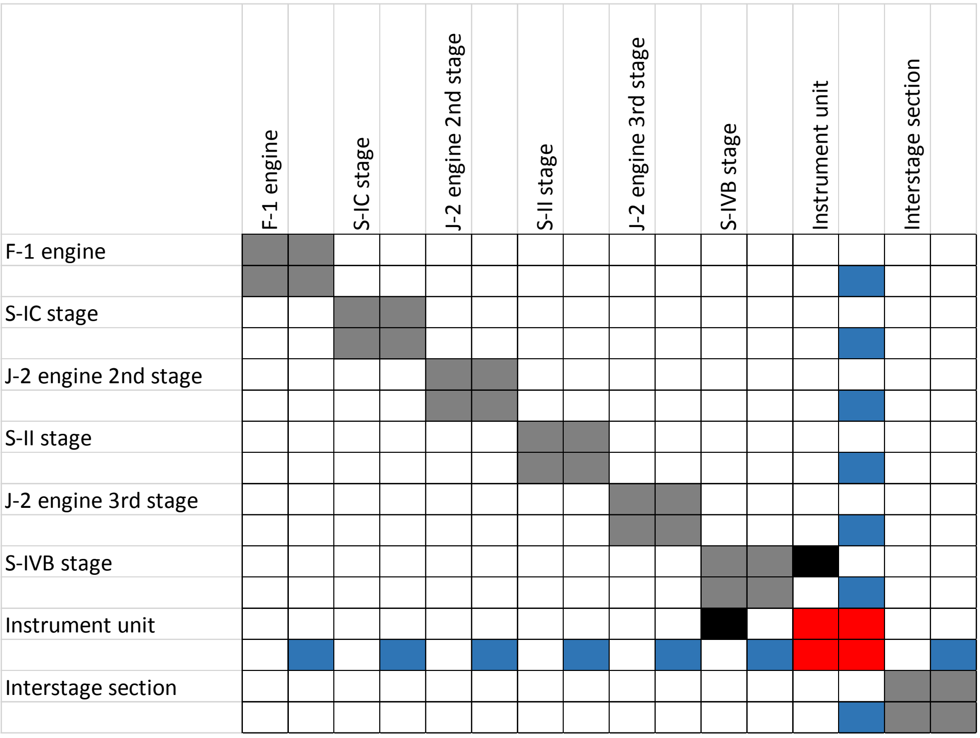

Fig. B-1: DSM representation of Saturn V changes due to new instrument unit

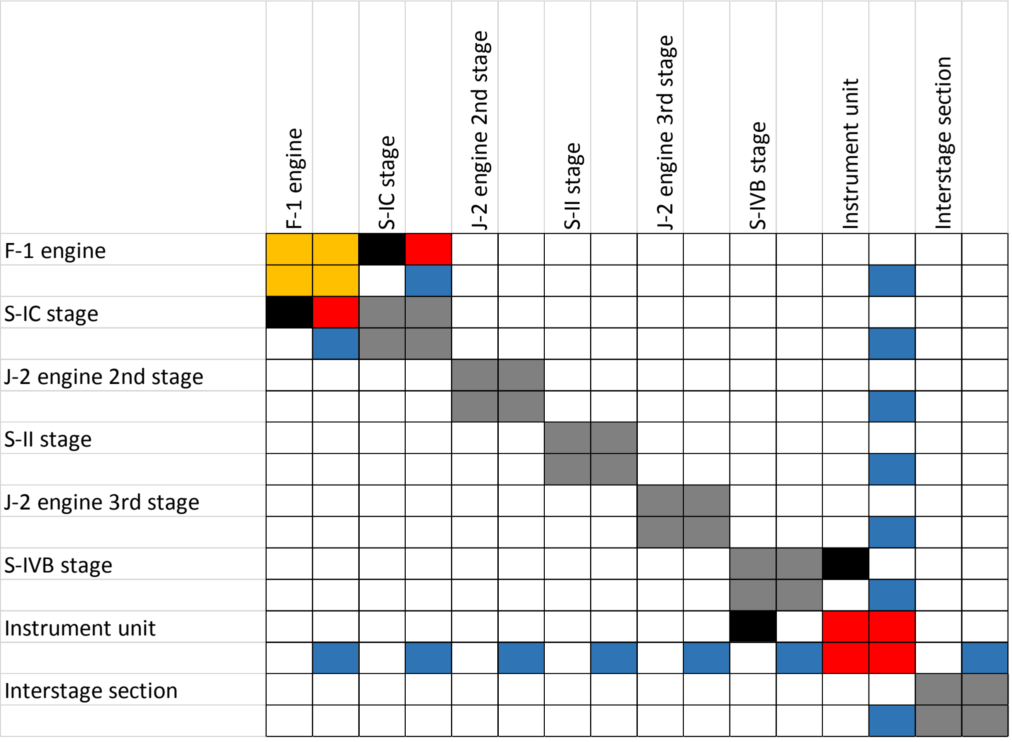

Fig. B-2: DSM representation of Saturn V changes due to new instrument unit and F-1b engine

