Systems Engineering for Computing Systems at Accelerator based Research Facilities

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Doctoral Thesis
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Abstract

Large research facilities are major research enablers for expanding fields in various natural sciences. Traditionally built for physics and astronomy, nowadays fields like life sciences, medicine, molecular sciences and material sciences have become the driving forces, especially for particle accelerator based research facilities. Driven by the ever-increasing expectations of the scientific user community, new research facilities usually introduce novel technical concepts and architectures customised for the addressed research communities. Thus they represent the state-of-the-art in the domain, usually in a unique configuration. Continuous upgrades and adjustments to research trends entail that research facilities maintain a prototypical character throughout their lifetime, leading to a significant degree of openness as a system.

This persistent trend among research facilities has resulted in high degrees of technical and operational complexity. Today's research facilities are *complex socio-technical systems* posing challenges to their development, construction, operation and maintenance. The need for multi-disciplinary engineering and the coordination between the diverse internal and external stakeholders make the application of Systems Engineering (SE) highly desirable. Therefore, this thesis assesses the socio-technical factors and proposes methods for applying SE in the particle accelerator domain for effective operational management.

A common theme in the technical design of large research facilities is the heavy reliance on control and computing systems in virtually all operational and maintenance processes. The application areas of control and computing systems include system control and monitoring tasks, data acquisition and processing, the provision of networks and a variety of software-based services. Both in-house users and temporarily visiting research groups depend on these control and computing systems. The controls and computing systems domain is especially affected by the mentioned engineering challenges due to its broad range of application cases and its highly integrative role in the research facilities; the facilities are thus complex socio-technical *cyber-physical systems*.

The thesis addresses the application of Systems Engineering and Systems Thinking at large research facilities, in particular for the development of control and computing systems. The research has been performed as Action Research activities at the European Spallation Source, a world leading spallation neutron source currently in construction and at the synchrotron light source MAX IV, both located in Lund, Sweden. The research contributions of this thesis are in the areas of System Integration, Requirements Engineering, Communication pragmatics in engineering, Systems of Systems Engineering, reliability and Systems Engineering Management. More specifically, the following contributions are presented:

An Integration Strategy that establishes SE for control systems at the ESS has been elaborated. It is based on the informational needs for successful integration. The approach guides the generation of integration-relevant

information, and supports its accessibility and management by utilising System Integration Management Plans.

A novel approach to the process implementation for Requirements Engineering (RE) has been developed. It is based on tailoring views, activity patterns, informational structures, tools and services, and has been applied to the ESS control system development. Benefits of treating the RE process implementation itself as an Agile project are presented.

Systems of Systems (SoS) Engineering has been tailored for application at the ESS regarding mission critical systems. This case study investigates the SoS concepts for research facilities and indicates their suitability. Further, the Systems of Systems Engineering tailoring has been inspired by and drawing upon key concepts from functional safety standards in order to meet the high reliability expectations towards the ESS. **This approach presents a way to achieve high reliability goals for complex systems that surpass more traditional system complexity levels.**

A support concept for Systems Engineering Management (SEM) in environments with low degrees of stable, consistent development processes and documentation quality is also presented. The concept, named Conceptual Reasoning, describes the utilisation of viewpoints and the interrelation of elements between them on a conceptual level. Conscious improvement of Conceptual Reasoning practices in system developments is a way to enhance the success of crucial stakeholder communication.

All solutions were derived from and tested in the Action Research setting. The practical utilization of Systems Engineering in multiple, domain-typical system developments has been continuously analysed for barriers to SE application, and resulted in **recommendations for Systems Engineering Management (SEM) in the domain**. **An SEM reference model is presented as a support tool for Systems Engineering managers in the domain,** which aids in the identification of SE problems.

Future research goals are motivated and research methodology aspects in this field are discussed in order to encourage further progress.

Sammanfattning

Stora forskningsanläggningar möjliggör forskning för expanderande fält inom naturvetenskap. Traditionellt byggda för fysik och astronomi, har numera områden som biovetenskap, medicin, molekylär vetenskap och materialvetenskap blivit drivkrafter särskilt för forskningsanläggningar baserade på partikelacceleratorer. På grund av ständigt ökande förväntningar från vetenskapliga användare, introducerar nya forskningsanläggningar nya tekniska koncept och arkitekturer anpassade för de avsedda forskningsfälten. Således representerar de den mest moderna teknologin i området, vanligtvis i en unik konfiguration. Kontinuerliga uppgraderingar och anpassningar till forskningsutvecklingen innebär att forskningsanläggningar upprätthåller en prototypisk karaktär under hela sin livstid, de utgör till hög grad ”öppna system”.

Denna beständiga trend bland forskningsanläggningar har resulterat i en hög grad av teknisk och operativ komplexitet. Dagens forskningsanläggningar är *komplexa socio-tekniska system* som innebär utmaningar för deras utveckling, konstruktion, drift och underhåll. Behovet av tvärvetenskaplig verksamhet och samordningen mellan de olika interna och externa intressenterna gör tillämpningen av ”Systems Engineering” (SE) mycket önskvärd. Denna avhandling undersöker därför socio-tekniska aspekter och föreslår metoder för att tillämpa SE i partikelaccelerator-domänen för en effektiv operativ ledning.

Ett kännetecknande drag för den tekniska utformningen av stora forskningsanläggningar är det starka beroendet av styr- och datasystem i nästan alla drifts- och underhållsprocesser. Dessa processer och tillämpningsområden inkluderar styrsystem och övervakningsuppgifter, datainsamling och bearbetning, tillhandahållande av nätverk och åtskilliga mjukvarubaserade tjänster. Både internanvändare och tillfälligt besökande forskargrupper är beroende av dessa styr- och datasystem. Styrsystem och datasystem påverkas särskilt av de nämnda utmaningarna genom deras roll för integration i forskningsanläggningar; dessa anläggningar utgör alltså komplexa socio-tekniska *cyberfysiska system*.

Avhandlingen behandlar tillämpningen av ”Systems Engineering” och ”Systems Thinking” vid stora forskningsanläggningar, med speciell inriktning på utvecklingen av styr- och datasystem. Forskningen har bedrivits genom aktionsforskning på European Spallation Source, en världsledande spallations-neutronkälla (under konstruktion) samt på synkrotronljuskällan MAX IV, båda belägna i Lund, Sverige. I avhandlingen presenteras forskningsresultat inom områdena systemintegration, kravhantering, kommunikations-pragmatik inom ingenjörskonst, utveckling och underhåll av ”system av system” (Eng. ”Systems of Systems Engineering”), tillförlitlighet och ledning av ”System Engineering”. Mer specifikt presenteras följande resultat:

En integrationsstrategi som etablerar SE för styrsystem på ESS har utarbetats. Strategin är baserad på informationsbehoven för en framgångsrik integration. Strategin stödjer generering av information relevant för

systemintegration, och dess tillgänglighet och förvaltning genom att introducera förvaltningsplaner för systemintegration.

En ny metod för att införa en kravhanteringsprocess har utvecklats. Metoden baseras på skräddarsydda vyer, aktivitetsmönster, informationsstrukturer, verktyg och tjänster, och har tillämpats vid ESS styrsystem-utveckling. Fördelar med att behandla införande av kravhanteringsprocessen som ett agilt projekt presenteras.

Utveckling och underhåll av ”System av system” har skräddarsytts för tillämpning vid ESS verksamhetskritiska system. Denna fallstudie analyserar SoS-koncept för forskningsanläggningar och anger deras lämplighet. Denna anpassning har inspirerats av och utgått från grundläggande koncept från funktionella säkerhetsstandarder för att uppfylla de höga tillförlitlighetskrav som gäller vid ESS. **Detta tillvägagångssätt utgör ett sätt att uppnå höga tillförlitlighetsmål för komplexa system som överträffar mer traditionella systemkomplexitetsnivåer.**

Ett stödkoncept för ledning av ”Systems Engineering” (SEM) i miljöer med låg grad av stabila och konsekventa utvecklingsprocesser och dokumentationskvalitet presenteras också. Konceptet, som kallas ”Conceptual Reasoning”, beskriver användningen av ”meta-vyer” (Eng. ”viewpoints”) och det inbördes förhållandet mellan element inom dem på en konceptuell nivå. Medveten förbättring av ”Conceptual Reasoning” inom systemutveckling är ett sätt att förbättra kommunikationen mellan intressenter.

Alla lösningar härleddes från och testades inom ramen för aktionsforskning. Den praktiska användningen av ”Systems Engineering” i flera, domäntypiska systemutvecklingar har analyseras kontinuerligt och lett till att barriärer till SE-tillämpning identifierats. Detta har i sin tur resulterat i **rekommendationer för Systems Engineering Management (SEM) i domänen.** En SEM-referensmodell presenteras som ett stödverktyg för ”Systems Engineering”-koordinatorer i området, vilket underlättar identifieringen av SE-problem.

Framtida forskningmål presenteras och diskuteras tillsammans med aspekter på forskningsmetodik, i syfte att stimulera fortsatt forskning inom området.

List of appended papers

Paper A
Requirements Engineering for Control and Computing Systems at large research facilities: Process Implementation and a case study.
Thilo Friedrich, Miha Reščič.
25th Annual INCOSE International Symposium (IS2015)
Seattle, WA, July 13th-16th, 2015
Thilo wrote the text and developed the paper content. Miha contributed project management insights, reviewed and provided feedback based on the shared participation in the case study.

Paper B
Conceptual Reasoning in the Development of Particle Accelerator Control Systems. A case study on controls for a novel accelerator design.
Thilo Friedrich.
IEEE 11th International Conference on System of Systems Engineering (SoSE 2016)
Kongsberg, Norway, June 12th – 16th, 2016
Thilo is the sole author.

Paper C
An Integration Strategy for Controls and Computing Systems at a large Particle Accelerator based Research Facility.
Thilo Friedrich, Daniel Piso Fernández.
IEEE 11th International Conference on System of Systems Engineering (SoSE 2016)
Kongsberg, Norway, June 12th – 16th, 2016
Thilo wrote the text and developed the paper concept. Daniel reviewed and provided feedback, based on the shared work on elaborating the strategy for Daniel's group (Integration group in the Integrated Control System division at the European Spallation Source).

Paper D
Systems of Systems Engineering for Particle Accelerator based Research Facilities.
Thilo Friedrich, Christian Hilbes, Annika Nordt.
11th Annual IEEE International Systems Conference.
Montreal, Quebec, Canada. April 24th-27th, 2017 (accepted)
Thilo wrote the text. The presented approach originated from ideas from Christian, which together with Thilo and Annika were introduced and tailored to the ESS Machine Protection environment. Annika supported the effort as group leader of the ESS Machine Protection group. Christian and Annika reviewed and provided feedback.

Additional Publications

Theses

Engineering Aspects of Computing Systems for Accelerator based Light Sources
Friedrich, Thilo
KTH, School of Industrial Engineering and Management (ITM), Department of Machine Design, Mechatronics.
2013 (English) Licentiate thesis, monograph

Conference proceedings

Machine Protection Strategy for the ESS
Annika Nordt, Timo Korhonen, Thilo Friedrich, Christian Hilbes.
6th International Particle Accelerator Conference.
Richmond, VA, USA, May 3rd-8th, 2015

Systems and Software Engineering for the MAX IV Facility
Thilo Friedrich, Martin Törngren.
12th International Conference on Accelerator and Large Experimental Physics Control Systems.
Kobe, Japan, Oct. 12-16th, 2009

Surveying Software Technology for Accelerator Control Systems.
Thilo Friedrich, Martin Törngren.
7th international workshop on Personal Computers and Particle Accelerator Controls
Ljubljana, Slovenia, Oct. 20th-23rd, 2008

Technical Reports

Development of a Software based Control System for the I1011 Beamline Front End System.
T. Friedrich, J.H. Dunn, B. Wrenger, D. Arvanitis.
MAX-lab Activity Report 2006.

Table of Content

1 Introduction

This chapter introduces to the background of this research work, describes its motivation, and explains the structure of the thesis.

1.1 Background

Complex and capital-intense research facilities have become major research tools for expanding knowledge in different scientific fields and for the characterization of natural phenomena. Facilities that achieve breakthrough discoveries, such as the Large Hadron Collider (LHC)[1] at CERN with the discovery of the Higgs particle, or the Laser Interferometer Gravitational-Wave Observatory[2] (LIGO) for the first measurements of gravitational waves are widely recognized by the public. These are important and popular "lighthouse" results that demonstrate the capability and relevance of large research facilities and legitimise the investments. In a second row, behind the "lighthouse" research facilities however, further large research facilities exist and provide research enabling services to thousands of research groups world wide. These are usually recognised mostly within their research communities and their regional contexts. The fields of application of these large research facilities span material science, life sciences, environmental sciences, molecular sciences and sub-atomic sciences. They also cross disciplines such as physics, chemistry, biology, engineering, astronomy, geology and even archaeology. As focal points and catalysts of scientific advancement, such research facilities are and will be central elements in the scientific landscape of the 21st century.

Some of these large research facilities are strongly domain-focused installations (such as the mentioned LHC and LIGO), designed purposely for answering quite specific research questions. Complementing these, there are also many highly flexible, multi-purpose research facilities, which typically provide a wide range of research support centred on a core service provided by an advanced machine. Such facilities serve a wide range of user groups, who are not permanently based at the facility, but 'use' its experimental possibilities for a limited amount of time. Hence they are widely, admittedly colloquially, called "user facilities"[3].

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[1] e.g. Large Hadron Collider (LHC) for particle physics research; or the International Thermonuclear Experimental Reactor (ITER) for nuclear fusion

[2] see ligo.org

[3] Obviously, also very domain-specific facilities built to answer very narrow research questions, have users. In spite of this ambiguity, the term 'user facility' shall be used in this work to denote multi-purpose facilities as described, this as a concession to the probably largest community with genuine interest in research facilities, which is the 'temporary visiting researcher', colloquially called 'user'.

Prominent and numerous among user facilities are *particle accelerator based research facilities,* which provide particle beams of special qualities and experimental infrastructures tailored to a variety of different research fields. Particle accelerator based research facilities are commonly distinguished by the particle beam they provide as the primary service:

- *synchrotron light source* based laboratories provide photon beams (light) [4],
- *neutron sources* provide neutron beams[5],
- other facilities provide beams of e.g. protons, electrons, myons, or heavy particles.

In particular, synchrotron light sources and neutron sources are typically built as user facilities. They host a range of experiment installations based on the provision of synchrotron light or neutron beams, respectively.

Controls and Computing Systems in research facilities. A persistent trend among large research facilities of all kinds is the heavy reliance on *control and computing systems* to fulfil their tasks. These systems are utilized for control and monitoring, data acquisition and processing, equipment integration and a variety of information services. System types in this domain include complex SCADA [6] installations, safety related protection systems, custom-made software services, equipment controllers, timing systems, data acquisition and processing systems and information management systems. In essence, the controls and computing infrastructure is of practical relevance for anyone interacting with the technical systems of a research facility.

Construction and operation of research facilities. The construction and operation of research facilities constitute considerable investments, typically financed on the national or international level. Depending on the chosen technologies, the aspired research support and quality, the typical costs for new particle accelerator facility projects are several hundred million Euros or more. Research facility development and construction projects usually span several years, in some cases even decades, from ideation to operation start. Operation and maintenance also encompasses decades. While the worldwide yearly turnover within this domain is nowhere captured, it can be roughly assumed to be in the one-digit billion[7] Euro range.

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[4] E.g.; Diamond Light Source, MAX IV or European XFEL for synchrotron light based research.

[5] E.g. Spallation Neutron Source (SNS), European Spallation Source

[6] Supervisory Control And Data Acquisition. It refers to the integrative control layer in industrial, process, power or other plants.

[7] To the best knowledge of the author, the yearly turnover in this domain has not been monitored or estimated elsewhere. The following approximation led to the given estimate: Numerically, most large accelerator based research facilities are light sources. www.lightsources.org lists 47 Synchrotron light

The development, construction and continuous operation of research facilities introduce some domain-typical challenges to the executing organisation:

- Research facilities introduce novel technical concepts and architectures in various technological areas, resulting in an exploratory style of design and development with significant degree of uncertainties.
- Research facilities are typically unique, representing the current state-of-the-art in research engineering customized for the needs of particular research communities.
- Research facilities typically maintain a prototypical character throughout their lifetime. Continuous upgrade activities according to technological progress and changing research demands are difficult to anticipate over a facility's lifetime.
- Research facilities are typically designed by a mix of highly specialized individuals with heterogeneous professional backgrounds in often temporary, singular project conditions. Significant integration efforts on the technical level as well as on the organizational and information management level are required.

Engineering at research facilities. Modern particle accelerator facilities are realised by complex constellations of interacting systems, forming overall a complex socio-technical system. The controls and computing infrastructure within a particle accelerator research facility plays a special role here, as it pervades a facility in the very technical sense (controls are distributed, 'everywhere'). Further, control systems are the primary way for humans to interact with the research machinery, as they provide information and enable to steer the physical processes that are required to conduct research. This encompasses the operation of the machinery, but also ties into managerial information used in system maintenance and management.

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source based facilities and 14 FEL facilities. This includes such different facilities as the university facility DELTA as well as the European XFEL. Still, if we assume further an average life time costs of 500 Mio Euro per facility, and an average life time of 25 years, we reach a ~1200 Mio Euro turnover for light sources alone. To this, we add comparable life cycle costs per operational year for ~5 neutron sources (ESS, SNS, ISIS), some heavy ion sources or high energy physics facilities (LHC, FRIB, FAIR), and the largest ground-based space observatories (LIGO, ALMA), which altogether should sum up at a comparable magnitude as the light sources. Thus the proposed 'one-digit billion Euro' range seems to be a reasonable, albeit crude, estimation of magnitude.

1.2 Motivation of this research

The creation of research facilities using appropriate engineering methods constitutes an engineering problem for the overall facility as well as for the controls and computing infrastructure in particular. **This thesis explores the relevance of Systems Engineering of controls and computing systems for particle accelerator based research facilities.**

The aspiration of this thesis is

- to support the engineering success of the studied and future research facilities,
- to contribute to the understanding of Systems Engineering and its application in general,
- to give insights into the development of control and computing systems for large complex facilities.

The target audiences for this thesis include

- the community of engineers, scientists, practitioners working for and at large research facilities (accelerators, observatories, etc.),
- the Systems Engineering community and its related fields, interested in the application of SE,
- the controls and computing systems community, interested in engineering methodology for control and computing systems in large complex facilities.

Finally, it is the aspiration of this thesis to outline the topic of "Systems Engineering at Research Facilities" as a research field in its own right. This is based on the differences in industry domain characteristics, when comparing to other industry domains such as industrial plant construction, software engineering, aerospace, defence or electronic product design. While "System Engineering at Research Facilities" has clear overlaps with all the aforementioned domains, it also needs to combine and tailor SE based on its own particular domain and project characteristics. Relevant factors arise from system properties, operational characteristics, organisational and cultural factors. An overview on these factors can be found in chapter 3, which outlines operational characteristics of research facilities. The application of Systems Engineering in the construction of research facilities is overall not well described in the literature and problematic in practice. A reason for this situation is the difficulty of researching successful SE application in the domain. So, characterising "Systems Engineering at Research Facilities" as a research field here means to (I) identify the difficulties for *understanding* the successful application of SE in the domain, and (II) to outline an approach to SE research in the domain that fits the domain-typical characteristics, providing *practical viability* of such research.

Further, this thesis aims to open the view for studies beyond the scope and possibilities of this singular PhD thesis work. Characterising the research field is also intended to stimulate follow-up research, both in regard to SE topics and its research methodology concerns.

The following chapter 1.3 explains how the structure of this thesis responds to these goals.

The work for this thesis has contributed to the construction of two large, world-leading research facilities, the European Spallation Source ESS, a neutron source based facility, and the MAX IV laboratory, a synchrotron light source. Both are located in the city of Lund, Sweden, in close vicinity to each other. An artist's aerial view is given in Figure 1.