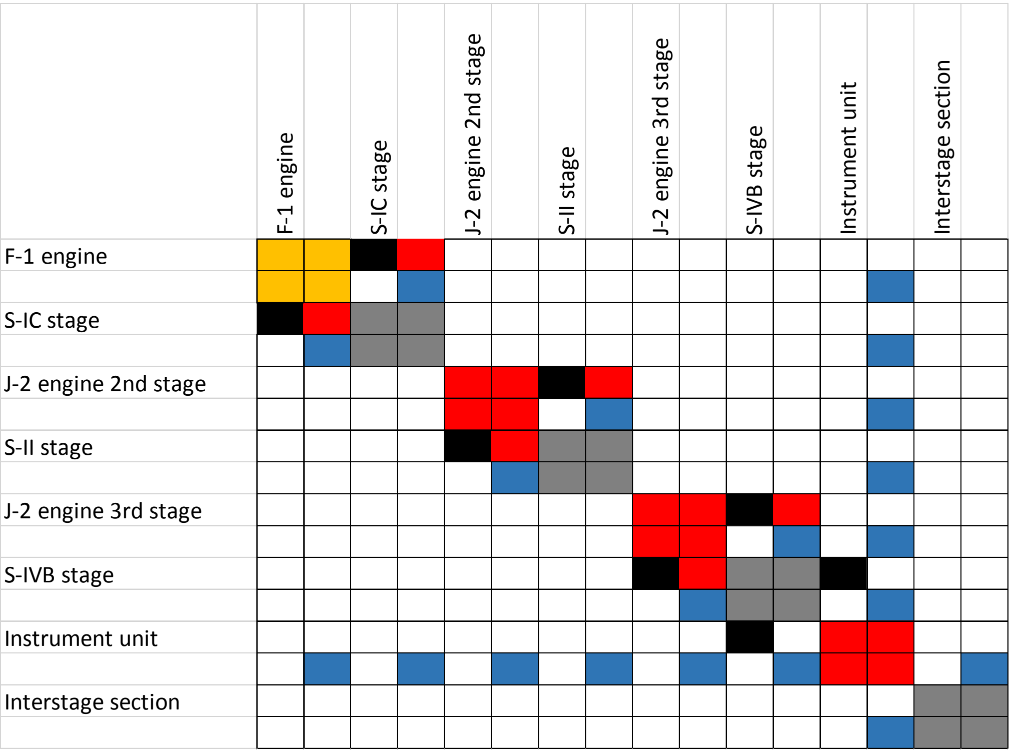

Fig. B-3: DSM representation of Saturn V changes due to new insutrument unit, F-1b, and J-2X engine

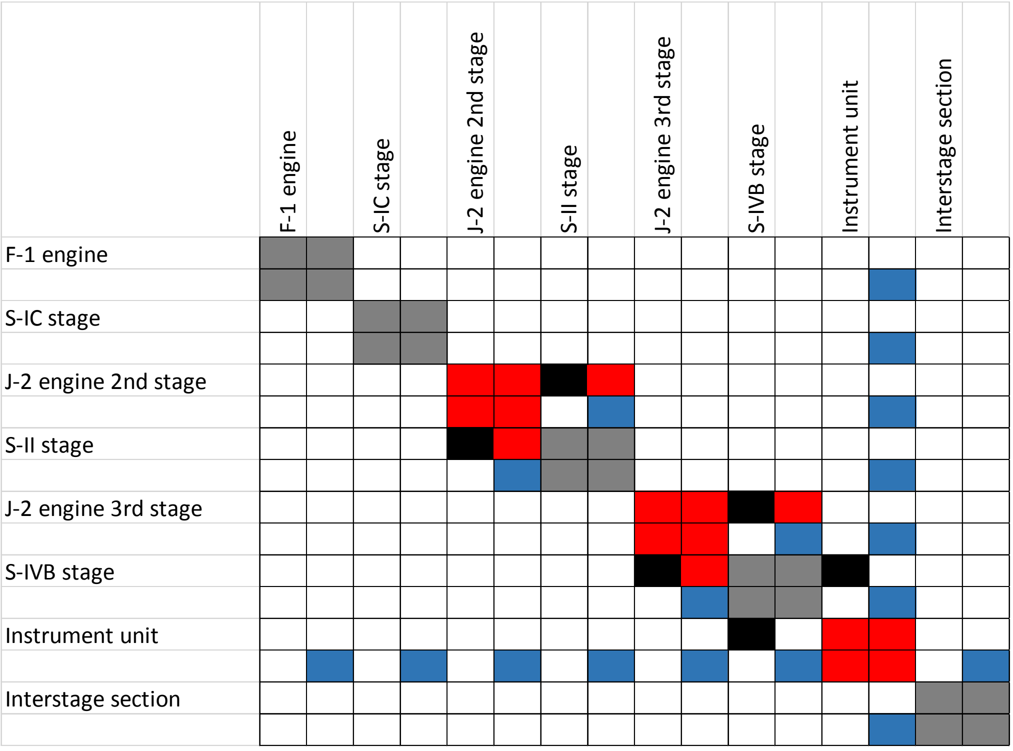

Fig. B-4: Saturn V changes due to new instrument unit, and J-2X engine

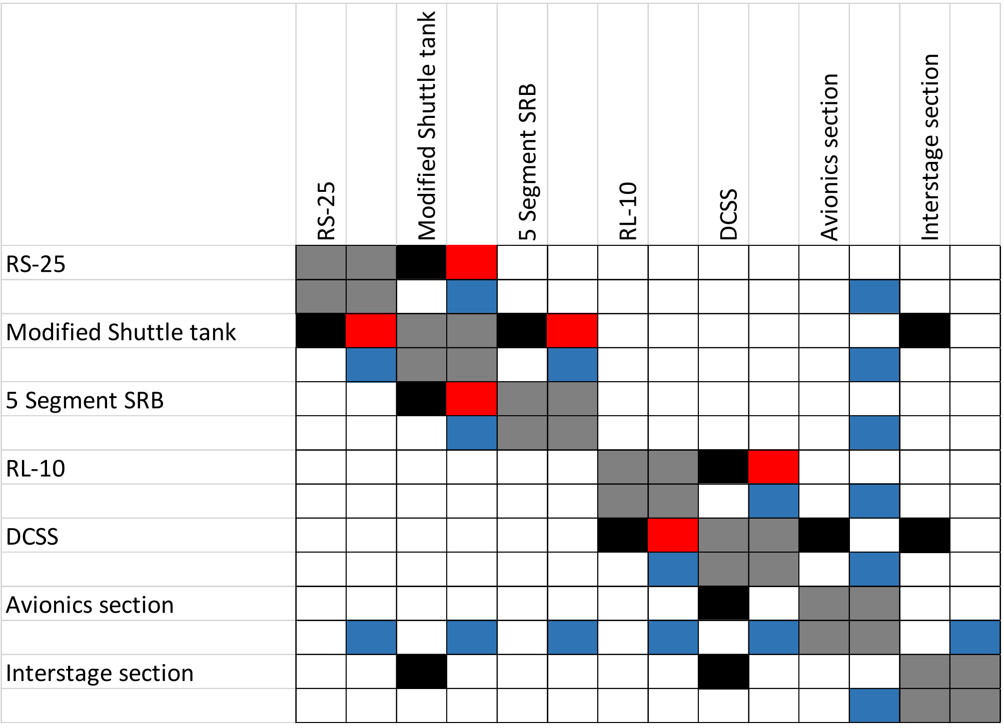

Fig. B-5: DSM representation of SLS standard configuration, ICPS or EUS upper stage

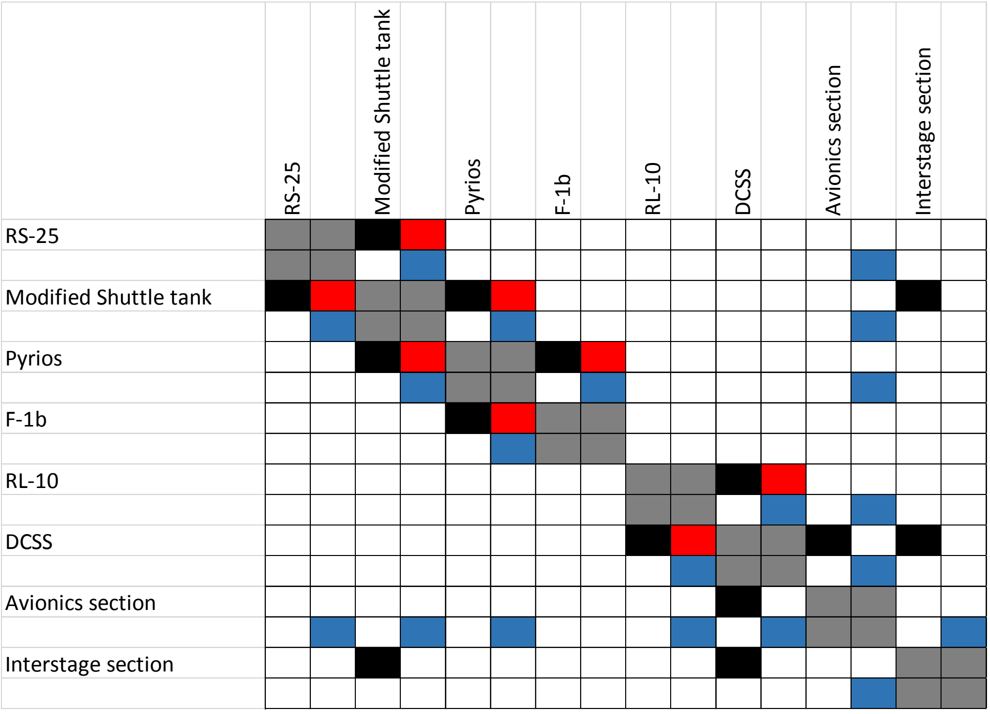

Fig. B-6: DSM representation of SLS with Pyrios boosters, ICPS or EUS upper stage

B.4) Heritage Technology Survey

The survey presented in the following was used for eliciting expert opinions on the elements that constitute a heritage technology. The results from the survey are presented in Section 5.7. Note that the metric in this survey does not represent the final metric presented in the thesis, as the purpose of the survey was to confirm the completeness of the heritage metric.