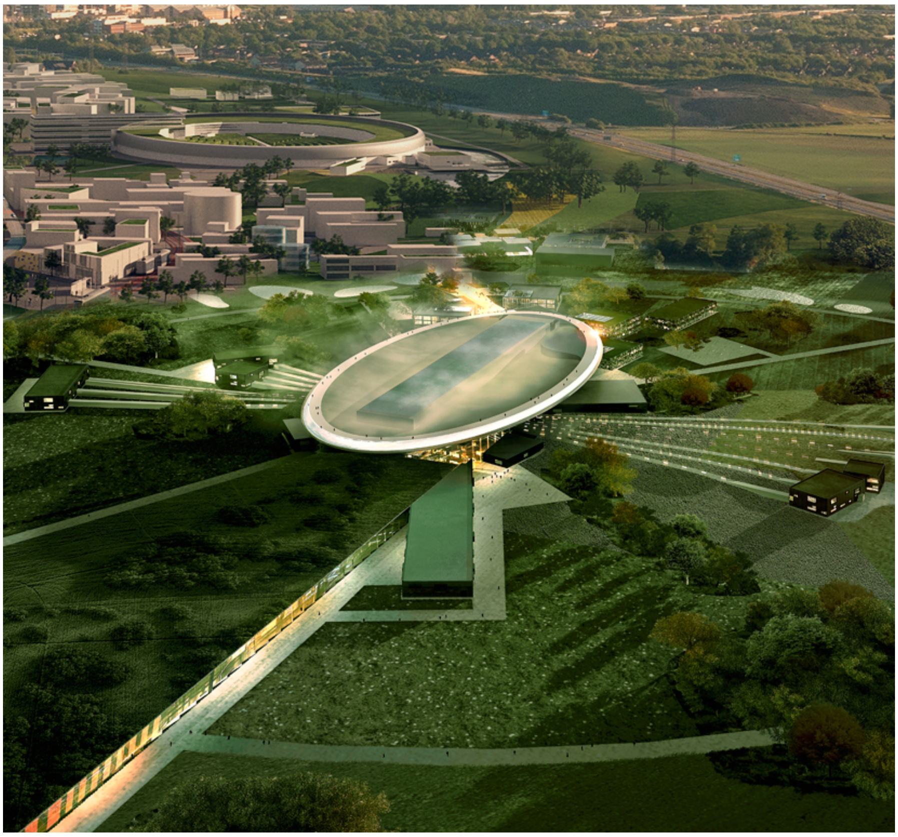


Figure 1: Aerial view of the European Spallation Source ESS and MAX IV laboratory in Lund

It shows the ESS in the foreground, focusing on the Target Station building with several surrounding buildings for neutron science stations and utility. The ESS proton accelerator is underground, incoming from the lower left side of the picture. The round structure in the background is the main building of the MAX IV facility, which hosts a 3 GeV storage ring and its synchrotron light experiments.

1.3 Structure of the thesis

This thesis aspires to present and analyse a wide range of aspects on Systems Engineering for a peculiar type of super-high-tech socio-technical system in a structured form. The approach for this thesis follows this train of thought:

- An introduction to the domain motivates this research work.
- The overall research goals and the more focused research questions are presented in chapter 2. Further, the research approach is explained and motivated, both in theory and its practical application. The research contributions of the practical impact of the work are outlined.
- The engineering domain is outlined in chapter 3. Large particle accelerator based research facilities are introduced and characterised in regard to their main operational processes and organisational context. This chapter builds an understanding of the engineering environment.
- Chapter 4 introduces to various Systems Engineering aspects and related disciplines. It outlines the state of the art in the SE community, and compares to the state of practice in the engineering domain. The relevance of SE for accelerator based research facilities, especially for controls and computing systems, is outlined.
- The research findings, their validity and transferability are discussed in chapter 5. Reflections on the research approach are presented. Overarching conclusions are discussed on the application and management of SE in the domain.
- Future research topics on SE in the domain are proposed in chapter 6.

The appended papers are referenced from various places within the thesis. They complement the thesis with a more focused view on a particular subject.

2 Research Goals and Approach

2.1 Research goals and questions

The overall purpose of this research work is to contribute to an encompassing understanding of Systems Engineering (SE) for the effective and efficient management of the controls and information systems infrastructure at large, primarily accelerator based research facilities[8].

To motivate and guide this research work on a more programmatic level, *research goals* have been identified that are oriented at the demands and challenges in the domain. These research goals turned out to be quite wide and extend beyond the achievement horizon of a singular thesis. Based on the research goals, more specific *research questions* have been formulated that have guided a focused investigation.

In this sense, the following wider research goals have been identified as relevant to this domain:

1. To obtain an understanding of the relation of state-of-the-art technologies used in the domain and their relation to the Systems Engineering practices.
2. To obtain an understanding of the *best practices* in Systems Engineering and related fields for computing systems at accelerator based research facilities.
3. To gain an overview of the state-of-the-art methods of Systems Engineering that are *compatible*, or applicable, to accelerator based research facilities. Criteria for compatibility, or applicability, include Systems Engineering management aspects as well as technological and organisational properties. The purpose of this goal is to inspire methodological cross-fertilisation.
4. To develop a *body of knowledge on Systems Engineering Management* for the studied domain, computing systems at accelerator based research facilities. This includes

[8] The majority of large research facilities are particle accelerator based. Other large research facilities, e.g. for astrophysics, are large telescopes or installations such as ALMA or LIGO use other basal physics phenomena, but nevertheless share a lot of systems engineering characteristics with accelerators and also use similar or the same technologies, especially in the controls domain.

   a. A comprehensive overview on the core and related disciplines and their relations.
   b. A collection of method frameworks suitable to the domain, including system life cycle approaches.
   c. An information model suitable for the domain.
   d. Application in practice: tools, training, management.
5. To develop the domain as a *research field*. This includes guidance and reflections on research methodology and validity. It also leads towards a map of uncharted territory, i.e. topics for future research in the domain.

These wider goals describe essentially a continuous program for the involved communities, which are primarily the accelerator community, Systems Engineering community and control and computing systems community. These goals set the programmatic frame of reference for the more detailed contributions of this thesis work. The conducted investigations have been guided by more specific research questions. These research questions are listed in Table 1, which gives an overview and links to the thesis and papers that are the main contributions in answering them.

Table 1: Research questions

Q1: What characterises Systems Engineering at accelerator based research facilities? What operational and organisational factors influence the currently predominant approaches to SE?	chapter 3
Q2: What standards and frameworks exist for Systems Engineering at accelerator based research facilities?	chapter 4
Q3: What are characteristic challenges for the Systems Engineering Management (SEM) in the control systems and computing systems domain at accelerator based research facilities? How can SEM issues be approached?	chapter 4, esp. section 4.1 section 5.5 - 5.8
Q4: What are the relevant aspects for the implementation of Requirements Engineering in the control systems and computing systems domain at accelerator based research facilities?	paper A section 3.6.1
Q5: How can the SE-related communication among stakeholders be improved in environments with largely immature SE practices?	paper B sections 5.5 - 5.8
Q6: How can Integration be facilitated in the control systems and computing systems domain at accelerator based research facilities?	paper C section 4.5.3
Q7: How can Machine Protection (high reliability and availability goals) be realised at large, complex accelerator facilities with Systems of Systems characteristics?	paper D sections 4.7, 4.8
Q8: What is the state of research on SE for large research facilities? What are relevant future trends and research topics for Systems Engineering in the particle accelerator domain?	section 5.9 chapter 6
Q9: What methodological problems for Systems Engineering research in the domain exist, and how can they be addressed?	section 2.3 sections 5.2 - 5.4

2.2 Research Contributions and Impact

Systems Engineering as a multi-disciplinary approach is applied for the creation of large, complex systems since the middle of the 20th century. While initially in particular in the aerospace and defence sectors, SE has also been applied in the more research-oriented NASA space programs (e.g. Apollo program). Other capital-intense industry sectors picked up the methods and adopted them for their needs (INCOSE SE Handbook, 2015).

Since roughly the same time, large research facilities based on particle accelerators have been built, initially for the advancement of physics and later for many other sciences. Yet to the present day SE never reached a comparable practical relevance in the accelerator construction domain. As part of this thesis work, an analysis of the organisational and process context of SE in the construction and operation of research facilities is presented (chapter 3). This analysis describes the multitude of organisational roles and processes that particle accelerator facility organisations have to cope with. Factors are outlined that distinguish the accelerator research facility construction and operation from e.g. the design and operation of space shuttles, oil rigs or consumer products. The relative broadness of these roles and processes, together with the relative uniqueness of individual project conditions, indicates the difficulty of this sector to settle on a commonly applicable and accepted set of Systems Engineering methods and concepts for this domain.

In the course of this thesis work, a number of contributions and impacts have been achieved with the goal improving SE knowledge for its application at research facilities, and improving the engineering practices in this sector. An overview of these contributions and impacts is given in this chapter. To distinguish the *generation of general knowledge on Systems Engineering* from *beneficial achievements within the study environments* (i.e. the ESS and MAX IV organisations), the former is here called *research contribution*, and the latter is called *impact*.

While the agreement with ESS set the frame for the whole PhD project, peer-reviewed publications have been produced in the course of this work (see attached papers) and other publications have been produced. These publications focused the work for a certain time period on a particular topic within the scope of this thesis, present partial research contributions and allowed to acquire intermediate feedback.

The key conclusion of this thesis is: ***For the successful development and operation of highly complex, modern particle accelerator based research facilities, the careful and conscious application of Systems Engineering approaches is beneficial in order to meet the facility's overall goals.*** The reasons for this and application aspects of System Engineering are explained throughout this thesis and its related publications. In the following, the research contributions are summarised (2.2.1), the research approach is explained (2.3) and the key research activities are described, including their impact on the study environment (2.4).

2.2.1 Research contributions

More concretely, in the course of this thesis work, the following contributions have been provided:

- *Contribution I* - A systematic analysis of the *organisational and process context* of SE in the construction and operation of research facilities is described in chapter 3. The findings frame the choices of SE methods and concepts used in the domain. They also give relevant context for the research approach of this thesis work, such as the selection of Action Research activity threads and the reliance on qualitative evaluations. The analysis is oriented at the process analysis approach in (Muller, 2012).

- *Contribution II* - A novel *approach to the process implementation for Requirements Engineering* (RE) is presented in paper A, which is based on tailoring views, activity patterns, informational structures, tools and services to the domain, in particular to the ESS control system development. Benefits of treating the RE process implementation itself as an Agile project are presented.

- *Contribution III* - An *Integration Strategy* that establishes SE for control systems at the ESS has been elaborated in paper C. It is based on the informational needs for successful integration. The approach guides the generation of integration-relevant information, and supports its accessibility and management by utilising System Integration Management Plans.

- *Contribution IV* - *Systems of Systems (SoS) Engineering* has been tailored to application at the ESS for the engineering coordination of mission critical systems. This case study analyses and indicates the suitability of the SoS concept for research facilities. Further, the Systems of Systems Engineering tailoring has been oriented at *functional safety standards* in order to meet the high reliability expectations towards the ESS. This approach presents a way to achieve high reliability goals for complex systems that surpass more traditional system complexity levels. The approach is described in paper D.

- *Contribution V* - Systems Thinking and its application in the studied domain has been a key subject in the Action Research activities. The analysis of the case study environment exhibited significant potential for barriers to SE application in this area. *A theoretical explanation for Systems Thinking and its barriers* is presented in chapter 4.2, together with propositions for improvements. This chapter complements the attached papers which touch and build on Systems Thinking in the context of their respective subject, but have another main focus. Likewise, it complements the remaining sections chapter 4 which relate Systems Thinking to the according SE aspect.

- *Contribution VI* - Systems Engineering Management is the process that enables Systems Engineering activities for particular system developments. An *analysis of Systems Engineering Management and its domain-specific challenges and characteristics* has been presented in chapters 5.6 and 5.7, together with recommendations for practical improvements. Paper A includes an approach for managing system life cycle process implementation that is based on Agile methods, exemplified at the RE process, which is another contribution component to this topic.

- *Contribution VII* - The action research activities have been used to analyse communication practices in engineering within the case study environment, and resulted in a *support concept for Systems Engineering Management (SEM) in environments with low degrees of stable, consistent development processes and documentation quality.* The concept, named Conceptual Reasoning, describes the utilisation of viewpoints and the interrelation of elements between them on a conceptual level. Conscious improvement of Conceptual Reasoning practices in system developments is a way to enhance the success of crucial stakeholder communication. Paper B explains the subject in detail.

- *Contribution VIII* - A *reference model for Systems Engineering Management* has been presented in chapter 4.1. It is intended to support a Systems Engineering facilitator at a research facility, particularly for the controls and computing systems domain, in the identification of SEM aspects. It is intended to be a quick or mental reference model that helps in maintaining a holistic overview on SEM aspects under daily work conditions.

Research opportunities for the scarcely explored field of Systems Engineering and its management at research facilities are rare, and need to be utilised as much as the situations allow. In this thesis, the domain of SE for large research facilities has been characterised as a research field, including discussions of research relevance, problems and methodology, with the intention to encourage further improvements in the domain. The key message here is:

Systems Engineering in the field of large research facilities faces serious challenges and barriers that hinder its application to the full desirable degree. The understanding of these challenges and barriers and ways to overcome them are partially understood, but require further examination. Further research in this domain is advisable in order to improve the knowledge about successful SE application (outlined in chapter 1).

This thesis outlines the field and magnitude of the problem complex, and indicates ways to improve the research field by outlining future research goals, content and methods.

2.2.2 Progression of this thesis compared to the research at MAX IV

In addition to the contributions of this thesis, a comprehensive *synopsis of technical and non-technical aspects of engineering controls and computing systems* for the most wide-spread type of large research facilities, synchrotron light sources, has been presented in the Licentiate thesis preceding this PhD thesis, "Engineering Aspects of Computing Systems for Accelerator based Light Sources" (Friedrich, 2013). The technical architecture aspects on control systems presented in the Licentiate are mostly generalisable to other types of particle accelerators and also other large research facilities: observatories and fusion reactors have adopted base technologies and concepts for the development of control and computing systems from the accelerator world (e.g. the EPICS software technology is used at ITER and LIGO).

Clearly, there have been shifts in attention between this PhD thesis work at the ESS and the previous work at MAX IV, which have been influenced by the characteristics and challenges of the primary case study environment: The research goals have increased in scope, emphasizing Systems Engineering aspects in a wider sense, such as Information Management on a larger scale (as visible from the compilation of the activity threads in 2.4). Systems Engineering aspects oriented at system life cycle management have been deepened, as in the elaboration of the Integration strategy (paper C) and RE process implementation aspects (paper A). Pragmatic and educational aspects gained more attention (paper B). System-of-systems aspects and came more into focus (paper D), as overall the SE for the entire facility gained increased attention. The shift of the primary case study object, from a synchrotron light source to a spallation neutron source, introduced new technologies and corresponding challenges; these include safety and protection aspects (e.g. paper D). The organisational size and the green-field organisation-building initiated a continuous analysis of the enterprise architecture and its relation to the technical processes. The pronounced international collaboration aspects and the In-kind contribution model necessitated taking the multi-site development aspects much more into account.

This shift and expansion of focus in the research work however also led to a de-prioritisation of the more technical aspects: For example, investigations on the technical architecture of research facilities' SCADA systems and controls technologies went into the background. For an introduction to the architecture of control and computing systems infrastructure at synchrotron light sources, see (Friedrich, 2013). The architectural aspects outlined there are widely generalisable to other large research facilities, too, such as neutron spallation sources.

2.2.3 Impact on the study environment

Finally, the practical engineering work at two large research facilities, each world-leading in their particular domain, the ESS and MAX IV, could profit from the research work that lead to the two theses. The participation in these environments increased their staff's internal awareness of Systems Engineering issues, in particular where related to control and computing systems, and by taking measures to improve their Systems Engineering practices.

The impact of each activity threads executed at the ESS is described in chapter 2.4.

Impact of activities in the MAX IV design phase included

- significant increases in awareness of control system concerns, which accelerated the establishment of a dedicated controls group,
- influencing strategic decisions on technological choices in the controls and computing domain for the MAX IV laboratory,
- introducing concepts of Systems Engineering, which supported the formalisation of workflows and technical information management, e.g. the concept of Requirements Engineering.

These developments, further elaborated in the Licentiate thesis (Friedrich, 2013), have been part of the evolution of the preceding organisation, MAX-lab, a comparatively small laboratory with a notable university-style, to today's MAX IV laboratory, a world-leading synchrotron light source facility.

2.3 Research approach and methods

The research project has initially been based on the following assumptions of the participating PhD student (the thesis author), the academic supervisor at KTH Stockholm and the financer, the Integrated Control System division (ICS) division at ESS:

- The application of Systems Engineering in the particle accelerator based research facility domain is generally not sufficiently well understood. Research in this field can contribute to the Systems Engineering community, the accelerator construction and operation community and the control and computing system development community.
- Furthermore, the ESS and ICS should benefit from the studies by feedback and by practical improvements (impact) of the researcher's activities.
- Systems Engineering in the domain is best understood by combining both practical work as SE facilitator and theoretical studies. This combination has been expected to be suitable for acquiring realistic, believable results, based on theoretical foundations and validated by experience.

Thus, participation and intervention of the researcher at ESS and ICS have been the key concepts in this research work from the beginning. Participatory research means that the researcher interacts in the studied environment - as opposed to an external observer. Intervention means that the researcher interferes in the existing organisational situation with the aims of a) improvement of the organisational situation and b) learning generalisable lessons from the results of the intervention. The benefits for the organisation, ESS and ICS division, have been expected primarily in the form of *organisational learning*, meaning, an increased awareness and understanding of Systems Engineering concerns, and additionally in the form of improvements of the applied SE practices in the engineering processes, which in this thesis is referred to as 'impact'.

The chosen path for this thesis contrasts to, for example, a non-invasive, purely observational study approach, as such would have diminished means of inquiry and lack validation of SE proposals in practice. To compare into another direction: A participatory approach that would build on SE interventions, but be limited to a singular subsystem development, would likely lack in breadth and transferability to other domain-typical systems.

In the following, the structure and methods of the research approach leading to this thesis are presented and discussed in regard to validity.

2.3.1 Review of the state of the art

This chapter describes the review of the state of the art in Systems Engineering, research facility construction and the controls and computing systems domain.

This PhD thesis is a continuation of the research work that led to the publication of the licentiate thesis "Engineering Aspects of Computing Systems at Accelerator based Light Sources" (Friedrich, 2013), which had as primary case study environment the MAX IV laboratory, a synchrotron light source based research facility. The research goals have a strong continuity, but have also evolved. The presentation of best practices and state of the art presentation in (Friedrich, 2013) have formed the broad basis for this work, too.

The following activities have been performed to explore the state of the art for this thesis work:

Literature review. Literature has been reviewed in various related fields, including Systems Engineering, research on software engineering and computing systems, and philosophy of science. A bibliography is enlisted in chapter 8. It should be noted that the amount of publications that explicitly target Systems Engineering at large research facilities is overall surprisingly scarce, even more so for controls and computing systems as a subfield. Hence, the focus has been on generic Systems Engineering standards and their application, preferably in research facility contexts, but also in other domains that produce large complex systems. Notable standards or literature with guideline character included:

- ISO/IEC/IEEE 15288: Systems and software engineering – Systems life cycle processes INCOSE Systems Engineering Handbook (ISO 15288, 2015)
- NASA Systems Engineering Handbook (NASA, 2007)
- IEC 61508: Functional safety of electrical/electronic/programmable electronic safety-related systems. (IEC 61508, 2010)
- IEC61511 Functional safety – Safety instrumented systems for the process industry sector. (IEC 61511, 2004)
- IAEA Safety Standards. The Management System for Facilities and Activities. (IAEA Mngt Sys, 2006)
- CAFCR framework (Muller, 2012)
- Oil & Gas Engineering Guide (Baron, 2015)

A notable approach to establish an SE framework tailored to accelerator facilities has been started with the openSE framework (Bonnal, 2016), which has been developed at CERN and has been presented in 2016. Its main artefact is a document[9], which gives a life cycle framework for accelerator facility projects that focuses on project management, roles and processes on the highest level (typically directorate interests). As such, it is inspired by e.g. the INCOSE and the NASA SE handbook. The domain tailoring addresses conventions of naming and regulatory aspects for facilities that produce ionising radiation. While obviously related to the themes in this thesis, in comparison, this thesis work is more interested in the system engineering aspects on the technical mid and lower levels, which are the daily work in the technical, engineering or science divisions.

Technology-centric literature regarding the particle accelerator domain, and in particular, the controls and computing systems domain has been reviewed mostly in the form of conference papers. A number of regular conferences and events exist that can be seen as the primary ways of the accelerator construction community to share their progress regarding computing systems and controls:

- ICALEPCS - International Conference on Accelerator and Large Experimental Physics Control Systems
- PCaPAC - International workshop on Personal Computers and Particle Accelerator Controls

[9]found at http: //opense.web.cern.ch/sites/opense.web.cern.ch/files/openSE_Framework /openSE_Framework.pdf

- workshops centred around the particle accelerator control system frameworks (primarily EPICS, TANGO)
- IPAC - International Particle Accelerator Conference.
- NOBUGS - New Opportunities for Better User Group Software. A conference series focusing on software for data acquisition and analysis for users of particle accelerator based experiments.