Heritage technology survey

Author: Andreas Hein

Introduction

Heritage technologies play an important role in space systems as they can reduce cost and risk in space programs. However, there is currently no approach for quantifying the heritage of a technology. In the following, we propose a heritage technology metric for measuring heritage. We define a "technology" as "*a method, system, process, or knowledge or a combination of these. A technology uses resources for realizing a function or to solve a problem or performing a task.* "

Heritage technology elements

The heritage of a heritage technology consists of the following elements:

- *The technology's successful verification, validation, testing, and operations (VVTO) history (V)*: An essential element of a heritage technology is that it is proven in a relevant environment. In other words, it has been shown that "it works". The more proven a technology is, the more heritage it has.
- *The technology's design (D):* The design of a technology consists of its attributes and attribute values. For example, the form, fit, and function of a part or the composition for a material. For more complex systems, it is often impossible to list all attributes and their values. More abstract representations can be the architecture of the system, i.e. its components and relationships between components. If the design is changed, heritage is (partly) lost.
- *The underlying capabilities / competencies associated with the technology (C)*, e.g. a company's capability to manufacture a component or system. If competencies are lost (personnel retires or company goes out of business), heritage is (partly) lost.

Heritage technology evaluation

We use the following formula for calculating the heritage of a technology (how much has been inherited):

$$H = V \times D \times C; \;\; H, V, D, C \in [0,1]$$

H is the heritage of a technology, V the technology's successful verification, validation, testing, and operations (VVTO) history, measured in terms of Technology Readiness Level (TRL), D is the degree to which the design is changed, and C is the degree to which the underlying capabilities of a technology exist. Multiplication is used for aggregation in order to express that any of the heritage elements reaching 0 leads to 0 heritage, e.g. completely different design leads to 0 heritage, no VVTO history leads to 0 heritage, and no capability means 0 heritage.

Questions:

- Are essential elements that you think belong to heritage technologies missing? If yes, what are these elements?
- Do the three elements that are currently included in the metric make sense to you?
- Do you think the metric is applicable to heritage technology assessment situations you encounter? Please explain your answer.

Back-up: Detailed description of metric

Verification, validation, testing, and operations history (V)

Two general statements about events in a systems or technology's VVTO history can be made:

- Some events are cumulative and follow the rule "more is better". Examples are hours of operation or number of launches. In general we say that events are cumulative, if they belong to a certain event category and can be counted as members of this category. For example, hours of operation is one category and the number of hours can be counted. "Launches" is another category where the "number of launches" can be counted. Cumulative events can thus provide the basis for a statistical analysis.
- Some events are binary. Examples are qualification tests, certification, or reaching a certain TRL. A technology has either been subject to such an event or it has not. Furthermore, these events are sequential. For example, a spacecraft component technology has usually reached TRL 6 before it passes a qualification test. Hence, there is an order in which these events can take place.

We cannot use these events in their raw form for representing their contribution to heritage. We have to translate them to a scale that expresses their contribution to VVTO history. This is done in two ways. First, via a mapping between TRL and VVTO history, shown in Fig. B-7 that is based on a survey among NASA engineers and maps TRL to degree of VVTO history. Note that according to the NASA Systems Engineering Handbook the TRL of a technology is downgraded if it is used in a different type of system and/or environment (a priori to TRL 6). If there is evidence that the technology will work in the changed environment (for example, sufficient design margins), a higher TRL can be selected.