Study visits, Inquiry and Reflection with domain experts and practitioners. The controls and computing domain at accelerators has numerous publications on technical aspects, mostly non-peer reviewed conference contributions[10], but comparatively few publications on the SE and SE management aspects. Understanding the factual state of practice here requires investigations "in the field". The author visited *in persona* numerous particle accelerator facilities, either individually or in an organised fashion. This allowed for study visits of approximately 15 to 20 (depending on definition) particle accelerator machines of different types and sizes in European countries, USA and Japan. These visits were used to *inquire* practitioners in various positions (engineering and systems engineering functions) about the common practices and encountered problems. Such occasions have been perceived as fruitful for *reflections* on the current state of the art and future trends. These activities are deemed highly recommendable by the author as they introduce to the multiplicity and relativity of views on the discussed topic, and also serve as a mean to validate the own insights, or identify bias.

2.3.2 The overall methodology - Action Research (AR)

The work of this thesis is heavily influenced by the Action Research (AR) approach (Herr & Anderson, 2015) to research on Systems Engineering. Action Research involves *active participation* (intervention) in a *problem-solving process* in an organization with the goal of additionally *contributing to scientific knowledge*. The term Action Research has been first introduced by Kurt Lewin for research on social issues in psychology (Lewin, 1946). Action Research in Systems Engineering has a certain tradition, with a widely recognised landmark being the book "Systems Thinking, Systems Practice" by Peter Checkland, first published in 1981 (Checkland, 1999).

As a scientific method, Action Research constitutes an interactive inquiry process: The researcher studies by injecting content (methods, design principles, information structures, tools) into the studied environment (the hosting organisation), and analyses the effects. The general expectation on Action Research activities is of course to obtain beneficial effects for the organisation. Hence agreements between researcher and the hosting organisation are preceding the Action Research activities that clarify the goals

[10]Prominent conferences that are relevant for accelerator controls, including ICALEPCS, PCAPAC and IPAC, have typically no peer-review processes.

and form of the Action Research activities. The injection of content into the organisation can and should be done in iterations that allow for reflections on the progress and adjustments. Beyond the scope of the organisation's interests in the Action Research activity, the reflections and adjustments are also used to distil scientifically valid conclusions on the research questions.

The Action Research methodology is generally considered suitable for the introduction of new methods, design principles and tools to organisations. The interactive aspect of the method facilitates adjustment, tailoring of the proposed content to the specific environment. This makes research support by an organisation with primarily other goals more open and interested in enabling the research activities. For the researcher, the interactive aspect enables a strong feedback loop, thus allowing for continuous verification and validation of the intervention, respectively the injected content.

The Action Research Agreement. As summarised in "Principles of Canonical Action Research" by Davison et al. (Davison, Martinsons, & Kock, Principles of Canonical Action Research, 2004), "The action researcher serves at least two demanding masters - the client and the academic community." To create a shared understanding and trust between the involved parties, it is further recommended to elaborate an Action Research agreement. Setting the scene for an Action Research project is described by (Davison, Martinsons, & Kock, Principles of Canonical Action Research, 2004) by the "Principle of Client-Researcher Agreement". It involves clarifying of the purpose of the research and the research approach; specifying personnel roles, responsibilities, and expected behaviours; and anticipating changes and benefits for the organisation. Guided by this principle, the following agreements were made and put into practice.

The Action Research activities focused on the implementation of SE in the Integrated Control System division (ICS) of the European Spallation Source ERIC[11] (ESS) in the form of case studies that allowed for multiple study subjects. These study topics were approached in descriptive and prescriptive study cycles, following the outline in the following chapter 2.3.3. To enable the AR activities to mutual benefit, the organisation (ICS) facilitated the active involvement of the thesis author by role assignment: the author acted as the ICS division's "System and Standardisation Engineer", which involved a variety of SE coordination and information management tasks. With this role, a frame had been created that allowed for numerous larger and smaller participations in the daily work of the organisation. Due to the course of the research work and driven by needs of the ESS and ICS, the scope of interventions expanded from confined ICS impact and included also participation in the ESS wide SE management, as representative of the ICS division.

[11] ERIC is the legal organisation type "European Research Infrastructure Consortium".

For ESS and ICS, a large motivation for improvements of Systems Engineering practices is the expected reduction of a variety of risks for an organization such as ICS. Such risks concern

- Technical shortcomings, e.g. systems are not delivered up to the desired functionality or quality.
- Project management risks, i.e. budget and schedule overruns.
- Organizational risks, perhaps indirectly, such as the subjective satisfaction level of staff. Poorly coordinated engineering can lead to avoidable re-work, shortcuts, quality compromises or unintentional double-work. Such phenomena provoke engineers and scientists to question the meaningfulness and purpose of their personal efforts, which altogether tends to raise frustration levels. High frustration levels can lead to increased staff fluctuation and negative reputation. In a relatively small community (such as the particle accelerator engineering community, and the specialists' communities within) this can impair future recruitments and retention of valuable domain experts.

The ESS will feature a number of experimental stations for various disciplines in neutron science, and is based on a world-leading particle accelerator installation. ICS is tasked with the development and integration of the majority of the ESS's controls and computing systems, including mission critical protection systems. The ESS is currently in the construction phase, planned to be fully operational in 2023, with first beam expected in 2019. The ESS architecture is presented in further detail in 3.2. The ICS division constitutes a research environment that is representative for contemporary practice and encompasses prospective trends in the domain, such as increasingly internationalised projects with diversified stakeholder configurations.

2.3.3 Descriptive and prescriptive study cycles

Participations and interventions have been embedded in larger, topic-centred study cycles. These cycles can be described as *descriptive* and *prescriptive* in nature (Blessing & Chakrabati, 2009).

Descriptive study cycle. Phases of interactive exploration and observation of the problem space are called descriptive study cycles. They comprise the following processes, graphically shown in Figure 2:

1. understanding needs of the organisation for SE management (system life cycle processes, information kinds, supporting tools),
2. analysis of SE aspects for a specific system/concern that is of high relevance or representative for the engineering environment, and could serve as introduction example for organizational improvement,
3. study of typical domain practices and best practices (also in other industry domains),
4. evaluation of the situation:

a. assessment of the current SE processes (suitable to help people?)
b. assessment of the SE information, content and management,
c. assessment of the SE support tools (templates, databases, applicable guidelines)

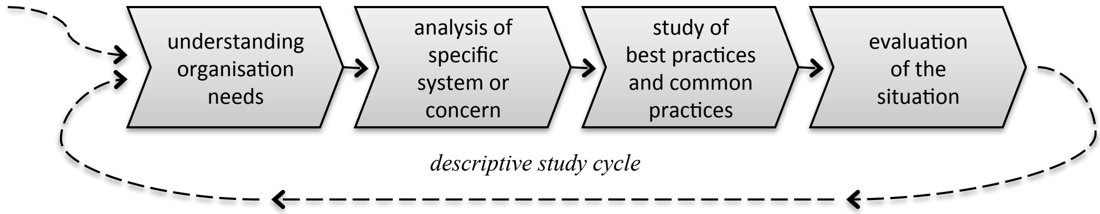


Figure 2: Descriptive study cycles

The first process in the descriptive study cycle aims at understanding the organisation's reasoning and expectations for applying SE in a given context.

The second process analyses the application of the SE in practice, at real systems, which are either of high relevance or representative for a class of systems that are to be engineered. Besides examining the organisational SE needs more in-depth, this process serves as reality check for already existing SE processes (are they actually applied, and how helpful are they?) and potential introductions of improvements. The involved personnel's competence in SE, familiarity with SE concepts and previous experiences needs to be understood. In the end of the analysis, a picture of the practical SE maturity in a given context emerges, as it is a determining factor in the success of SE application.

The third process, study of best practices and common practices, gives a reference frame for comparison of the encountered SE practices. It is used to compare the intra-organisational SE findings with e.g. international SE standards or common practices in comparable facilities or industry domains. It is needed to make improvement potential visible and helpful to stimulate the adoption of better SE methods and tools.

The fourth process, evaluation of the situation, combines the findings of the previous processes in order to evaluate the *status quo*. For conclusions on the findings, quality criteria have to be defined, which can be justified by comparison of the situation analysis with the reference frame acquired by the third process. Based on the determined SE improvement potential, the priority, effort and realisation chances for such improvements can be determined given the factual constraints.

Descriptive study cycles are iterative, as indicated in Figure 2, in the sense that their study subjects are repeatedly refined, and new study subjects are identified as a result of previous cycles. Descriptive study cycles have been performed using the division's systems engineer role in order to gain insights into practical SE needs, problems, situations, limitations and hindrances.

Prescriptive Study cycle. Active participation in the engineering environment with the goal of changing the environment is called intervention. The purposeful, guided intervention based on previously acquired analyses (descriptions) is hence called prescriptive study cycle.

A prescriptive study cycle builds on the results of a descriptive study cycle, which analysed an engineering process or the usage of an information kind. This gives the status quo within the organisation, which is complemented by insight into best practices in comparable environments and literature on the topic. An evaluation of this status quo needs to be based on quality criteria that depend on the studied subject. For example, for a facility's system model, which is an information structure used for product life cycle management, the consistency of system definitions and decompositions with the intended viewpoints is a core quality. For the supporting tool (product life cycle management tool), the content management functionality and usability are core qualities.

On this basis, the needs of the organisation can be understood and directions or goals for the intervention can be defined. The most suitable set of factors for improvement need to be identified. This decision needs to take theoretical SE aspects into account as well as the organisation's priorities, existing SE capabilities and resources available for implementing improvements. A concept for intervention needs to be elaborated which outlines and motivates the introduced changes. This is the 'prescriptive' content. This concept needs to be validated and adjusted to find acceptance by the involved stakeholders. Once the intervention concept is sufficiently elaborated and legitimised, it is realised by injecting it into the business processes. This can take the form of using new or upgraded databases, document templates, etc. in the daily work, and may require staff education or training. An evaluation to finalise the intervention captures the degree of its success according to the intervention goals, and analyses the relevance of factors that influenced the intervention outcomes. The overall prescriptive study cycles can be described by the following processes, with each process's output being the input for the logically succeeding one, as shown in Figure 3:

1. determination of most suitable factors for improvement by intervention based on the descriptive study phase, including considerations of practical viability and constraints (resources, time, organisational SE maturity, ...)
2. concept development: choice of SE concepts, development of SE support (e.g. templates, databases), plan for introduction to the real processes
3. exposure of intervention concept to stakeholders to validate suitability, adjust based on feedback
4. realisation of the SE support by introducing SE concepts, processes or artefacts to actual engineering activities
5. evaluation of the intervention, recurring to quality criteria defined in the evaluation of the descriptive cycle.

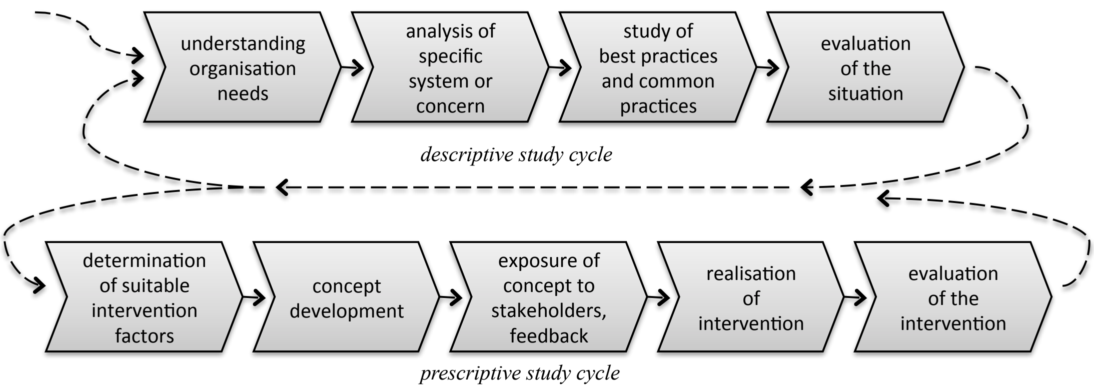


Figure 3: Descriptive and prescriptive study cycle

Prescriptive study cycles have two different goals. First, an *impact* on the organisation is intended, e.g. establishing a SE process or information concept with some benefit to the organisation. Secondly, a *research contribution* is achieved by learning from the intervention as an ‘experiment’ and enhancing the understanding of SE in the domain. The degree of success for both goals is de-coupled: For example, an intervention that is un-successful in organisational improvement can be particular revealing for identifying SE barriers and generate explanation patterns for the observed phenomenon.

The sequential character in this presentation reflects the dependencies of the *inputs* and *outputs* of the different processes; e.g. the determination of suitable intervention factors provides input for the intervention concept development. It is not necessarily very sequential in time, as leaps back can occur at almost any stage, usually aiming to improve the overall results.

Descriptive and prescriptive study cycles have been conducted in this research work many times, over varying time lengths and on varying levels of detail. Chapter 2.4 gives an overview on the activity threads that were addressed in descriptive and prescriptive study cycles. As indicated in Figure 4, prescriptive and descriptive cycles could be iterated repeatedly, depending on intermediate results, external factors or newly emerged aspects in the evaluations, before realising some form of continuous application or impact.

Evaluations of previous study cycles led to adjustments in the activity threads, and also raised attention on related issues, spawning new activity threads. For example, the work in RE domain early on in this thesis work initiated more detailed analysis of the Systems Thinking aspects, which over time became an activity thread in its own right. This openness towards topic adjustments is a fundamental difference between action research and e.g. physics research, and as Checkland pinpointed: “You cannot do action research on magnetism because the researcher has no alternative but to accept the role of outside observer of a phenomenon which he must take to be unalterably following a fixed pattern which he can discover. But when the phenomena under study are social interactions the researcher will find it almost impossible to stay outside them.” p. 153 (Checkland, 1999).

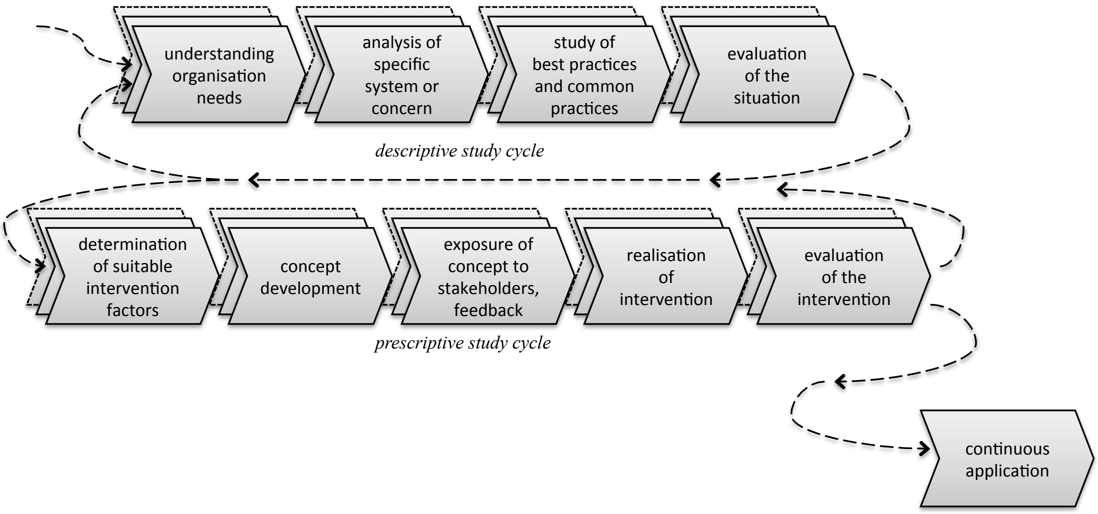


Figure 4: Iterations of study cycles

Organisational SE improvements such as the establishment of well-structured, sufficiently tool-supported engineering processes need to be distinguished from a particular *system* development project (e.g. a particular input/output controller for a certain accelerator subsystem). A particular system development is typically funded only to develop and deliver the technical system, not to improve the organisation's generic processes. Such particular system projects are nonetheless the practical anchor points for the interventions outlined in this chapter, as they allow to introduce the benefits of SE in a practical, tangible manner. These interventions were then intended to be the first example in a longer organisational learning process. Chapter 2.4.2 presents such system-bound study cycles separately from the SE management focused activity threads in 2.4.1 and 2.4.3.

2.3.4 Ethnographical stance or attitude

Ethnographical methods aim to describe cultures or communities scientifically with the researcher taking a subjective point of view for a limited time. An example of a pronouncedly ethnographic study of an engineering environment is given in (Sharp & Robinson, 2004), which presents an ethnographic description of extreme Programming (XP) practices and its cultural aspects in a small software business. This means the researcher explores the subjective meaningfulness of cultural phenomena by participating in the studied culture's practices (researcher's participatory role). Thus the researcher gathers material in a sort of "field work".

In a second stage, the researcher 'switches back' to the 'objective point of view' and uses this material in order to identify patterns of meaning, common beliefs, open or tacit norms, assumptions or values (researcher's scientific role). Here, the researcher delivers positivistic descriptions of the studied community, its communication patterns and how the community attributes sense, meaningfulness to phenomena. Thus the researcher keeps an inner professional distance to the subjective experiences encountered during the "field work", and uses these as analysis material. In this view, his/her measure of the *relevance* of encountered phenomena shifts to other criteria. This ethnographical stance strongly resembles or describes the participatory research situation in an engineering community, as performed for this thesis work. Table 2 shows the relevance shift in regard to engineering aspects. The ethnographical stance also emphasizes the need for a position of neutrality towards the engineering environment and colleagues for the generation of knowledge with scientific validity. Personal identification with the participatory role and “field work” is desirable, just like for a normal employee. For the scientific role however, which analyses e.g. the work culture, values, the professional bias and ontologies, the creation of sense, etc. this identification needs to be set aside. Altogether, the participating researcher can rather see him/herself as an ethnographer of an engineering culture.

This corresponds well to the description by Davison (Davison, Martinsons, & Kock, Principles of Canonical Action Research, 2004) on the examination of the “values, beliefs and intentions of the client employees”, which concludes, the “researcher must also get ‘close to the action’ in order to gather rich data, but avoid ‘going native’, whereby objectivity is sacrificed through over-identification with the organisation and its members”.

Table 2: Relevancies for the participatory and scientific role

Aspect:	Relevance for the participatory role	Relevance for the scientific role
Reaching the goals of the studied project	maximum relevance	relevant only for evaluation of the factual engineering process
Understanding the encountered world views (conceptualization of reality)	Relevance is eventually tied to reaching the project goals. E.g. for explaining and resolving project-internal communication problems. Can be applied in regard to problem formulation, requirements, agreement on validation criteria, etc.	relevant for formulating theories on domain-typical viewpoints or general viewpoint management
Understanding the relation of system views (e.g. designs, architectures) and resulting systems and their properties	relevant for establishing appropriate information systems (applicable conventions and tools) within the project	relevant for formulation of theories on systems representation (e.g. multi-view modeling of systems), which are used in the different system life cycle stages
Qualities of the engineered system	relevant for fulfilling stakeholder expectations	relevant only for evaluation of the factual engineering process
Budget and schedule concerns	critical for project success	interesting as factors in the evaluation of engineering methods

The application of explicitly ethnographic methods in the study of engineering environments is not wide spread in spite of the fundamental parallels shown here. However, the approach of this research work made an ethnographic stance or attitude towards the engineering environment a persistent background thought.

2.3.5 Validity of the approach

A challenge for research on Systems Engineering and its management is the validity of claims. A straightforward causality relationship between SE Management measures and intended effects is typically hard to tackle down, and open to side effects, which may be hidden or turn up unexpectedly - SE deals with humans, and humans are to a degree unpredictable. Statistical means might help here, such as acquired by sufficient numbers of case studies in very controlled settings; this however forbids itself in the particle accelerator domain due to the rarity and uniqueness of the projects. The impact of introducing or improving SE practices in an engineering environment for particle accelerators can better be described by ‘influence’ rather than causality - for example, influence suits better to the subtle yet paradigmatic changes that the introduction of Systems Thinking entails. A purpose for investing in Systems Engineering is the *reduction of engineering risks* related to the final product (qualities) or development aspects (resources, schedule, organisational evolution). The nature of avoided risks is obviously their non-realisation, hence non-measurability.

To show conclusions with a reasonable degree of scientific validity, as this thesis intends, one has to apply qualitative, argumentative means. The relation of argumentative means and the generation is discussed in the following sections. First, validity concerns in regard to the presented research approach are discussed on a theoretical, method level. Then, the validity of the findings (meaning the application of the research approach) of this thesis is discussed in chapter 5.4. Where appropriate, validity is discussed in the different parts of the thesis, e.g. in the papers.

Inference to the best explanation. In this section the conditions for reverting to explanation as a mean for giving scientific validity is explained. The underlying philosophy of science has been described by Peter Lipton by the term *inference to the best explanation* (Lipton, 2004).

We may consider statements (conclusion, rule) that claim a causality relationship between human communication characteristics during a system’s early engineering time and system qualities at operation time. To use some example statements (Ex), we begin with the claim (E1): “Applying Systems Thinking from early on in the development of ESS neutron experiment installations will improve their system qualities for research enabling services.” How can we distinguish this statement’s validity from an opposed one? Such as (E2): “Skipping Systems Engineering concepts for the ESS neutron experiments gives the developers time to improve the system qualities for research enabling services.”

Even if for a given case such relationship can be shown quite directly, the generalisation to a generally applicable rule introduces further difficulties, e.g. (E3) “The qualities of all main systems at large accelerator research facilities benefit from the application of Systems Thinking.”

Here, the transferability to unknown application cases is additionally claimed, which means that pre-conditions of the validity of the rule (E3) need to be clarified too. The problem of formulating and applying such rules, quintessential pieces of wisdom is discussed in (Maier & Rechtin, The Art of Systems Architecting, 2009), subsumed under the term heuristics. The fact that Systems Engineering Management operates in a multi-dimensional problem space, comprising technical, social, legal, managerial, cultural aspects incurs that interferences can emanate from any of these fields. Unfortunately this indicates that exhaustive presentations of all necessary conditions for Systems Engineering rules or heuristics are in practice impossible to achieve.

For this thesis work, we assume that it is possible to outline the main reasons why a certain rule makes a certain outcome more probable, and that these statements are justified to be called *scientific* if their validity is sufficiently shown. In philosophy of science terms, we take for our field the stance of *scientific realism* (Scientific Realism, 2011): we assume that our scientific theories (statement, rule) describe the reality of the world correctly to at least some extent, if our theories are reasonably well validated.

Furthermore, we assume that the validity of our theories can be established by the quality of their *explanatory* character. To explain a phenomenon means to describe its constituting relations, inherently and to its environment. For SE phenomena, (e.g. the degrees of success of a certain SE approach) the explanations need to take into consideration multi-disciplinary aspects. The spectrum of potential influences spans from the inherent logical dependencies and consistency of informational SE entities, structures and processes, and reaches to pragmatic aspects, such as organisational maturity, competence development, communicative, social, cultural, or pedagogical aspects.

This means that such contradicting statements as E1 and E2 receive their validity by their potential of explaining the transformations, which they refer to. To conclude the example: arguments for E1 could iterate through the relevance of Systems Thinking for establishing life cycle processes, structuring technical data, analysing reliability and availability etc. and expand on time losses and diverging engineering efforts due to poor system definitions. E2 is, as narrow statement, actually true, but in comparison with E1 exhibits rather limited explanation potential. Hence, if we can show how E1 and E2 relate to the problem space, and our evaluation of explanatory character favours E1, we infer to E1 as the best available explanation. We now claim E1 (and the related theory around it) to be a justified scientific theory. It might still be fallible or incomplete - all science is - but it brings us at least closer to the (unobservable) reality than any other option.

The generalised example statement E3 demands a discussion of framing conditions for its application; e.g. what are ‘main systems’, how does this apply to lower levels, what practical problems can appear in the application of Systems Thinking and how could these be solved, etc. So, the validity of a SE theory benefits from the explicit description of transferability and applicability (including their limitations), as well as the role of influencing conditions in the SE problem space (technical, organisational, information management, people, legal, etc. aspects). This can be understood as explanation in a wider sense.

Inference to the best explanation is in this thesis for SE phenomena indeed the primary instrument for generating scientific credibility. As an interesting side note: In the Action Research activities, particularly regarding Systems Engineering Management, the author repeatedly used inferences to best explanations; such as for explaining encountered SE problems to stakeholders or for gathering support for SE improvements in prescriptive study cycles.

Review and Reflection. Building an overview on various existing Systems Engineering methods, technologies and their application in engineering contexts has been an important part of the work for this thesis. This has been done by literature reviews, participation and intervention and social tests as described in the section on the state of the art (2.3.1).

Publications on SE with a relation to the research facility domain are unfortunately rather limited in volume, so general SE and SE for other domains has been consulted. Courses have been attended that covered Systems Engineering subjects (Architecture, Integration, etc.) as well as domain aspects (accelerator technology, experimental methods). Many SE topics, both in general and within the case study projects, have been discussed with practitioners in the accelerator domain and with experts of other industrial sectors. This comparative examination can be seen as a form of gaining external validity.

Participation and Intervention. Systems Engineering research is concerned with the understanding and improvement of certain aspects of human work. Building an understanding of these work situations, and developing improvement hypotheses is in principle possible from a purely observatory position by an un-involved researcher. The nature of the Systems Engineering and SE Management activities however, at least in the outlined environment that this thesis covers, has characteristics that make a participatory and interventive research approach highly advisable.

A core advantage of participatory research is the continuous and repeated possibility of observations of engineering practices. In this kind of highly interdisciplinary environment, the daily engineering work involves significant amounts of time that are not spent in discipline-typical activities, but coordination, communication, documentation, specification, etc. These practices are substantial for the integration of the discipline-specific efforts, and easily can lead discipline-specific efforts into disarray if not handled sufficiently well. Studying these practices is a matter of building both theoretical knowledge (in particular Systems Engineering theory) and practical experience. The latter, experience within a certain environment, is beneficial for forming judgements on the viability and applicability of theoretical methods in that environment, as it exposes constraints and sources of interferences. Practical experience from participation can also serve as source for new concepts or for refined application approaches. This can be induced by a pattern recognition in the environment, e.g. a recurring pattern of misunderstandings in oral communication can lead to a focused study of system concept confusion, which can lead to more general insights on conceptualisation and reasoning in engineering. This thesis work moved into this direction with Contribution VII, in more detail described in paper B.

To the contrary, an un-involved research approach would make its results open to validity questions, too: How would an uninvolved researcher build a realistic, convincing understanding of the characteristics of the research facility engineering environment, which resonates with the experiences of practitioners? How could an uninvolved researcher, in a case study, monitor group dynamics as well as organisational development (SE maturity) over time, some of which require a finely tuned understanding of the organisation? How should an uninvolved researcher recognize and evaluate undocumented communication regarding SE issues? Convincing answers to such methodological questions are not straight-forward.

For large, singular projects such as the ESS, an un-involved, purely observatory approach would be a much less attractive approach, as the evaluation and reaction would likely be late in the life cycle, - and chances for improvement may have been missed, or have diminished impact.

Participatory research also has some potential to introduce sources of errors. These must be aware to the conducting researcher in order to minimise their potentially distorting effects. The following considerations have been persistent topics in this work.

The role of *bias and sources of error* specifically in qualitative research has been described by Norris (Norris, 1997). Bias and error can result from a researcher's personal, educational and professional background as well as the research environment. Checkland uses the German term *Weltanschauung* (eng. 'world-image', world view) to describe one of the core characteristics for root definitions in Soft Systems Methodology (Checkland, 1999), which he defines as "[...] (unquestioned) image or model of the world [...]". It is indeed the very own *Weltanschauung*[12] that the Action Research practitioner, in Systems Engineering research or elsewhere, needs to be able to question. Norris (Norris, 1997) enlists a range of sources for bias and error in qualitative research, which are slightly restructured and related to participatory SE research in the following.

Researcher bias is related to the characteristics of the research him/herself. Norris distinguishes researcher-induced bias in regard to

- affinity with certain kinds people, designs, data, theories, concepts explanations;
- ability including knowledge, skills, methodological strengths, capacity for imagination;

[12] With all due respect to Checkland's clarity in his excurses into philosophy of science around the term *Weltanschauung*, it remains strangely obscure why he characterises the term as "useful, accurate but *ungainly*" p. 215 (Checkland, 1999). Hence we shall not follow his practice beginning with p. 215ff (Checkland, 1999) to abbreviate this mysteriously captivating term with a mere "W", as if it was an insult to the eye; instead, we will endorse the beauty of its full spelling.

- value preferences and commitments;
- personal qualities of researchers, including their capacity for concentration and patience; tolerance of boredom and ambiguity; their need for resolution, conclusion and certainty.

Action Research SE researchers can have an inclination to favour or disfavour certain SE concepts, SE techniques, SE frameworks, SE related ontologies, people with certain mind-sets, etc. which influence the SE researcher's expectations. Such affinities may lead to prejudices in an on-going prescriptive research cycle and influence the concept development or evaluation. Affinities may arise from the perceived degree of success of the application of SE methods in previous experiences.

Abilities for an AR SE researcher in the research facility domain should include knowledge of SE as well as a broad knowledge on domain-specific issues. Such include technologies and disciplines (fundamental principles of accelerator physics, software development, etc.), but also operational aspects - how are experiments conducted? How are accelerators operated? What information is required for continuous maintenance and overhaul of the facility? The detailed answers are not the key here, but the issues need to be seen by the researcher.

To minimise one's own bias in the research work is exceptionally important for a researcher in a highly multi-disciplinary field, where a variety of discipline concerns and traditions have to be expected. Yet it is unrealistic to call for high-minded "freedom of bias", as it is only natural to have and draw on personal preferences. To the individual engineer, strong personal preference or certain engineering methods, concepts or technologies can be a motivating factor - engineers typically like the technologies, concepts etc. they work with, and wish to bring them to good use; this also applies to system engineers. It is however duly for an SE researcher in the outlined field to engage in self-exploration in order to identify these personal favours and disfavours, consequently avoid hidden, unaware influence on the evaluations, i.e. maintaining a critical posture towards the own *Weltanschauung*. Bias needs to be countered by the consciously "open-minded" analysis of causes and effects of the studied SE phenomena; that means, with the determination to identify the relative importance of all involved causal relationships disregarding personal interests, preferences or expected results. Where the causal relations are not very clear, argumentative descriptions of influence relations are needed, or description of probability factors for desirable or undesirables outcomes.

Recommendable personal qualities for AR SE researchers in the accelerator domain include, perhaps first of all, the ability and willingness to actively adopt other people's viewpoints. Beyond mere understanding, this means the ability do develop thoughts further in other's viewpoints, even though one does not initially agree to the correctness or suitability of that viewpoint. This ability is not only rewarding in cases where it broadens the own horizon. It is required for the long-term anticipation of other's SE management proposals and for the analysis of tacit or unaware motivations. The acquired knowledge can be used in the optimisation of compromises and in educational activities.

Further, a readiness should be given to deal with disorder of information, ambiguity in communication and uncertainty of future developments. This leads to the need of patience paired with perseverance, which is the combination that motivates for conducting long-term improvements with little visible progress in the intermediate. Establishing and researching SE in this domain can easily span several years, given the life cycles of the study objects.

Norris also lists sources of error and bias that stem from the research environment (Norris, 1997):

- selection biases including the sampling of times, places, events, people, issues, questions and the balance between the dramatic and the mundane;
- the availability and reliability of various sources or kinds of data, either in general or their availability to different researchers;
- the reactivity of researchers with the providers and consumers of information.

In the evaluations of participatory research activities, *selection bias* can lead to the unbalanced presentation of factually influencing factors of the studied phenomena. This can cause *over-emphasis* of influencing factors. Norris presents as the source the sampling selection. Additionally, one can think of circumstantial, project-specific characteristics that play persistently into the foreground of the participatory activity. Selection bias can also cause *under-emphasis*, which is the disregard or even omitting of influencing factors. Under-emphasis can occur when relevant factors of the studied phenomena are taken for granted, which are not necessarily given in comparable contexts.

Circumstantial, project-specific factors can impact the outcomes of participatory activities in the SE domain quite heavily. E.g. the personnel SE competence can easily become a determining factor in activity threads aimed at introducing SE concepts or methods. A problem here is that the SE competence cannot always be sufficiently estimated at the beginning, and may change during the SE intervention. This is in particular true for dynamic organisations such as greenfield accelerator facilities. In such cases, the AR interventions may need re-adjustment according to the emerging situation.

Social tests. Exposing ideas to an engineering environment can be seen as a sort of “social testing” of System Engineering concepts. It is commonly an early and repeated step in the process of interventions, as it provides feedback for adjustments on aspects that the facilitators of the intervention are initially not aware of. Social tests can also serve educational purposes, acquainting affected personnel with the new concepts introduced in an intervention. If successful, this early inclusion of affected personnel can increase the perceived legitimacy for the intervention and lead to informal support.

2.4 Key activities and achievements in the Action Research (AR) approach

During the time as division systems engineer at the ICS division, a number of participatory activities or activity threads[13] have been conducted by the author of this thesis. These activities formed descriptive and prescriptive study cycles as outlined in 2.3. In the following, an outline of these activities is given. They were conducted by the author in overlapping time spans over the course of approx. 3 years.

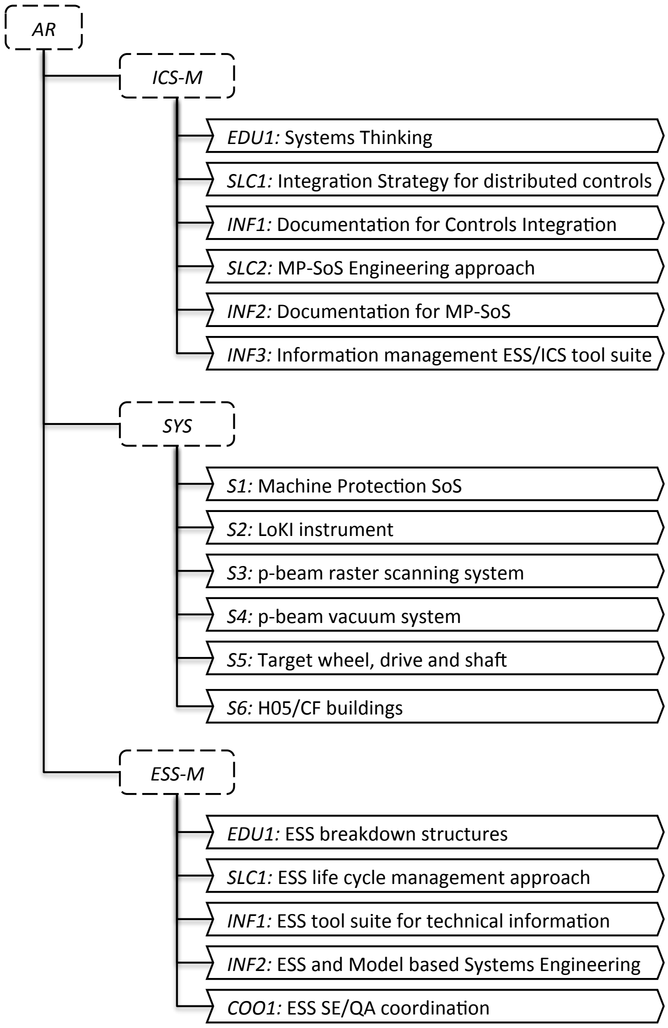
The compilation of activity threads has been designed to cover a *broad spectrum* of SE related issues: They include system development examples of all parts of the facility. They are concerned with engineering management from small-scale systems as well as multi-disciplinary meso-level systems and touches upon the highest-level systems. While due to the life cycle of the ESS Requirements Engineering, architecture and integration have been predominant, in principle the full system life cycles have been in the scope to some extent.

Most importantly, these active participations enabled ‘unfiltered’ insights: They exposed the true state of the organisational maturity and real-life problems of discipline engineers as well as SE facilitators. Working on remedies for these problems exposed practical obstacles and hindrances in the problem resolving processes. The success of these problem solving processes with their many stakeholders, interests, etc. can be described as ‘mixed’ in regard to the ESS project (listed under ‘Achievements’) and certainly not optimal in regard to SE textbooks; however for the purpose of *studying SE management in the domain* this approach turned out to be productive.

It should be noted that partially comparable activities had been carried out by the author in the MAX IV project for his licentiate thesis, which preceded this PhD thesis (compare “Additional Publications”). The increment is outlined in chapter 2.2.

In the following, the grouping of activities is explained. The remaining subchapters then outline the individual activity threads and their ties into each other are explained. The activity threads are shown in Figure 5, structured in three groups:

[13] While some of the outlined participations are ”activities” in the sense of a relatively clear set of actions, others are by nature very scattered in practice. This includes e.g. short educational actions, which may occur as part of another topic discussion or presentation, or the coordination of contacts and communication flows in order to initiate a technical discussion. Such scattered actions still have commonality in character and purpose, a common ‘red thread’: hence the term “activity threads” is used here.



AR	Action Research
ICS-M	Integrated Control System division management (SE support)
ESS-M	ESS management (SE support
SYS, S	Development of ESS systems in ICS division; supporting engineers in SE matters
EDU	Staff education, SE concept dissemination
SLC	System life cycle management/ tailoring
INF	Technical information management (elaborating templates, databases, tools)
COO	Coordination, cooperation enabling activities

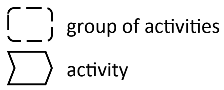


Figure 5: Action Research activities overview tree

ICS Systems Engineering Management (ICS-M). This group contains activities aimed at establishing or improving SE concepts and processes within the ICS division. The stakeholders of these activities have been primarily members of the ICS division's management team (group leaders and managers).

Development of ESS systems (SYS). The author participated in system development processes of systems for the ESS facility (see 2.4.2). These system developments are part of the ESS' Facility Creation Process and Generic Development Process, as characterises Chapter 3.6. The engagement was temporary in the role of an advisor and supporter in regard to Systems Engineering application for the particular system development. Hence the interactions were mostly with the developing engineers and scientists.

ESS Systems Engineering Management (ESS-M). The third group contains activities on Systems Engineering issues on the facility level, relevant for several technical divisions (see 2.4.3). These activities concerned the specification and realisation of ESS wide information structures and the according information management systems. The elaboration of an ESS life cycle management approach has been a recurring topic. The primary stakeholders in these activities have been the

- ICS management team, which the author represented in many venues,
- Systems Engineering coordinators of other technical divisions, who acted in a comparable role as the author for their division,
- the central ESS Systems Engineering division (a rather high level SE coordination function until approx. 2015, which however has been re-allocated during organisational re-structuring)
- the Engineering and Integration Support division (providing e.g. the product life cycle management system for the ESS and other servicers)
- the ESS Quality division.

In the following, Table 3 gives a broad overview on the impact status at the time of writing, and then the various activity threads are explained in detail. For each thread, the *preconditions*, *goals*, *interventions*, *impact* and *research relevance* of the engagement are described. The preconditions of the activity threads have been found by descriptive study cycles, while the goals correspond to the intervention purpose in the prescriptive study cycles. The intervention actions are described, e.g. educational, work on tools, elaboration of artefacts. Impact outlines by which degree goals have been reached at the time of writing. Research relevance outlines the findings and references the contributions in this thesis that were affected by the activity thread.

Table 3: Activity threads and status of intervention impact

Activity thread	**Intervention goal impact**
ICS SE management:	
AR_ICS-M_EDU1: Systems Thinking	adopted for Facility Creation Process
AR_ICS-M_SLC1: Integration strategy for distributed controls	approved, in implementation
AR_ICS-M_INF1: System Life Cycle Documentation for Controls Integration	approved, in implementation
AR_ICS-M_SLC2: Machine Protection SoS Engineering approach	approved, in implementation
AR_ICS-M_INF2: System Life Cycle Documentation for MP-SoS	approved on high-level, in elaboration
AR_ICS-M_INF3: Information Management ESS/ICS tool suite	partially in work, partially discarded. avoided unsuitable approaches.
Development of systems:	
AR_SYS_S1: MP-SoS development	supported SE application
AR_SYS_S2: LoKI instrument	supported SE application
AR_SYS_S3: p-beam raster scanning system	supported SE application
AR_SYS_S4: p-beam vacuum system	supported SE application
AR_SYS_S5: Target wheel, drive and shaft system	supported SE application
AR_SYS_S6: H05/CF buildings	supported SE application
ESS SE management:	
AR_ESS-M_EDU1: ESS Breakdown Structures	partial educational success
AR_ESS-M_SLC1: ESS system life cycle management approach	partial influence on abstract specifications, but no meaningful outcomes realised yet
AR_ESS-M_INF1: Information Management ESS tool suite	influenced on concepts and tool development (PLM, RE)
AR_ESS-M_INF2: ESS and Model based Systems Engineering	MBSE has been discarded due to organisational SE maturity
AR_ESS-M_COO1: ESS SE/QA coordination	coordination has been performed

2.4.1 Activity threads concerning ICS Systems Engineering Management

This section presents the activity threads of the ICS Systems Engineering Management group. Their interrelations are outlined in Figure 6.