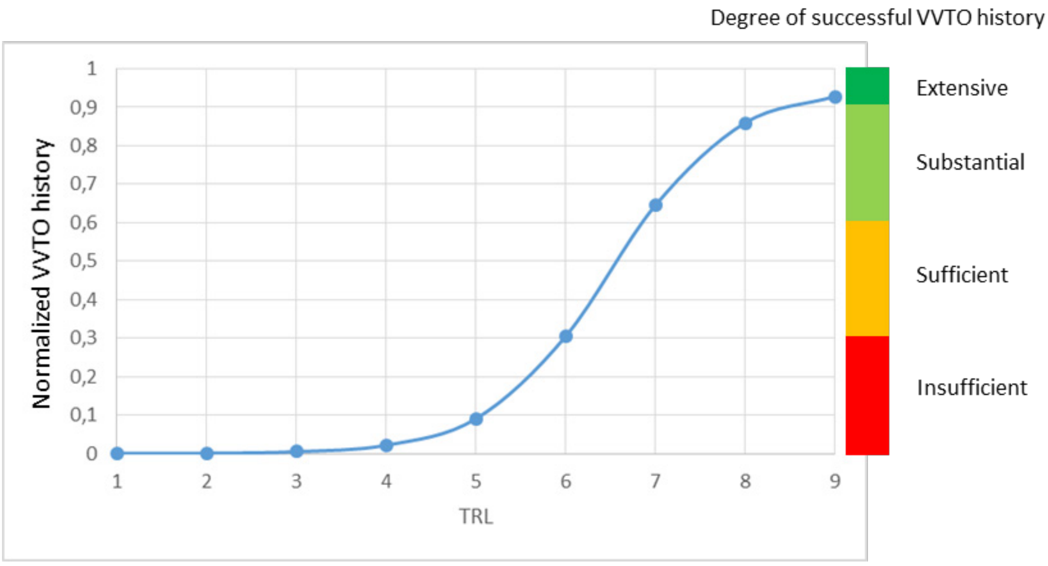

Fig. B-7: TRL mapped to normalized VVTO history (V)

The second approach is more generic and can be used for technologies that cannot be easily categorized with the TRL scale. The four categories are shown in Table B-16. For the type of technology under consideration, threshold criteria for sufficient, substantial, and extensive VVTO are defined. Once a technology is categorized, there is some leeway in choosing the numerical value within the range assigned to the category.

Table B-16: Heritage categories and respective heritage values (V)

Color indicator	Successful VVTO history category	VVTO Confidence Value V
(green)	Extensive	$V \geq 0.9$
(light green)	Substantial	$0.6 \leq V < 0.9$
(yellow)	Sufficient	$0.3 \leq V < 0.6$
(red)	Insufficient heritage	$V < 0.3$

The technology's design (D)

The following technology design metric is targeted at the spacecraft systems, subsystems, and component levels. For other technologies such as materials, processes, and methods, alternative design metrics have to be developed. In the following, a "design" is defined as the components and relationships between components for an operational system. For other technologies such as a material, it is the material's composition or for a process, it is the steps of the process and how they are related to each other. If the "design" changes, heritage is lost, as we cannot be sure that the technology "works" as it did before. As heritage technology assessments mostly concern components or sometimes systems, we focus on the design of components / systems. The design heritage values were estimated by the number and degree to which subsystems were based on inherited designs. The more heritage components and subsystems are used, the higher the associated design heritage value. The value is calculated by the following equation:

$$D = \frac{1}{n}\sum_{i=1}^{n} w_i D_i$$

D is the degree of design heritage for the system / technology, D_i are the degree of design heritage for component technologies. The values for component design heritage area shown in Table B-17. w_i is a weighting that is assigned to a component that is a proxy for its complexity or associated design effort. By default the weightings are set to 1.

Table B-17: Categories for component design heritage and their respective values Values

Design heritage categories	Values for D_i
New design	$0 < D_i \leq 0.25$
Component design with large modifications or new design with few heritage parts	$0.25 < D_i \leq 0.5$
Component design with major modifications	$0.5 < D_i \leq 0.75$
Component design used as-is or minor modifications	$0.75 < D_i \leq 1$

The underlying capabilities / competencies associated with the technology (C)

The most relevant capabilities for systems acquisition are the development and production capabilities. For these two capabilities, categories and metric values were defined, as shown in Table B-18 and

Table B-19.

The value for C is calculated, based on the respective sub-capabilities C_i and taking their arithmetic mean. The arithmetic mean can be interpreted as "the degree to which capabilities exist".

$$C = \frac{1}{n}\sum_{i=1}^{n} C_i$$

Table B-18: Technology development & systems engineering capability similarity metric (C)

Technology development / systems engineering capability similarity	**Values for capability C**
- A similar technology has been developed by the organization. - The type of technology, its application, performance range, quality and reliability are similar. - The technology is within the experience base of the organization. - Key personnel is the same as for previous technology - Proven development processes exist. - Proven development methods and tools exist.	$0.9 < C \leq 1.0$
- A similar technology has been developed by the organization. - The type of technology has to be similar, as well its application. - The performance range, quality and reliability may differ. - The technology is within the experience base of the organization. - Key personnel is the same as for previous technology - Proven development processes exist. - Proven development methods and tools exist.	$0.5 < C \leq 0.9$
- A technology based on similar capabilities has been developed. - The technology type is different, e.g. jet engine versus rocket engine. - The technology or parts of the technology are outside the experience base of the organization. - Key personnel is the same as for previous technology - Proven development processes exist. - Proven development methods and tools exist.	$0.2 < C \leq 0.5$
- Marginal to no capability similarity. - The technology is significantly outside of the experience base of the organization.	$0 \leq C \leq 0.2$