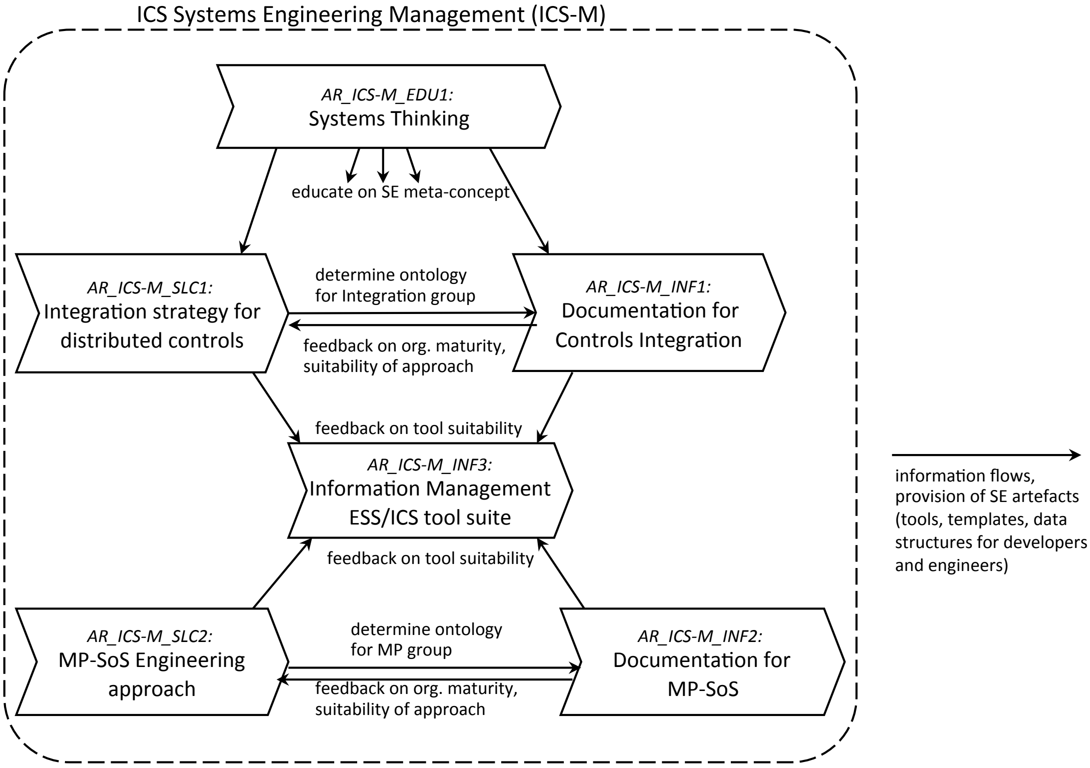


Figure 6: ICS Systems Engineering activity threads and illustrative interactions

AR_ICS-M_EDU1: **Systems Thinking**

Systems Thinking, in particular the application of a functional viewpoint on the developed systems, forms the base for the application of SE methods and system life cycle management. Hence, explaining and promoting Systems Thinking has been a recurrent activity throughout the research work, as a necessary precondition to establishing SE methods.

Preconditions: While intuitively Systems Thinking is widely used in the ESS environment, this is primarily applied to natural systems, communicative systems, or the like. Thinking in 'functional' systems required for Systems Engineering is however not intuitive to many practitioners. This is further explained in 4.2.

Goals: Establish SE based on function-oriented Systems Thinking at ICS and ESS.

Intervention: Dedicated educational material was prepared and used in meetings with the purpose to explain the application of Systems Thinking in the ESS and ICS. The material used domain-typical as well as ESS-specific examples, and showed their relevance for system life cycle management. The discussions were also used to explain the relation of the prevalent lack of Systems Thinking and widely perceived problems at ESS (e.g. lack of integration, shared understanding). Furthermore, the relevance of Systems Thinking, or respectively the lack thereof, has also been raised in many other discussions.

Impact: Significant increase in function-oriented Systems Thinking within ICS division has been achieved. This is visible in particular in the ICS Integration Group, where it has been well adopted. In particular positive is that the proposed Systems Thinking approach has migrated into the neutron science experiments domain at ESS. Also individual members of other divisions picked up on the concept, and to varying degrees, become multipliers for concept dissemination. Yet there are still significant parts of ESS where Systems Thinking is not yet sufficiently applied in a functional sense.

Research relevance: The repeated introduction of engineers and scientists working in system developments to Systems Thinking revealed difficulties in the adoption by practitioners and lead to analyses of the reasons for these (see 4.2). The subject permeates all contributions of this thesis.

AR_ICS-M_SLC1: **Integration strategy for distributed controls.**

The “Integration group” within ICS division has the task of developing and operating most of the distributed control systems at the ESS. These ‘integrate’ in the technical sense the bulk of the distributed equipment (power supplies, cooling modules, pumps, etc.) for physical processes at the ESS.

Preconditions: The need for a common, guiding framework for this group had been established for organising its activities and information in regard to systems development, installation, and integration. More explicitly, the group had been tasked with the elaboration of an “integration strategy” that would serve as guidance for its members and external stakeholders.

Goals: The Integration Group should have established a framework for coordinating its engineering activities and outcomes.

Intervention: The author proposed an Integration Strategy based System Thinking, system life cycle stages, processes and related documentation with a special emphasize on integration concerns. For dedicated integration management, the generation of Integration Plans has been proposed and outlined, with further detailing in the closely related “System Life Cycle Documentation for Controls Integration” activity thread. The strategy has been elaborated in a series of meetings with the Integration group leader, which included the clarification and tailoring of processes and documentation concepts for the Integration group.

Impact: The proposal has been formally approved and is being used by the Integration Groups members since late 2015. Further detailing and adjustments are on-going and continuously expected with increasing SE maturity of the involved staff and feedback to the “Integration Strategy” facilitators. This discourse appears to have reached a critical relevance now among the participants to be self-sustaining, meaning, it would continue without repeated incitation by the Systems Engineering facilitator (i.e. the author).

Research relevance: The case study enabled the identification and description of an approach to elaboration of Integration Strategy in the accelerator controls domain, which is centred on the informational needs and according viewpoints. It allowed the introduction of Integration Plans as a document type tailored to this domain, which is to the best knowledge of the involved persons a novelty in the accelerator controls domain. Further, this activity thread is concerned with addressing hard-to-resolve issues that derive from Systems of Systems characteristics, such as the complex configuration of independent stakeholders, resulting partially from the in-kind contribution model. This requires dealing with inconsistent viewpoints, and incomplete provision of documentation. The Integration Strategy activity thread is also an anchor point for establishing minimal documentation conventions and establishing communication channels. This activity thread and its results are more detailed in the appended paper C.

AR_ICS-M_INF1: **System Life Cycle Documentation for Controls Integration.**

The activity thread includes the actions that supported the Integration group within ICS to generate and maintain their technical documentation for system life cycle management.

Preconditions: The Integration Group of ICS has a need for support for generating and managing their system documentation.

Goals: The Integration Group should have established an established set of suitable document templates and database structures, and have received sufficient training for its utilisation.

Intervention: The author proposed a set of document types with generic content specifications that correspond to the Integration Strategy. The document types and their content specification have been defined in consideration of the typical system properties and stakeholder constellations for the ICS Integration group. Their generation has been put into the context of the ESS plans for document management, such as the evolving tool landscape (PLM etc.).

In an effort preceding the elaboration of the Integration Strategy, the author has engaged in the elaboration of a concept for interface management and documentation, focusing on a concept for "Interface Control Documents" for the Integration Group to be used with systems in the conventional facility domain (mostly process control). This preceding activity has lead had raised awareness of various issues (problems) related to documentation management, system life cycle management and the existing system definitions; thus it gave created critical momentum to the elaboration of an over-arching Integration Strategy (*AR_ICS-M_SLC1)*.

Impact: At the time of writing, the document templates and the usage of ESS document management systems are iteratively refined. It is realistic to expect further refinement throughout the construction time of the ESS, e.g. the documentation conventions for verification and validation activities will likely settle only after some practical experience is gained (approx. 2020-2022).

Research relevance: The elaboration of the documentation for the Integration Strategy allowed the introduction of viewpoints (e.g. on quality, integration dependencies, system decomposition) and document types for system life cycle management to the case study environment. The application of the proposed documents and according templates and their iterative refinement is enabling the realisation of the 'abstract' Integration Strategy' in the practices of engineers in their daily work. It is a critical step in the practical implementation of SE in the domain, as it includes viewpoint refinement and adaptation to the given tool environment.

The participation in this activity thread contributed primarily to paper B, and to some extent to paper A and C.

AR_ICS-M_SLC2: **Machine Protection SoS Engineering approach**

In order to achieve high reliability and availability expectations, the ESS is constructing a Machine Protection System of Systems (MP-SoS) for its accelerator machinery. It is basically composed of

- MP-related proton beam monitoring systems,
- MP-related systems in the accelerator, the target station, and the Neutron Science Segment,
- the Beam Interlock System (BIS),
- MP-related beam switch-off actuation systems.

The Machine Protection group in ICS has the task of coordinating the overall MP-SoS realisation and the design and production of the controls equipment within the MP-SoS.

Preconditions: The Machine Protection group in ICS had started out with the idea of designing the MP related systems in fashion oriented the functional safety standards IEC 61508/61511 in order to enable the ESS to reach its availability goals for beam production. The translation of the standards were however not straightforward in regard to system definitions, organisational responsibilities and authorities, definition and validation of protection functions, information generation and conservation. As the overall MP situation was suffered from ambiguities and parochialism, the author engaged with the MP group leader and an external consultant in the elaboration of a remedy concept for the situation.

Goals: The goal of the participation engagement was to present a tailored approach for the MP domain that would allow realising the MP goals by solving the aforementioned problems to a reasonable degree.

Intervention: A tailored approach has been elaborated based on applying Systems of Systems Engineering for the MP domain. It specifies systems, organisational entities (e.g. Machine Protection Committee) and informational entities oriented at and IEC 61508/IEC 61511.

Impact: The elaborated Machine Protection approach has been formally adopted by ESS. This includes governance and system architecture description, which reflect the SoS character of the approach. Further refinement of the approach is to be expected during the ESS and MP-SoS construction time (approx. until 2021).

Research relevance: The generalisable aspects of the MP-SoS approach will be presented in a paper that has been accepted for publication at the SysCon conference 2017 (paper D). To the knowledge of the participants in the elaboration of the approach, this combination of functional safety engineering and systems-of-systems engineering is a novelty in the particle accelerator domain. The MP-SoS can serve as case study of interest not only for the accelerator community, but also for the Systems of Systems community and for the functional safety community.

AR_ICS-M_INF2: **System Life Cycle Documentation for MP-SoS**

The elaboration of the engineering approach for the MP-SoS requires a detailed tailoring of the documentation related to the MP-SoS.

Preconditions: The elaboration of the engineering approach for the MP-SoS requires a detailed tailoring of the documentation related to the MP-SoS dependent on abstraction level, stakeholder and information kind.

Goals: The Machine Protection group should be able to produce all necessary documentation and support other MP stakeholders with the means to produce the required documentation.

Intervention: Higher-level documentation (architectural) has been produced, for which the author contributed on the conceptual level and with reviews. This included creating compatibility with other ESS life documentation concepts and information management tools.

Impact: Documentation of the MP-SoS according to the MP-SoS engineering approach is in work and partially approved.

Research relevance: The participation in this area allows defining the mapping of information required by functional safety standard into an over-arching SoS concept. The activity thread contributed to paper D.

AR_ICS-M_INF3: **Information Management ESS/ICS tool suite**

During the overall study period, ICS has utilised a variety of Information Management tools. Some have been ESS tools, some have been internal to ICS division and some are dedicated to a special application field, such as the controls configuration. This activity thread aimed customising these tools for SE at ICS.

Preconditions: The tools available for SE and SE management required customisation for usage in ICS. This applied to the centrally provided requirements tools (DOORS), content management tools (Atlassian suite) and the product life cycle management tool (CHESS).

Goals: Preparing the available tool suite for use in SE application at ICS.

Interventions: Content structuring, template generation, and testing thereof has been performed in the various tools.

Impact: The engagement resulted in available tools being tailored for ICS usage as good as possible given the practical limitations. Thus this activity also explored the practical barriers and hindrances to SE application resulting from the ESS tool landscape. Repeatedly, these barriers eventually prevented the continuous utilisation of a tool in daily work.

Overall, the practical utilisation of the ESS and ICS tool suite within ICS division has progressed at a slower pace than initially expected and intended. The reasons for this include disagreements on SE ontologies, technical limitations, issues with the ESS roadmaps for tool support and content maintenance resources.

Research relevance: The engagement in tool content tailoring and administration exposed quite detailed, yet significant barriers to the successful utilisation of information management tools for SE purposes. Such barriers can be technical (limits of tool functionality) or and usability related (time, effort and training it takes to make a tool work in the desired way, for users or tool configurators). These problems tend to materialise as hard barriers in the daily work[14] of SE management, and can hinder or prevent the implementation of a desirable or 'decided' SE concept. The preparation of SE artefacts (templates for documents, tables etc.) has been experienced as a highly recommendable practice for early validation of RE process specification, as it requires to check the consistency of the stakeholders' RE ontologies on a, detailed level, e.g. attributes of requirements, common understanding of traceability links and their representation on the tool level. This activity thread primarily influenced paper A.

2.4.2 Activity threads in the development of ESS systems

This section describes the activity threads were involvements in the development of technical systems. Figure 7 gives an overview on these and their relations to the ICS management activity threads.

Participation in actual system developments served a variety of goals:

- understanding the factual SE maturity of in different parts of the organisation, down to the individual,

[14] As an example, technical limitations of the requirements engineering tool (DOORS 9.5) prevented the realisation of the desired templates and data structures, which entailed the exploration of alternative remedies (upgrade, expansion purchases, alternative tool usage). This process was influenced by the ESS roadmap for the requirements tool, which was delayed for various reasons. The delay entailed temporary solutions on wiki and database technologies, which had usability problems. These problems produced temporary fall-backs to word documents that were intended to be avoided due to their significant managerial disadvantages (traceability, updates). More issues could be added.

- education and support of the stakeholders in Systems Thinking and SE application in their ‘real life’, as opposed to giving text book examples,
- gathering the necessary understanding of the domain and case study environment for developing tailored SE approaches and artefacts,
- finding entrance and gaining legitimacy within the organisation for the introduction of these tailored approaches for actual system developments,
- contributing practically to the success of the facility creation project and technology developments.

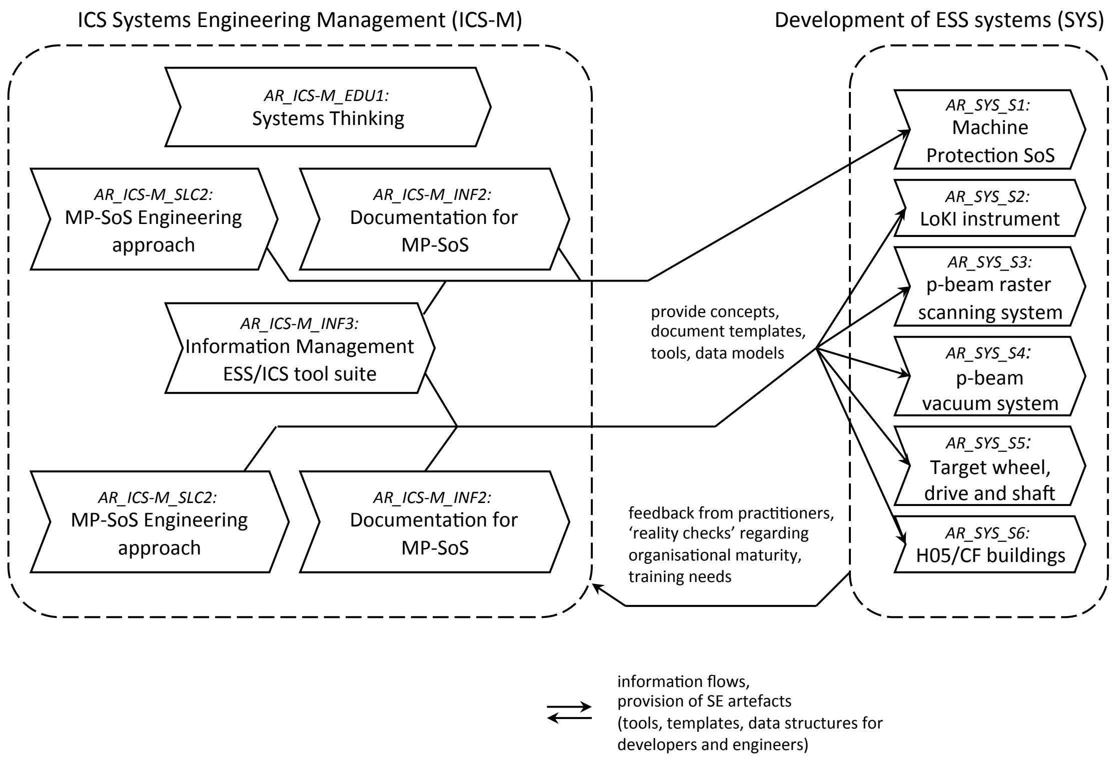


Figure 7: Activity threads in ESS system developments

AR_SYS_S1: **MP-SoS development.** Development work for the MP-SoS on the engineering level concerns technical system developments (e.g. electronics) and the engineering of the required reliability and availability properties.

Preconditions: MP-SoS engineers required training in the application of the MP-SoS approach.

Goals: The involved MP-SoS engineers should be able to implement the MP-SoS approach as planned.

Interventions: The author provided feedback on documentation for the MP-SoS and on the reliability and availability engineering in meetings with involved engineers. Consequences of the insufficient Systems Thinking practices on the level of multi-disciplinary systems were exposed in regard to reliability and availability engineering; instigating further discussions.

Impact: The activity thread helped to clarify the application of the MP-SoS approach for specific systems and their documentation. Further involvement with dedicated educational material (presentations etc.) is likely advisable, especially due to the involvement of in-kind contributors as suppliers of constituent systems.

Research relevance: The activities indicated the suitability of the proposed MP-SoS approach for practical application, and thus served as a mean of validation. The activities influenced paper D.

AR_SYS_S2: **LoKI instrument.** The LoKI instrument installation enables the small angle neutron scattering (SANS) technique to be used for material studies in various scientific disciplines. It is considered the 'lead' instrument of the ESS instrument suite, as furthest advanced in its life cycle, thus setting examples for other instruments to follow.

Preconditions: When ICS and LoKI engineers started to coordinate the controls development for LoKI systems, an initial breakdown existed that contained various kinds of information.

Goals: The SE concepts of the Integration Strategy were meant to be guiding the controls development and system integration of the LoKI systems.

Intervention: In a series of meetings, a clarification of the purpose of a functional systems breakdown could be achieved, which instigated a consolidation of the LoKI information structures.

Impact: A common base could be established among ICS and LoKI engineers based on Systems Thinking and according concepts on system life cycle management. This shared understanding is intended to have model character for further instruments, and thus propagate to SE activities with other NSS instruments.

Research relevance: The activity thread has been relevant to applying Systems Thinking in the domain, and for introducing and validating of the Integration Strategy of the ICS Integration group (paper C).

AR_SYS_S3: **p-beam raster scanning system.** The proton beam raster scanning system has the purpose of moving the proton beam impact area on the target within a defined window at high frequencies. Thereby a homogenous spread of spallation over a larger volume within the target is achieved. This prevents local overheating and damage to the target, enabling an overall higher neutron production cap.

Preconditions: A rastering concept for the proton beam as physical process had been developed, and partial designs on components had been achieved. However, a full, encompassing system had not been defined for application of a system life cycle model.

Goals: The goal of this activity thread was to establish the notion of the p-beam raster magnet system as a functional system with its own life cycle, thereby creating a parent system for ICS contributions (electrons, software). Further, it has been the goal to apply the System Integration strategy to the ICS equipment in the raster scanning system.

Intervention: The author outlined to the involved engineers the application Systems Thinking for the p-beam raster scanning system, and gave feedback one the generation of the system's technical documentation. This resulted in system definitions guided by function-oriented Systems Thinking.

Impact: A shared system view could be created among at least some of the involved engineers among ICS and Accelerator division. Steps towards applying the Integration Strategy could be achieved. Progress is dependent on participation of technical experts, as the system owner division does not actively support a systems approach.

Research relevance: This activity thread forms a case study for SE management and Systems Thinking application in an advanced, multi-disciplinary accelerator system. It influenced the SE Management findings in this thesis and influenced the Integration strategy (paper C).

AR_SYS_S4: **p-beam vacuum system.** The proton beam vacuum system generates an ultra-high vacuum system in the beam pipe for the proton beam, which enables protons to be accelerated on a linear trajectory without collisions with other molecules. The vacuum equipment (pumps, gauges, etc.) is controlled by ICS delivered industrial control equipment.

Preconditions: The physical process (vacuum quality requirements) and the vacuum equipment distribution had been performed, but a p-beam vacuum system as a whole had not been defined and elaborated in regard to its life cycle or operational and maintenance aspects of its operation that touch on controls functionality.

Goals: Goals of this activity thread included to establish the notion of an encompassing p-beam vacuum system, and enable the involved ICS engineers to apply the ICS Integration Strategy.

Intervention: The author supported the involved ICS engineer in the practical application of the ICS Integration Strategy by advising on system definition and documentation generation.

Impact: Improvements in the application of Systems Thinking could be achieved in the form system definitions. The application of the Integration Strategy has started, and initial documentation has been drafted accordingly. Continued SE management efforts are needed. Progress is dependent on participation of technical experts, as the system owner division does not actively support a systems approach.

Research relevance: The activity thread is another part of the case study on applying Systems Thinking and the Integration strategy. It influenced overall SE management concerns and paper C.

AR_SYS_S5: **Target wheel, drive and shaft system.** The Target wheel, drive and shaft system (TWDS) consists of a wheel mostly made of tungsten, the actual target for the ESS proton beam, a support shaft and related motion control and positioning systems needed for operation and maintenance. ICS has been tasked with the provision of controls for the system.

Preconditions: The TWDS has been designed in respect to physical and mechanical concerns. Due to a lack of functional system definitions, the inclusion of controls development was ambiguous.

Goals: The goals of this activity thread included the establishment of a systems approach for the TWDS, in particular for its controls development, and the application of the Integration Strategy.

Intervention: Some progress in system definition could be made for the TWDS and for the Target station as a whole, however restricted to engineers within ICS. As part of applying the Integration Strategy to the TWDS, the author elaborated a draft example for an Integration Plan for the TWDS, which presented information related to e.g. integration dependencies, system qualities, integration risks and system decomposition.

Impact: In the ICS Integration group, this activity increased the awareness of various SE aspects from an integration-focused perspective on a core ESS system its life cycle management. Thereby this activity thread gave momentum to the elaboration of the Integration strategy of the ICS Integration group (*AR_ICS-M_SLC1*). It also introduced a practical example of a collection of integration-relevant information (for *AR_ICS-M_INF1).* The Integration Plan draft served further as example in later discussions on integration management for other ESS systems. Still, further SE management activities are needed for the realisation of the Integration Strategy for the remaining years of TWDS construction. Progress is dependent on participation of technical experts, as the system owner division does not actively support a systems approach.

Research relevance: The Integration Plan example for the TWDS served as feedback source for the proposed technical viewpoints (Integration dependencies, qualities, system decomposition), and for the document type as a whole. The activity thread influenced mainly paper C and the SE management chapters of this thesis.

AR_SYS_S6: **H05/CF buildings.** ICS division has been tasked with integrating the various industrial control systems on the ESS site that potentially may have impact on the neutron production process. This includes the main electricity (high voltage) systems and the site's major cooling systems, as these provide crucial services to the accelerator, target and experiments. These systems are hosted in a variety of 'conventional facilities' structures, one which is the H05 building, which hosts the site's connections to the regional electricity. From here, the ESS's provision fans out.

Preconditions: ICS and the Conventional Facilities division, responsible for the design of the systems described afore, had to establish communication and coordination channels for the engineering work. The general requirement of full integration of the distributed systems was noticeably unfamiliar to the CF stakeholders.

Goals: The initial goal of the activity thread was to establish a shared convention for interface documentation and management using Interface Control Documents by both ICS and CF division.

Intervention: The activity thread resulted in a proposal for an ICD convention (viewpoints and content structure, template), which has been elaborated with the Systems Engineering facilitator counterpart of the Conventional Facilities division. It was approved by the management teams and partially implemented. The activity raised further awareness for the need of shared system definitions and further system life cycle documentation conventions, giving momentum to the elaboration of the Integration Strategy.

Impact: The proposals for SE management have been accepted and partially implemented (ICD conventions). The activity thread raised awareness for the need for the Integration strategy elaboration (*AR_ICS-M_SLC1*) and also tied into tool customisation (*AR_ICS-M_SLC1*). It continued with refinements, later governed by newly approved Integration Strategy.

Research relevance: Primarily, this activity thread influenced paper C, regarding the Integration Strategy.

2.4.3 Activity threads concerning ESS Systems Engineering Management

This section describes activity threads, in which the author engaged as general representative of ICS division in ESS wide matters that concerned SE and quality management. As such, the author pursued active participation in regular and intermittent venues that had the purpose of SE coordination on an ESS level. These engagements had the research-related aims

- to understand SE matters beyond the controls and computing systems area, in particular, to study SE management on the facility level,
- to understand SE issues and problems that are typical for the integration of controls and computing systems with the rest of the facility,
- to disseminate knowledge on SE matters on ESS level, in particular those of concern for the controls and computing systems engineering. This concerned especially the definition of multi-disciplinary systems and their life cycle management.

Figure 8 shows the activity threads on ESS SE Management and their interaction with the ICS SE management area.

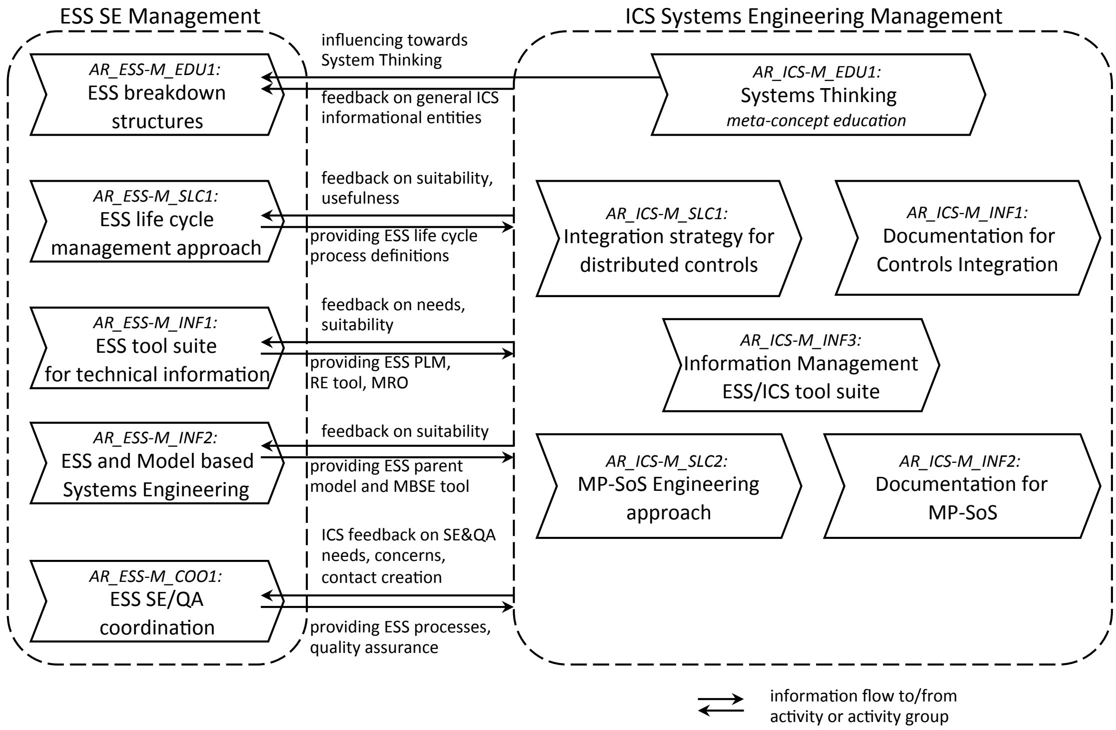


Figure 8: Activity threads concerning ESS Systems Engineering Management

AR_ESS-M_EDU1: **ESS Breakdown Structures.** For a large, complex, multi-disciplinary system such as a particle accelerator the structuring and management of technical information is a crucial aspect of successful and efficient engineering. Hence, the author engaged the establishment of the ESS information structures as representative of ICS division. This activity thread aimed at establishing a reasonably complete and consist information model for the ESS and ICS.

Preconditions: The ESS did not have an *over-arching information model*; instead a variety of information processing systems were developed based on the sectional (parochial) identification of information management needs (e.g. within technical divisions). The corresponding information models had not been systematically checked for overlap, gaps and consistency. The field presented itself as prone to controversies due to the sectional developments.

Goals: As for the far-reaching goal, this activity thread aimed at establishing a model for technical information at ESS that would allow, in principle, a comprehensive view on all technical information across the ESS divisions, with a common fundamental ontology (system breakdowns, location breakdown, system requirements management structure, product life cycle management structure, etc.). Mid-range goals have been to promote an ESS-wide systems-oriented decomposition of the ESS for the purpose of system life cycle management in the product life cycle management (PLM) tool of the ESS and later the realisation of a maintenance, repair and overhaul system (MRO).

Intervention: An important discussion thread has been repeatedly pushed by the author among the SE facilitators in different divisions at the ESS, using various meetings or events. It concerned the benefits for replacing an existing 'ESS breakdown structure' without a consistent partitioning principle, effectively dysfunctional for system life cycle management, with breakdowns based on consistent viewpoint application (functional systems, location, system classes, 'physical').

Impact: Surprisingly, this initiative was received highly controversial by the ESS SE facilitators and met significant resistances. The stated reasons for these resistances included short-term schedule concerns, unjustified high confidence in parochial approaches, or basal misunderstandings of SE concepts (practical application of Systems Thinking in the accelerator domain). Human factors may have played a role as well. Essentially, this activity thread exposed an insufficient understanding of SE information management needs in the organisation.

Some progress could however be achieved. At a workshop of the ESS top and mid-level management, a proposal was strongly influenced by the author that presented a systems-oriented approach to ESS systems definition. It was well received, and in the trail of this development, a major upgrade for the product life cycle management tool at the ESS was brought on the way. This upgrade has been intended to include an update of its informational structure, taking in into consideration the results of the aforementioned workshop. Furthermore, the author engaged in several occasions with the developers of this upgrade, as he could explain information management needs with examples from the controls and computing system domain. The ubiquity of controls and computing systems in the research facility made the role of "SE facilitator in the controls division" a naturally well suited source of information and examples for the developers of the PLM upgrade.

Based on this activity thread, the author has initiated discussions between the ICS software group and the PLM/MRO developers regarding potential overlap, gaps and synchronisation needs on system maintenance data.

Research relevance: The activity thread's subject pervades virtually all aspects of SE and its management in the accelerator domain; however, it influenced in particular the Systems Thinking considerations in 4.2, which in return determined the weight this activity gained during the study period - it became increasingly clear over time that the ICS and ESS as a whole would benefit greatly of Systems Thinking practices, which would find directly impact in the ESS breakdown structures.

AR_ESS-M_SLC1: **ESS system life cycle management approach.**

Preconditions: During the Action Research time of this thesis, a generic set of system life cycle processes has been defined for the ESS as a whole. The definition, iteration and implementation of this set of high-level process has been driven primarily by the central SE division, and was expected to guide the system developments in the various technical divisions.

Goals: This activity thread had the goal of improving the generic system life cycle management on the overall ESS level by providing feedback on the proposed life cycle processes from an ICS perspective. Practically speaking, the author participated in discussions of the matter in various meetings and events with the intention of contributing to the elaboration of the ESS system life cycle model.

Impact: The generic set of system life cycle processes (proposed by the central SE division) was found to be problematic to 'implement' on the engineering level in the technical divisions (ICS and others). Problems derived from various sources, depending also on the iteration of the proposed set. A continuous hindrance has been the system definition practice at ESS (lack of Systems Thinking). Additionally, the proposed set of process definitions showed inherent problems that can be described as a mixture over-determination and under-determination. Over-determination here means, the processes contained prescriptive elements that lead to insufficient adaptability or flexibility for process tailoring according to discipline or system characteristics. In these cases, the process definition was felt to be overly restrictive to be used in practice. Under-determination means that the highly generic, abstract description and writing style made them too unspecific to be of actual practical help. Consequentially, they hardly achieved a visible beneficial impact on engineering coordination.

Research relevance: The findings based on the participation in the ESS system life cycle management discussions influenced the SE management chapters in this thesis, and the papers A, C, and D in regard to system life cycle management. In particular, this activity thread helped to identify problems regarding the practical application of process definitions. The activity thread also gave insight in the need to support process tailoring for specific systems, and the managerial problems that come with it.

AR_ESS-M_INF1: **Information Management ESS tool suite.** During the overall study period, ICS had to determine the utilisation of a variety of Information Management tools (PLM, document management tools, issue tracker, wikis and requirements tool). Some tools have been provided by other divisions and for all of ESS. This activity thread describes the involvement in the acquisition and customisation of ESS-wide tools on behalf of ICS division.

Preconditions: The ESS decided to use for SE related information management tools (DOORS 9), a PLM technology (ENOVIA) that initially was used for document management. More technologies were in use within the divisions. The overall ESS tool suite has been changing over time due to new versions from the vendors, ESS internal developments and additional technology introduction to the overall ESS level. Hence ICS has to continuously re-adjust its tool utilisation based on those external factors, coordinate this with other technical divisions on the ESS level. The tool customisation for ICS has to be performed either by ICS, or the customisation needs have to be communicated to the organisational 'owner' of the tool.

Goals: The goal of this activity thread was to provide ICS division with reasonably well customised, practically useful tools for SE tasks.

Intervention: The author engaged in tool customisation and partially administration tasks; e.g. the author set up content in the initially deployed DOORS version. Further, the author represented ICS in tool related development events, e.g. the specification of use cases for the PLM or the new requirements management tool (DOORS NG was deployed in 2016), which were developed or customised by other parties within ESS.

Impact: The goal has been pursued in coordination with other parts of ESS, with overall mixed results. A significant increase of awareness of the shortcomings of the present situation (preconditions) could be achieved. The repeated discussions regarding the SE-related tool suite lead to a spread of conceptual understanding of the preferable direction for ICS and ESS. This manifested in improvements realised in the RE tool and PLM developments, e.g. the ability to produce requirements documents that incorporate database content and free text efficiently, or use case specifications for the PLM that support the MP-SoS engineering (compare *AR_ICS-M_INF2*). Yet, significant efforts and achievements maintain to be realised in order to achieve the goal of this activity thread.

Research relevance: The analytical research purpose for these activities included

- to gain an understanding of the benefit potential of the tools in the domain of controls and computing systems at research facilities,
- to identify barriers for the successful tool customisation rooted in contemporary technology,
- to identify barriers for the successful tool customisation rooted within the engineering environment.

So this activity thread has been intended to yield findings of interest for tool developers (regarding customisation functionality of tools) and SE managers in the research facility domain (regarding the tailoring of tools to a specific environment, taking into consideration the SE maturity of intended users). The activity thread influenced paper A and the SE management findings of this thesis.

AR_ESS-M_INF2: **ESS and Model based Systems Engineering.**

Preconditions: ESS had engaged in an attempt to establish MBSE based on SysML modeling, primarily driven by the central SE division. The author acted as coordination representative for ICS in this matter.

Goals: The goal of this activity thread has been to establish tool based modeling of systems as a beneficial practice in the ESS and ICS design processes.

Intervention: The author engaged in the proposed MBSE approach by content generation and giving feedback on the approach.

Impact: The practical implementation of MBSE proved to be more difficult than anticipated and realised by the proponents of the approach. Insufficient conceptual elaboration of the overall model made it unusable on more local scales, which was a result of the lack of Systems Thinking in the definitions of ‘blocks’, systems. The model organisation on the tool level was also not as efficient as desirable for practical use. Further, it became clear that relevant MBSE stakeholders lacked to varying degrees practical experience as well as theoretical MBSE knowledge to manage and create a consistent model of the ESS. While these problems were in principle still solvable, differences among the stakeholders led to stagnation in this area.

Research relevance: The participation in this activity thread exposed barriers to the successful application of MBSE in the domain. This influenced various considerations in the SE management chapters of this thesis.

AR_ESS-M_COO1: **ESS SE/QA coordination.**

Preconditions: ICS division required a representative as contact person for SE matters in a variety of meetings and events.

Goals: To integrate the controls and computing systems development with other development activities at ESS.

Intervention: The author represented ICS in a number of repeated or singular meetings and events, including

- ESS System Engineers meeting (regular meeting, every 2-3 weeks)
- ESS Quality assurance meetings (regular meeting, every 3 weeks)
- ESS Standards and Norms group (regular meeting, every 2-3 weeks)
- Workshop “ESS Interface and Programme management forum”,
- a spin-off of the former, Working Group “Scope and Requirements” (group chairman),
- various singular focus meetings.

Impact: The participation in these meetings has been primarily used for coordination of ICS with other parts of the ESS organisation, e.g. by informing about SE matters, creating contacts, initiating discussions. Occasionally, these meetings have also been used for SE concept dissemination in the organisation.

Research relevance: The participation in these meetings have been beneficial for gaining a much broader overview on SE related concerns, ontologies, barriers and diverging views in various engineering and management disciplines than could have been gained within the ICS division alone. Thus the insights gained in these coordination activities improved the awareness of multi-disciplinary challenges in all parts of the research work, perhaps in a subtle way.

2.5 Delimitations

The following subjects are excluded from the scope of this thesis:

- Natural sciences, meaning e.g. physics phenomena have not been researched in this work.
- Engineering concerns specific to technical disciplines (electrical engineering, civil construction, accelerator physics, etc). The work

touches on these, but the contribution lies in the engineering coordination and integration of technical disciplines.

- Facility-specific systems or solutions for engineering coordination are used for the analysis of the existing situation, and serve as illustrative examples. The details of contributions to the ESS or MAX IV Systems Engineering that emerged from in this thesis work are by themselves not of general interest and thus omitted (e.g. detailed problems about usability of a requirements engineering tool). The thesis focuses on *generalizable insights*, in particular regarding Systems Engineering *Management*.
- The conduction of actual system life cycle processes (e.g. defining a requirement, producing a system design, defining a verification plan) for particular systems of the ESS are performed by technology experts/discipline engineers. The participatory part of the thesis work has been interested in facilitating and structuring these activities within the organisation, not conducting them.

3 Operational characteristics of large Research Facilities

This chapter introduces the engineering of large research facilities focusing on technical and organisational aspects. An overview is given on the types of accelerator based research facilities (3.1). The European Spallation Source ERIC is presented in more detail (3.2), as it has been the primary study environment for this thesis. Controls and computing systems technologies used in the domain (3.3) are introduced. The relevance of engineering for research facilities (3.4) and its typical implementation is explained in regard to roles of the organisation (3.5). The main processes within the organisation are described with an assessment of their interplay and problems (3.6), and typical organisational structures (3.7) at research facilities are presented.

3.1 What are large Accelerator based Research Facilities?

An overview sketch representing *groups* or *classes* of large research facilities is shown in Figure 9. For each group a few prominent example facilities are given by their abbreviation, and a list of these abbreviations is included in Table 4. Following this, short characterisations of the groups are given, which are meant for an audience that is not familiar with the underlying physics or technical concepts.