Table B-19: Production capability similarity metric

Production capability similarity	**Values**
All of the following conditions must be true: - Running production line for technology - Key personnel is the same as for previous technology - Proven manufacturing processes exist. - Proven development methods and tools exist. - Required materials are available - Manufacturing equipment exists - Manufacturing facilities exist	$0.9 < C \leq 1.0$
- Production line shut down 1-2 years ago or state of the art / state of experience All of the following conditions must be true: - Key personnel can be reactivated - Proven manufacturing processes exist. - Proven development methods and tools exist. - Required materials are available - Manufacturing equipment exists - Manufacturing facilities exist	$0.5 < C \leq 0.9$
One of the following conditions is true: - No running production line since several years; - Similar production line for different technology running and can be adapted. All of the following conditions must be true for a similar technology: - Key personnel available or can be reactivated - Proven manufacturing processes exist and can be adapted. - Proven development methods and tools exist and can be adapted. - Required materials are available - Manufacturing equipment exists - Manufacturing facilities exist	$0.2 < C \leq 0.5$
One or more of the following conditions are true: - No experience in producing the technology - Key personnel is not available or cannot be easily reactivated - Proven manufacturing processes do not exist or difficult to adapt them. - Proven development methods and tools exist do not exist. - Required materials are not available - Required manufacturing equipment does not exists - Manufacturing facilities do not exist.	$0 \leq C \leq 0.2$

B.4) Heritage Technology Assessment Guidelines

The following document provides a guideline for assessing heritage technologies and is complementary to the methodology presented in Chapter 5. It provides assessment steps at a more detailed level.

Heritage Technology Assessment Methodology

Author: Andreas Makoto Hein

Introduction

Heritage technologies play an important role in space systems as they can reduce cost and risk in space programs. However, there is currently no approach for quantifying the heritage of a technology. In the following, we propose a heritage technology metric for measuring heritage. We define a "technology" as "a set of technological capabilities, an artefact's design, and optionally artifacts based on the design."

Heritage technology elements

The heritage of a heritage technology consists of the following elements:

- *The technology's successful verification, validation, testing, and operations (VVTO) history (V)*: An essential element of a heritage technology is that it is proven in a relevant environment. In other words, it has been shown that "it works". The more proven a technology is, the more heritage it has.
- *The technology's design (D):* The design of a technology consists of its attributes and attribute values. For example, the form, fit, and function of a part or the composition for a material. For more complex systems, it is often impossible to list all attributes and their values. More abstract representations can be the architecture of the system, i.e. its components and relationships between components. If the design is changed, heritage is (partly) lost.
- *The underlying capabilities / competencies associated with the technology (C)*, e.g. a company's capability to manufacture a component or system. If competencies are lost (personnel retires or company goes out of business), heritage is (partly) lost.

Heritage technology evaluation

We use the following formula for calculating the heritage of a technology (how much has been inherited):

$$H = 0.35 * V + 0.25 * D + 0.4 * C - \frac{1}{2}(0.01 * |V - D| + 0.2 * |V - C| + 0.2 * |D - C|)$$

$$H, V, D, C \in [0,1]$$

H is the heritage of a technology, V the technology's successful verification, validation, testing, and operations (VVTO) history, measured in terms of Technology Readiness Level (TRL), D is the degree to which the design heritage exists, and C is the degree to which the underlying capabilities of a technology exist. Multiplication is used for aggregation in order to express that any of the heritage elements reaching 0 leads to 0 heritage, e.g. completely different design leads to 0 heritage, no VVTO history leads to 0 heritage, and no capability means 0 heritage.

Prescreening of heritage technologies

Before a heritage technology enters detailed assessment, the following criteria can knock a heritage technology out of the evaluation:

- The technology is not accessible due to, for example, political reasons such as sanctions, export restrictions, geographic return etc.
- The price for acquiring the technology is prohibitive.
- The technology cannot be acquired due to strategic reasons such as competition with the customer, decision to favor in-house development instead of using supplier.

- The supplier may not be able or willing to engage in a relationship with the customer.
- The technology is obviously not available as the supplier or all available suppliers went out of business.
- A technology is available but due to legal / normative reasons cannot be used. For example, a supplier has not been recertified and the prime contractor is no longer allowed to procure from this supplier. A technology might no longer be compliant with existing regulations.

The list is not complete and other criteria may also eliminate a technology from further consideration. Once the technology has passed this initial screening, the heritage metric elements are elicited.

Manual for eliciting metric elements

Verification, validation, testing, and operations history (V)

For eliciting the VVTO history metric, the following steps need to be performed:

Ground rules for estimating the TRL of the technology:

a. If the technology has been flown on a similar mission in a similar environment, the TRL is 9.
b. If the technology is used in a significantly different system or environment or its function in the system has significantly changed, the TRL of the technology is downgraded by default to TRL 5. If there are reasons to believe that the TRL is higher, these reasons need to be explicated and documented.
c. A technology that has been used successfully on several missions or a long duration is considered to have extensive VVTO history. In this case values between 0.9 and 1 can be selected for normalized VVTO history. In case the technology fails, depending on the severity of the failure and its root cause, the TRL needs to be discounted.

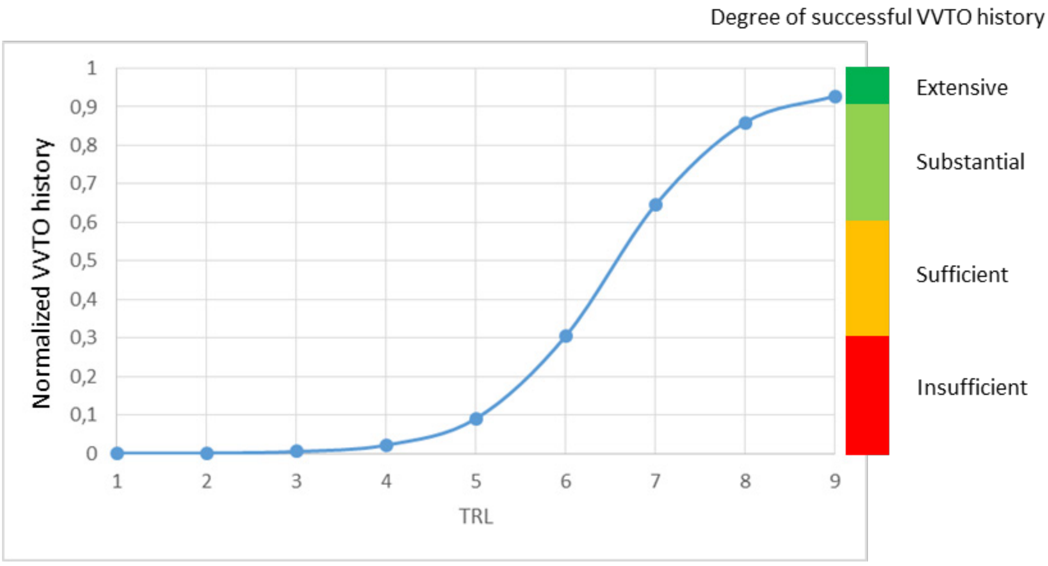

Fig. B-8: TRL mapped to normalized VVTO history (V)

The technology's design (D)

The design heritage values are estimated by the number and degree of subsystems that are based on heritage designs. Estimate the design heritage values for each of the subsystems according to

Table B-20. Once the appropriate category is selected, estimate a design heritage value D_i within the range.

Table B-20: Categories for component design heritage and their respective values Values

Design heritage categories	**Values for D_i**
New design	$0 < D_i \leq 0.25$
Component design with large modifications or new design with few heritage parts	$0.25 < D_i \leq 0.5$
Component design with major modifications	$0.5 < D_i \leq 0.75$
Component design used as-is or minor modifications	$0.75 < D_i \leq 1$

1. Assign weightings w_i to a component that is a proxy for its complexity. By default the weightings are set to 1.
2. Calculate the design heritage value by using the following equation:

$$D = \frac{\sum_{i=1}^{n} w_i D_i}{\sum_{i=1}^{n} w_i}$$

Discount on design heritage:

Unplanned modifications likely take place when heritage technologies are used. Hence, a sensitivity analysis should be performed. The following rule-of-thumb values are recommended for obtaining conservative values for design heritage. Multiply the design heritage by the following factors to obtain a conservative value:

- Factor 0.5 for assessments in Phase pre-0, 0, and A
- Factor 0.3 for assessments in Phase B
- Factor 0.1 for assessments in Phase C and later[19]

The underlying capabilities / competencies associated with the technology (C)

Pre-selection of potential suppliers:

1. Have they developed similar technologies or do they have a running production line (can the product be procured off-the-shelf)?
2. If potential suppliers currently do not have the capability, would they be able to acquire the capability within the given timeframe? If no, exclude the potential supplier.
3. Is the potential supplier a small / medium enterprise or large company? Small and medium enterprises are more likely to suffer capability loss, as they are more vulnerable to changes in personnel, equipment and facilities, etc. Large enterprises are more likely to be able to compensate changes as they have more mature processes and supply chains. However, personnel might often change its position in large enterprises.
4. If the technology is critical, it is worth performing an audit during a meeting with a potential supplier or to perform an on-site audit.
    a. Is key personnel available?
    b. Is key equipment and facilities available?
    c. Is documentation and data available?
    d. Are materials and other consumables for development / manufacturing available?

The most relevant capabilities for systems acquisition are the development and production capabilities. For these two capabilities, categories and metric values were defined, as shown in Table B-21 and Table B-22. If more than one

[19] Most unintended modifications occur in Phase C (Coonce et al., 2009).

capability needs to be assessed, we calculate the arithmetic mean of all capabilities. The arithmetic mean can be interpreted as "the degree to which capabilities exist".

$$C = \frac{1}{n}\sum_{i=1}^{n} C_i$$

For getting a conservative estimate, select the lowest capability out of all capabilities.