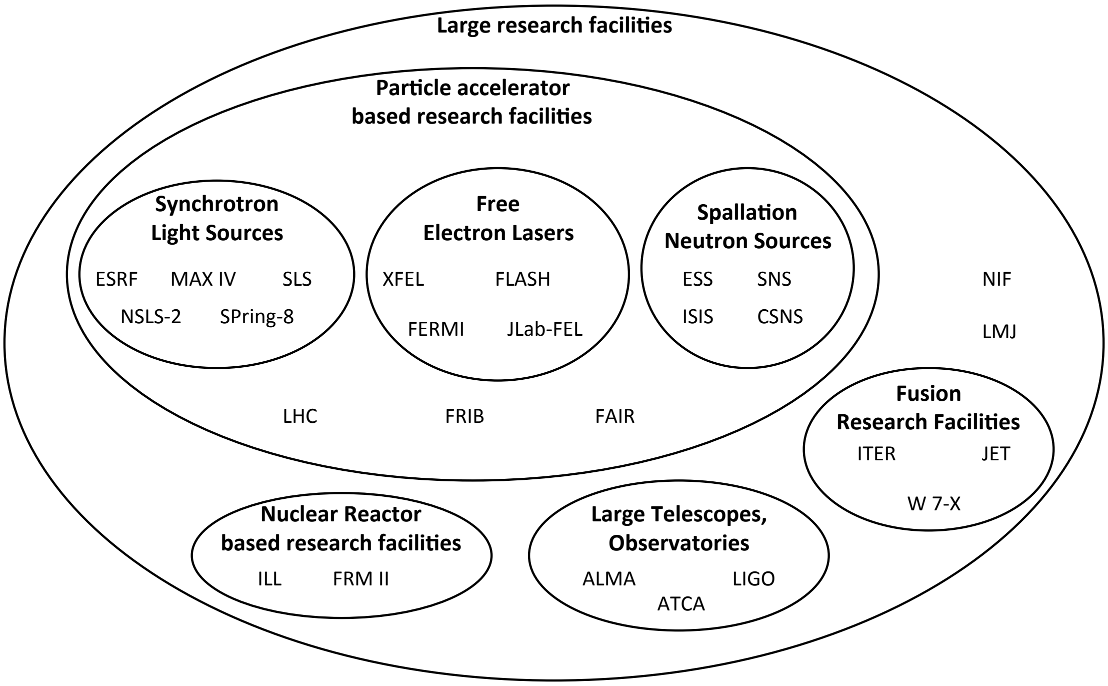


Figure 9: Overview of large research facility groups

Table 4: Examples of large research facilities

Synchrotron Light Sources		
ESRF	European Synchrotron Radiation Facility	France
MAX IV	MAX IV	Sweden
SLS	Swiss Light Source (Paul Scherrer Institute)	Switzerland
NSLS-2	National Synchrotron Light Source II	USA
SPring-8	Super Photon Ring 8 GeV	Japan
Free Electron Lasers		
XFEL	European x-ray free electron laser (DESY)	Germany
FLASH	Freie Elektronen Laser Hamburg (DESY)	Germany
FERMI	Free Electron laser Radiation for Multidisciplinary Investigations	Italy
JLab-FEL	Jefferson Lab Free Electron Laser	USA
Spallation Neutron Sources		
ESS	European Spallation Source	Sweden
SNS	Spallation Neutron Source	USA
ISIS	ISIS neutron and muon source	UK
CSNS	China Spallation Neutron Source	China
Other particle accelerator based research facilities		
FAIR	Facility for Antiproton and Ion Research	Germany
FRIB	Facility for Rare Isotope Beams	USA
LHC	Large Hadron Collider (CERN)	Switzerland/France
Nuclear Reactor based research facilities		
ILL	Institute Laue-Langevin High Flux Reactor	France
FRM II	Forschungs-Reaktor München II	Germany
Large telescopes, observatories		
ALMA	Atacama Large Millimeter Array	Chile
LIGO	Laser Inferometer Gravitational-Wave Observatory	USA
ATCA	Australia Telescope Compact Array	Australia
Fusion research facilities		
ITER	International Thermonuclear Experimental Reactor	France
JET	Joint European Torus	UK
W7-X	Wendelstein 7-X	Germany
Other research facilities		
NIF	National Ignition Facility	USA
LMJ	Laser Megajoule Facility	France

Synchrotron light sources and free electron lasers (FEL). Synchrotron light sources and free electron lasers accelerate electrons close to the speed of light and use them for the production of photon beams (“light”). Primary interest is in hard and soft x-rays, however the wide spectrum usually also covers the visible and UV light. The produced radiation is used for material characterisation in various natural sciences, including physics, life sciences, molecular sciences and material sciences.

Synchrotron light was first discovered in 1946, as an undesired side effect in electron accelerators. The phenomenon was first studied “parasitically” at accelerators designed for other purposes, in so-called 1st generation light sources. Beginning in the 1970’s, the first machines were designed and constructed for the production of synchrotron light (e.g. NSLS, National Synchrotron Light Source). These 2nd generation light sources enabled significant improvements in brightness and other beam properties. The introduction of "insertion devices", wigglers and undulators, beginning in the 1980's, defines 3rd generation of light sources, which enabled another improvement of the photon beam properties by orders of magnitude. Free electron lasers, in particular modern LINAC based FEL's, are often called the 4th generation of light sources, as they allow for high intensity, ultra-short light pulses. FEL's have been able to produce light in the (initially soft) x-ray regime for experimental usage since approx. the late 2000's. It should be noted that the 2nd and 3rd generation made the previous technology obsolete for the purpose of light production for experimental usage; however the FEL/4th generation is complementary to the synchrotron light sources due to significantly different beam properties that enable different experiment techniques.

Figure 10 shows a concept drawing of the MAX IV laboratory. The red lines symbolize the path of the electrons. A linear accelerator provides an electron beam up to 3 GeV for injection into the 1.5 GeV synchrotron ring and the 3 GeV synchrotron ring. It further provides electron beam for a short pulse facility and, as a potential future upgrade, a free electron laser. The electron beam in the storage rings is used to generate synchrotron light beams, symbolised by yellow arrows, for various experimental stations located around the ring. The 1.5 GeV ring is optimised for soft x-ray studies, while the 3 GeV ring primarily produces hard x-rays, see (MAX-lab, 2010) for more information.

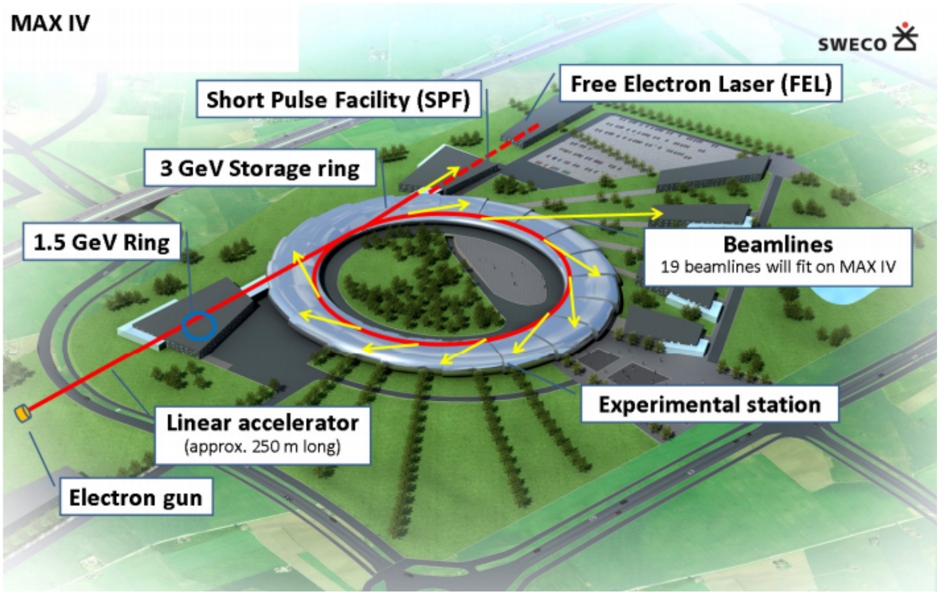


Figure 10: The MAX IV laboratory

An interesting work on the genesis of synchrotron radiation laboratories is the PhD thesis "Small science on big machines. Politics and practices of synchrotron radiation laboratories" (Hallonsten, 2009). It is a sociological work on national research policies, partially based on interviews with practitioners, and compares the policy background and practical creation of the MAX-lab laboratory, the Stanford light source and the European Synchrotron Research Facility ESRF.

Neutron sources. Neutron beams are useful for characterising materials for studies in physics, chemistry, life sciences and engineering. The techniques tend to be complementary to photon based studies, as neutrons interact differently with the materials. The production of neutrons on large scales is typically done either with nuclear reactors, resulting in continuous production, or pulsed spallation sources, which deliver high peaks of neutron brightness over short times. Neutron spallation is a process in which nuclei are split by accelerated particles. Spallation neutron sources typically accelerate protons to near-relativistic speeds (approx. 90% of the speed of light), and let the protons collide with a 'target', e.g. made of tungsten or mercury. Free neutrons emerge then as collision products, and they are utilised in experiment installations. A more detailed, tangible architecture of a modern spallation neutron source is outlined in section 3.2, the example of the European Spallation Source.

Other large research facilities. Large particle accelerators for ions are comparatively few and tend to be rather unique in their scope and architecture (e.g. LHC, FRIB, FAIR), even within the particle accelerator domain. Nuclear reactors for research (e.g. ILL, FRM II) have a strong overlap with neutron spallation sources in regard to experiment techniques and purpose, however the base neutron generation technology is more related to nuclear reactors for electricity production. Large telescope facilities (ALMA, ATCA) or other astronomy oriented observatories (LIGO) often use control and computing system technology from the particle accelerator world, even though the base technologies and study objects (very small phenomena vs. the very large and distant) are fundamentally different. Fusion research facilities (ITER, JET, W7-X) intersect partially with particle accelerators, again in particular in the controls and computing systems domain. For example, the EPICS technology for building SCADAs for large research facilities has its roots and main application field in the particle accelerator domain, but is also used at e.g. ITER, LIGO and other places. NIF and LMJ are examples of large, governmental research facilities operating high power lasers for the research of matter in special states, which are mostly of interest for countries with nuclear capabilities for defence purposes.

3.2 The European Spallation Source (ESS)

The European Spallation Source is a research facility for fields in natural, engineering and life sciences based on the world's most powerful pulsed neutron spallation source. At the time of writing, the ESS is under development and construction in the city of Lund, Sweden, and expected to be fully operational in 2025. The ESS is a collaborative project of currently 19 European nations.

Project finances and in-kind contribution. The ESS project has a budget of approximately 1800 million Euros, which to a large extent is provided in the form of in-kind contribution. Figure 11 gives an overview of the split among the main systems (Accelerator, Target station, Instruments) and the relative part delivered "in kind". Realising accelerator projects with such high degree of in-kind contribution is a relatively new trend, and poses new challenges for the accelerator construction community. The traditional, typical engineering approach in the domain is to have a design team residing in the facility's location. In the case of the ESS, numerous teams spread over most European countries work in a distributed fashion. The ESS team in Lund is responsible for the central integration as well as some parts of the system development.

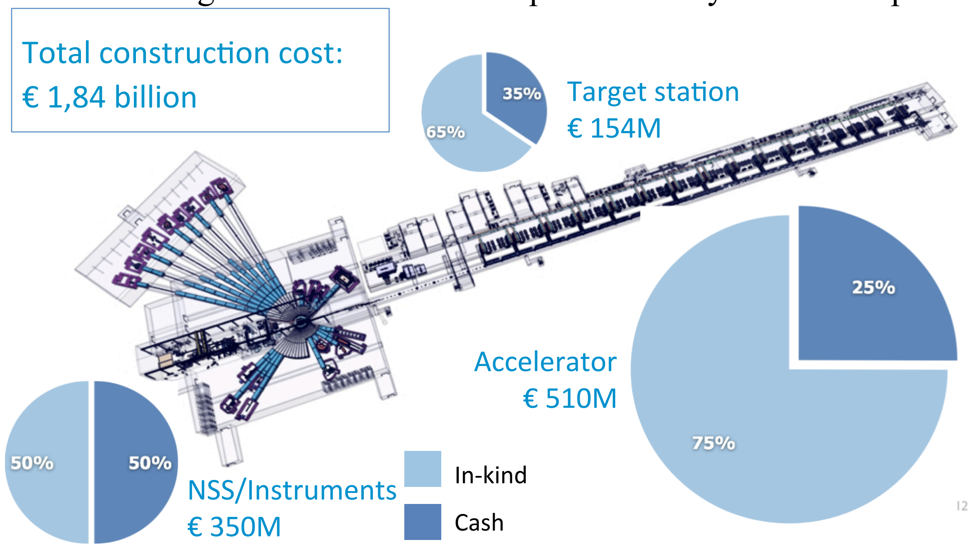


Figure 11: The ESS budget and in-kind contribution

Project timeline. The ESS project timeline is shown in Figure 12, with the red arrow indicating the time of writing. The time span from early design (conceptual) to construction completion spans about two decades, which is longer than for many light sources, but expectable for the larger facilities.

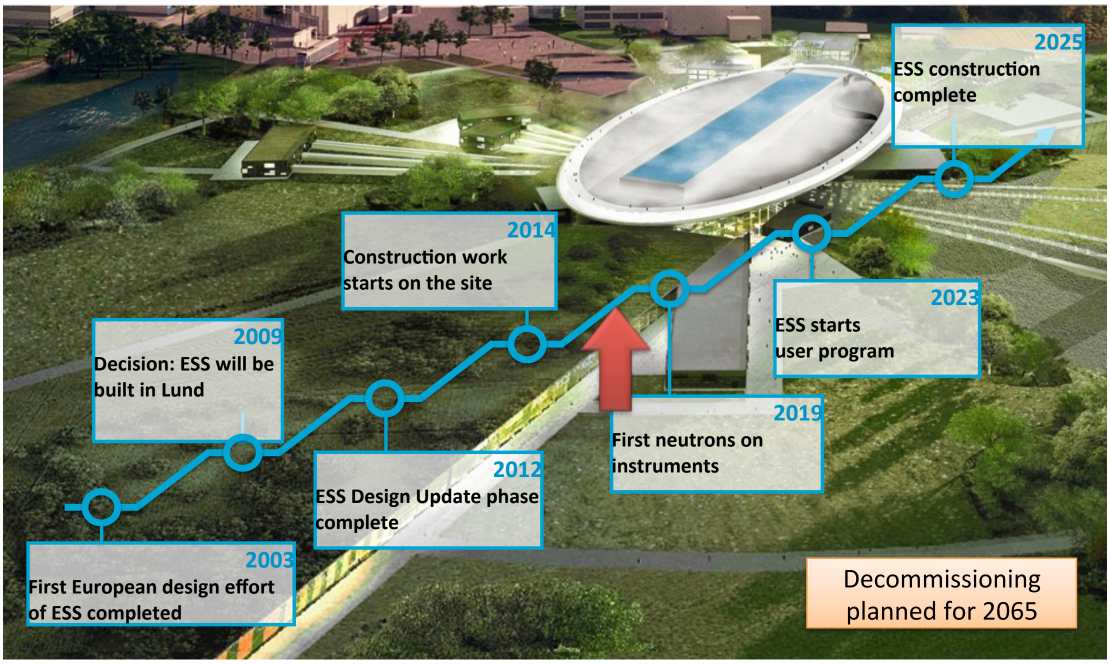


Figure 12: The ESS time line

Figure 13 shows the ESS site in an aerial view at the time of writing (picture from Dec 22nd, 2016). To the upper right, the approximately 600 m long proton accelerator tunnel is visible. In the centre, works for the Target station and experiment buildings are on-going.

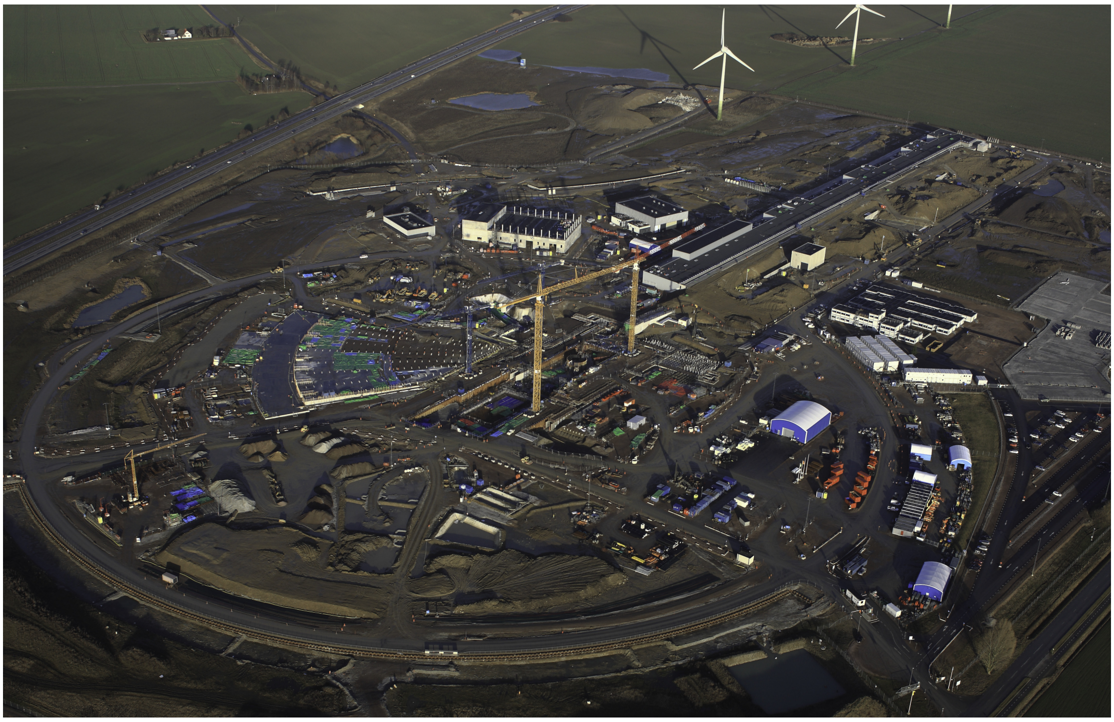


Figure 13: The ESS construction site, Dec. 22nd 2016

3.3 Why are Control Systems and Computing Systems of interest here?

Control systems are the mediating layers in the chain between humans and physical processes in a research facility. Figure 14 shows the typical layers in modern research facilities (left side), and gives an indication of their associated responsibility allocation (right side). Note that e.g. application layer software can be in either Operations, maintenance and user scope (and be programmed by e.g. experimental scientists) or in the typical group of control groups. Similarly, 'Analog or power electrons' can be in the control group scope or in an engineering expert group's scope (e.g. RF engineers). The diagonal borders between the scopes in Figure 14 indicate that the layers (horizontally) can relate to different scopes.

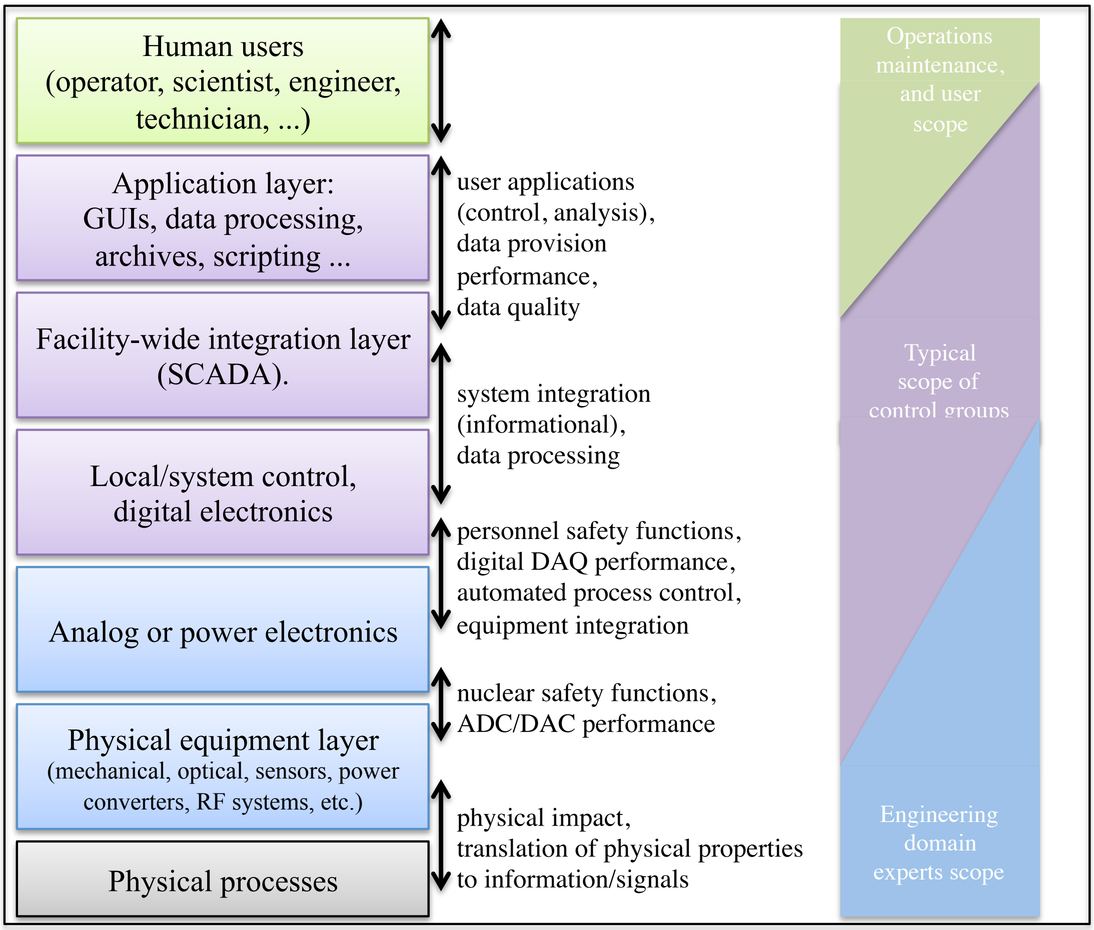


Figure 14: Control system layers

Human users utilise a variety of applications to acquire information on the physical processes (e.g. proton beam generation, vacuum generation) and on the distributed equipment (power supplies, pumps, etc.) that enables the physical processes. Based on this information, the human users control the equipment behaviour and thereby enable physical processes according to their mission. These interactions occur by using a set of applications, such as for equipment configuration, alarm applications, archiving applications for the analysis of the processes and machinery over time.