Table B-21: Technology development and systems engineering capability metric (C)

Technology development / systems engineering capability categories	**Values for capability C**
- A similar technology has been developed by the organization. - The class of technology, its application, performance range, quality and reliability are similar. - The technology is within the experience base of the organization. All of the following conditions must be true: - Data and documentation exists - Access to skilled key personnel that is the same as for the previous development - Proven development processes exist. - Proven development methods, tools, and models exist.	$0.9 < C_{dev} \leq 1.0$
- A similar technology has been developed by the organization. - The class of technology has to be similar, as well as its application. - The performance range, quality and reliability may differ. - The technology is within the experience base of the organization. All of the following conditions must be true: - Data and documentation exists - Access to skilled key personnel that is the same as for the previous development - Proven development processes exist. - Proven development methods, tools, and models exist.	$0.5 < C_{dev} \leq 0.9$
- A technology based on similar capabilities has been developed. - The class of technology is different, e.g. jet engine versus rocket engine. - The technology or parts of the technology are outside the experience base of the organization. All of the following conditions must be true: - Data and documentation exists - Access to skilled key personnel that is the same as for the previous development - Proven development processes exist. - Proven development methods, tools, and models exist.	$0.2 < C_{dev} \leq 0.5$
One or more of the following conditions are true: - Marginal to no capability similarity. - The technology is significantly outside of the experience base of the organization.	$0 \leq C_{dev} \leq 0.2$

Table B-22: Manufacturing capability similarity metric (C)

Manufacturing capability categories	Values
- Running production line for technology All of the following conditions must be true: - Data and documentation exists - Skilled key personnel is available and the same as for previous technology - Proven manufacturing processes are available - Proven development methods and tools are available - Required materials are available - Manufacturing equipment, software, and metrology is available - Manufacturing tooling is available - Manufacturing facilities is available	$0.9 < C_{prod} \leq 1.0$
- Production line shut down 1-2 years ago or state of the art / state of experience All of the following conditions must be true: - Skilled key personnel can be reactivated - Data and documentation exists - Proven manufacturing processes are available - Proven development methods and tools are available - Required materials are available - Manufacturing equipment, software, and metrology is available - Manufacturing tooling is available - Manufacturing facilities are available	$0.5 < C_{prod} \leq 0.9$
One of the following conditions is true: - No running production line since several years; - Similar production line for different technology running and can be adapted. All of the following conditions must be true for a similar technology: - Key personnel available or can be reactivated - Data and documentation exists - Proven manufacturing processes exist and can be adapted. - Proven development methods and tools exist and can be adapted. - Required materials are available - Manufacturing equipment, software, and metrology exists - Manufacturing tooling exists - Manufacturing facilities exist	$0.2 < C_{prod} \leq 0.5$
One or more of the following conditions are true: - No experience in producing the technology - Data and documentation does not exists - Key personnel is not available or cannot be easily reactivated - Proven manufacturing processes do not exist or difficult to adapt them. - Proven development methods and tools exist do not exist. - Required materials are not available - Required manufacturing equipment, software, and metrology does not exist - Manufacturing tooling exists - Manufacturing facilities do not exist.	$0 \leq C_{prod} \leq 0.2$

Table B-23: Customer-supplier relationships capability metric

Customer-supplier relationship capability categories	**Value**
Repeatedly successful customer – supplier relationship	$0.9 < C_{sup} \leq 1.0$
Customer and supplier have engaged in a successful relationship	$0.2 < C_{sup} \leq 0.9$
Customer and supplier have engaged in a successful trial relationship, e.g. trial project, trial order.	$0.1 < C_{sup} \leq 0.2$
No prior project has been realized successfully	$C_{sup} = 0$

Table B-24: Operational capability metric

Operational capability categories	**Value**
Repeatedly successful experience with operating a similar system. Operations process is formalized and is repeatable. All of the following conditions must be true for a similar technology: - Facilities are available - Data and documentation exists - Infrastructure is available, e.g. IT-infrastructure for data storage - Operations systems are available, e.g. antennae, command and control - Skilled key personnel is available	$0.9 < C_{op} \leq 1$
Successful experience with operating a similar system but knowledge is not captured formally. Operations is performed ad-hoc. All of the following conditions must be true for a similar technology: - Facilities are available - Data and documentation exists - Infrastructure is available, e.g. IT-infrastructure for data storage - Operations systems are available, e.g. antennae, command and control - Skilled key personnel is available	$0.2 < C_{op} \leq 0.9$
Successful experience with operating a different system but part of the knowledge can be transferred, e.g. driving a small van versus driving a truck. Knowledge is not captured formally. Operations is performed ad-hoc. All of the following conditions must be true for a similar technology: - Facilities are available - Data and documentation exists - Infrastructure is available, e.g. IT-infrastructure for data storage - Operations systems are available, e.g. antennae, command and control - Skilled key personnel is available	$0.1 < C_{op} \leq 0.2$
No prior experience with operating a similar system or one or more of the following elements is lacking: - Facilities - Data and documentation - Infrastructure, e.g. IT-infrastructure for data storage - Operations systems, e.g. antennae, command and control - Skilled key personnel	$C_{op} = 0$

Calculate the heritage metric

1. Calculate H for conservative values of D and C
2. Calculate H for the optimistic values of D and C
3. Report the optimistic and conservative values for H.
4. Compare values of H between different technologies