In large facilities, the applications do not communicate directly with distributed equipment. Instead, one or several intermediate layers are realised that allow control of the entire facility in a standardised, homogenous way for the purpose of *supervisory control and data acquisition* (SCADA). The SCADA systems integrate physically distributed systems technically. These systems typically comprise some form of local control, *distributed control systems.* Such distributed control systems can be realised by industrial control technology such as Programmable Logic Controllers (PLCs), high performance electronics (VME crates, microTCA technology), industrial PCs, stand-alone controllers or even domain-specific SCADAs (e.g. for the electrical/high voltage systems). Figure 15 shows some typical distributed electronics for local control.

Figure 15: mTCA crates (left, middle) and an industrial PLC (right)

The facility-wide SCADA uses a fairly wide range of industrial field-bus systems, Ethernet protocols and communication interfaces, APIs etc. to achieve the *informational integration* of the facility. The most prominent technologies used for informational integration in the research facility domain are the EPICS[15] and TANGO[16] control system frameworks. These control system frameworks support the utilisation of a wide range of control, communication and software technologies for equipment integration, and provide base applications or programmable libraries for archiving, alarm handling or managing configuration settings. The EPICS and TANGO control system frameworks are open source, driven by collaborative efforts of the research facility communities. An extensive overview on control system frameworks and other technologies that are typically used in light sources can be found in (Friedrich, 2013). A more detailed overview on control system technologies used at ICS and ESS is given in (Korhonen, 2015).

Information processing services. The operation of a large research facility requires also software based services for operational and managerial purposes that are not directly control systems, but tie into the control system

[15] EPICS http://www.aps.anl.gov/epics/
[16] TANGO http://www.tango-controls.org/

infrastructure. Due to the vicinity in application and technology, they are often provided by the same groups. The realised functions can include

- **Electronic logbook.** An electronic logbook is an operations logbook for hand-written entries that are complemented with screenshots, links, tables, etc. It is used by machine operators to log events and comments on them e.g. for work shift changes or later references.
- **Inventory.** Inventory databases of the machine are used in maintenance activities and can be used to acquire statistics on machine operation. E.g. an inventory database could allow the analysis of failure rates of certain machine parts, or equipment types over time, which may slip the attention of humans, and indicate potential for availability increases.
- **Web services.** For various reasons, it can be beneficial to enable limited access to facility data via web services. Remote (off-site) access can be interesting for machine analyses by expert staff that is off-site in case of emergencies. Remote access to experiments can reduce the need of users to travel long distances. Online demonstrations of general machine status data can communicate the overall organisation's activities and capabilities.

All these examples have in common that they benefit from retrieving live data from the facility, or data from the facility's data archives. This is achieved by adequate communication interfaces, typically based on web services technology.

3.4 How Engineering relates to the interests of researchers at accelerator facilities

Why is "engineering" important at large research facilities?

Research enabling services provided by large research facilities are commonly built around a core service, which stems from the operation of an advanced piece of machinery - a particle accelerator, a telescope, a fusion reactor, etc. These machines are often characterised by a "figure of merit" that indicates their potential for its scientific exploitation. For light sources, a core figure of merit is the brilliance of the delivered photon beam (among other beam properties, e.g. size, angle and temporal resolution). A more domain-specific figure of merit is the emittance, a value which describes spatial light emitting properties of charged particle beam, and thereby determines the brilliance. New research facility designs often aim to surpass comparable existing facilities in order to allow for novel experiments. Achieving the leaps to new performances requires a significant engineering effort during the design of the new machine.

At user facilities, a second reason for extensive engineering activities is the development of experimental facilities. Even with a standard performance of the core service, novel experiments can be enabled by the development of experimental stations using new experimental methods, or improvements of the state of the art. Also very practical concerns regarding the conduction of experiments contribute to the scientific value of an experimental station, and thereby to the facility as a whole.

The variety of technical and scientific disciplines involved in research facilities is among the highest considering all types of plants, as a research facility campus requires highly specialised scientific-purpose related engineering (e.g. accelerator physics, neutron science instrument design), several ‘exotic’ engineering domains (e.g. cryogenics, radiofrequency engineering, vacuum engineering), various control system and software development engineering flavours, industrial plant engineering (high voltage electrical engineering, nuclear engineering, industrial cooling systems engineering), as well as conventional civil engineering (for instrument and machine halls, but also for office buildings).

Figure 16 shows a customer key driver graph[17] that explores and explains the driving motivations of customers (in this case: visiting research groups, ‘users’) and relates them to common properties or functions of neutron experimental installations. The colours of the boxes refer correspond to views in the CAFCR[18] framework, which is further explained in (Muller, 2012). Typical system functions and related qualities of experimental installations at user facilities are shown in purple, to the right side, and are part of the Functional view. These systems and their functionality constitute the technical means which visiting researchers utilise by application. Applications and their relevant properties are shown in the Application view, represented by the blue boxes in the central part of the diagram. In Figure 18, a few typical application concerns of visiting researchers are shown. The application view is further leading back to the customers’ (visiting researchers’) objectives, the actual *key drivers* that form the value background for visiting researchers when they estimate the scientific value of research facility.

It should be noted that this little example already shows a multitude of technical system functions contributing to a few customer key drivers of visiting researchers. For a given experiment installation, or even a certain experimental techniques supported by the same experiment installation, the relative importance of these functions can differ. To achieve the best research-enabling support, the availability and quality of these functions needs to be balanced. It is not untypical that stakeholders assume tacitly a general knowledge about the proper balancing (according to *their* value system). The customer key driver graph is an example for how to make such assumptions explicit, as it relates relatively detailed technical functions to the key drivers of

[17] For customer key drivers and their graphical representation, see (Muller, 2012) p. 59-63.

[18] CAFCR is the abbreviation for the proposed views in (Muller, 2012) for Customer objectives, Application, Functional, Concept, Realisation.

visiting researchers. Once explicit, such a diagram can be used to validate the architectures of accelerators and experimental installations.

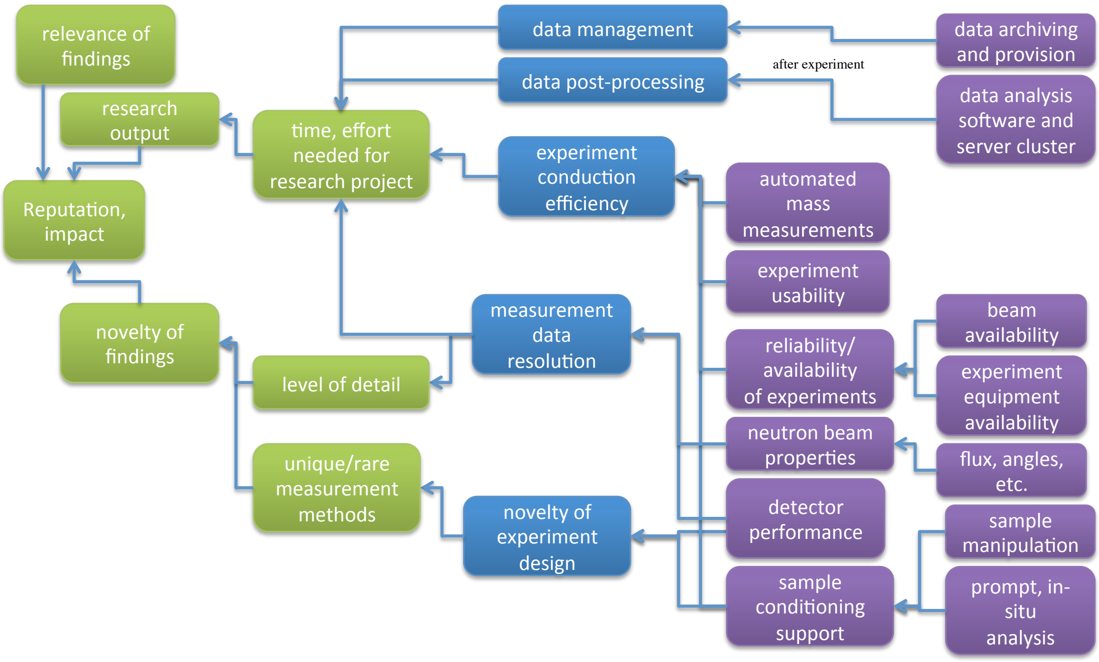


Figure 16: Customer key driver graph

It is the manifold properties and qualities of the systems that as a whole, enable - and delimit - the overall success of a research facility. *The identification and realisation of the research system characteristics is the purpose of the engineering processes that take place at research facilities. The success of the engineering processes enables and delimits the scientific value of the investment.* Systems Engineering at research facilities must be aware of this relation to the users' key drivers, and the multitude of influential system qualities and functionalities, and facilitate an *appropriate balancing* between these - balancing in the triangle of systems quality and functions versus resources versus time. Conversely, without a holistic Systems Engineering approach a research facility engineering project increases the risk of developments that are not calibrated against user (visiting researcher) needs, thus lowering the overall scientific value of the research facility. This is also formulated as key conclusion in 2.2, and while it may seem intuitively obvious to the SE initiated, it is not necessarily clear to the accelerator construction community as a whole.

3.5 Research facilities and their organisational roles

Research facilities require owner organisations for their realisation. For large physics experiments, these are typically governmental organisations, however in legal forms that can differ depending on national law and traditions. The European Union has established the European Research Infrastructure

Consortium (ERIC) as a legal option for organising international, pan-European organisations. This is an alternative to forming e.g. government-owned companies or legal entities within university contexts. Examples for research facility operator organisations include DESY, CERN, ESS, MAX IV, PSI, etc.

Such research facility owner organisations can operate several research facilities at the same time, often on a shared campus. For example, DESY operates three major particle accelerators in Hamburg, Germany: the synchrotron light source PETRA III, the free electron laser FLASH and the European XFEL. Over the life cycle of particular research facilities, the owner organisations act in a variety of roles. As *facility operator*, the owner organisation provides research-enabling services, including the continuous operation and maintenance of the facility. As *engineering, procurement and construction organisation (EPC)*, the owner delivers a fully constructed research facility ready for operation. The recipient is the owner, too, but in the role as facility operator. As *technology supplier*, the owner develops and delivers generic systems, similar to external suppliers. This role is realised in-house typically in cases where the external suppliers are not considered to be able to deliver components and subsystems in the required quality, time or cost constraints, or when in-house competence needs to be built up for operational, maintenance or regulatory reasons.

In comparison, these roles are typically much clearer in industrial facility construction, as here they are performed by different companies, or branches within large companies. In the oil and gas sector for instance, there are companies that own and operate oil production facilities (ESSO, Shell, etc.), companies that engineer production facilities (e.g. FMC Technologies, Siemens for power plant construction) and companies that deliver off-the-shelf products or components used in the construction (e.g. Rockwell Automation, Siemens for controls technology). A comprehensive description of EPC engineering in the oil and gas sector, including processes and information management aspects, is given by Baron (Baron, 2015). In comparison, research facility organisations have the challenge to have all aspects of the above under "one roof" - albeit on a smaller scale, still comparable in regard to Systems Engineering coordination aspects. A clear awareness of these roles is necessary in order to establish a suitable information management approach and life cycle processes, as these roles present different demands to the SE approach; alas the distinction between these roles in research facilities can often be found to be blurry in practice. The handover of a constructed facility from the EPC role to the operator role is not necessarily very clear, as both roles are in persona often executed by the same personnel. The distinction between the EPC of a research facility and the generic technology development role can also be confusing where the generic technology is developed with only the particular EPC project as customer.

The different owner roles are performed in main processes as illustrated in Figure 17.

- Research enabling process. At user facilities, this covers the support of the research facility for a multitude of visiting users. This begins with supporting the elaboration of suitable applications for experiments, includes the actual experiment tailoring and execution, and reaches to data post-processing and data provision services succeeding the experiment. At dedicated facilities, the experiment conception, conduction and analysis may correlate to the facility lifetime, for a focused, limited research community. With this process, a research facility resembles a service provider company (e.g. data processing services), and a facility operator company (such as big oil companies that operate oil field exploitation systems, but do not build these themselves).
- Facility creation process: The engineering, procurement, construction and continuous sustainment and improvement of the research facility are subsumed as facility creation. Its scope is the ‘physical’ creation of the systems that are needed to operate the facility machinery and to provide the Research enabling process. With this process, a research facility resembles an EPC company.
- Generic development process: A research facility needs to utilise commercial of the shelf technology, but oftentimes also needs to engage in technology development and product manufacturing for specialised or customised components. This can apply to hardware (e.g. specialised beam measurement electronics) or software (e.g. experiment-specific data processing and evaluation software). These developments are *generic*, meaning, development of hardware types that can be used in many places. With this process, a research facility resembles a product or software development company.

The engineering of research facilities can get inspiration for engineering management from different industrial sectors and branches, but needs to consider transferability. The consideration of these processes indicates potential for transferability from and to certain industries, e.g. the Facility Creation Process should most likely be compared to the EPC domain.

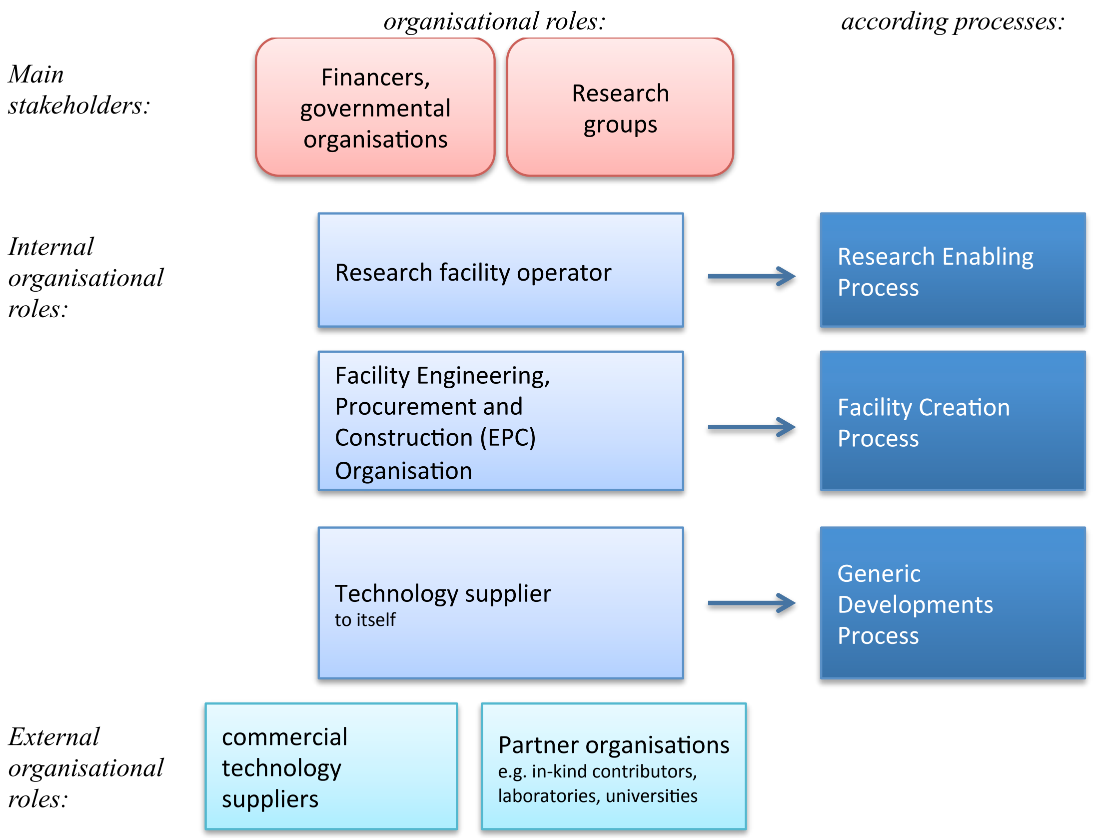


Figure 17: Roles and corresponding processes of a research facility organisation

3.6 A Research Facility's main processes

Processes are interrelated by the propagation of assets, resources and information. Figure 18 outlines the aforementioned processes and additionally their management processes and interrelations. The following process descriptions are based on the business process decomposition approach (Muller, 2012).

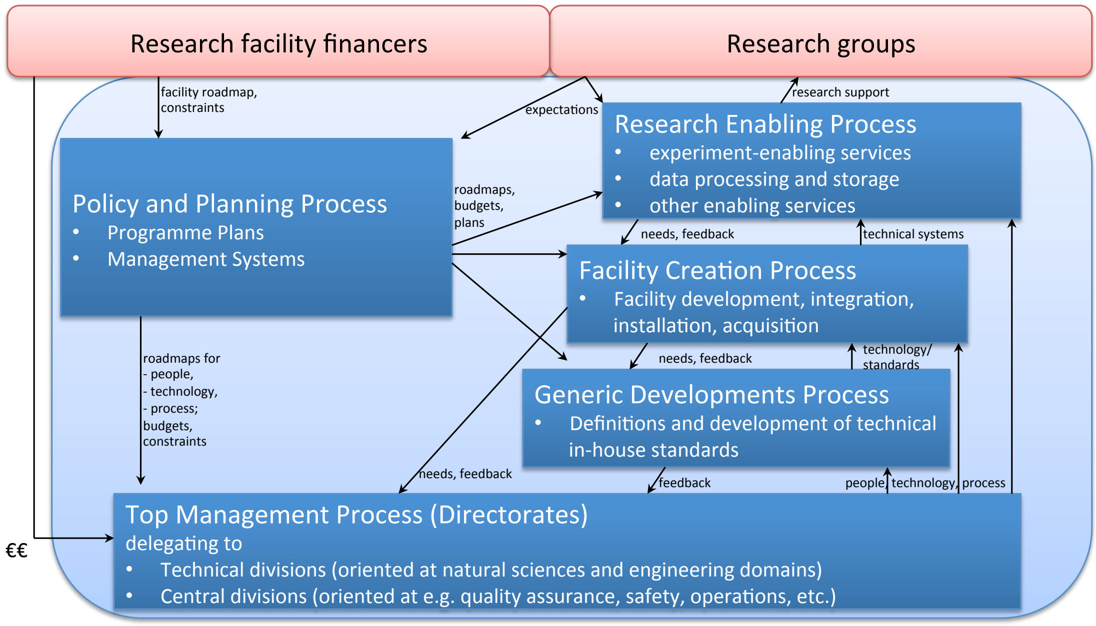


Figure 18: Major processes in a user-oriented research facility

Technical divisions (in some organisations called groups, sections etc.) engage primarily in the Science support process, Facility Creation Process and Generic Development Process, but may also participate in the Policy and Planning Process and Top Management Process to some degree, certainly by providing needed information and formulating coordination needs. The engagements in the former three processes vary in degree at different times. For example, a conventional facilities[19] division may be primarily involved during a facility's construction phase, and withdraw except for minimal maintenance services during later phases. Control system divisions engage in all of these processes over the full facility life time.

3.6.1 The Research Enabling Process.

The expectation for a user-oriented research facility is to enable external research groups to produce scientifically novel, relevant knowledge. To fulfil this expectation, research facilities have to engage in a Research Enabling Process that enables visiting research groups in their scientific goal achievement by various means.

The core feature of an accelerator based research facility is of course the provision of a particle beam (photons, neutrons, protons, etc.). This can be seen as a service, and is typically qualified by the beam properties (e.g. flux, angles and energies). The physical properties that are the figures of merit are however dependent on the type of experiment. For example, in synchrotron light absorption experiments, a synchrotron light beam with a high flux over a wide

[19] In the accelerator domain, "Conventional facilities" is a common term used to encompass anything related to 'buildings', including e.g. civil construction, HVAC, electric power supply, cooling systems, office and recreational facilities, etc. - in short, anything that is typically found in "conventional" industrial and office environments.

energy spectrum is typically filtered by a monochromator for a very narrow window of the energy spectrum. This window is moved over time, thus allowing the scanning of a sample over various energies in a highly defined manner. The interaction of the beam with the studied material sample is measured by a detector, and allows by further evaluation to characterise the physical properties of the sample. This setup shows already that for the applier of an experimental method the originally produced beam is a crucial factor, but only one among others. These factors need to be evaluated together (monochromator precision, detector resolution) in order to determine the experimental station's value for the material research community. Many more factors need to be taken into account, including those related to the experiment conduction: beam availability and reliability, data acquisition speed, sample handling and manipulation possibilities... - the point being that for the provision of an effective Research Enabling Process a multitude of qualities of the beam and the instrument setup are required to be balanced.

The traditional approach at research facilities has been a focus on physical properties, surely a consequence of the common primary interests of members of the physics community. Services related to experimental data processing are getting increasingly more attention. For some experiment types, automated experiment execution becomes the dominant model; it allows users to simply send in their samples, which are handled by robots. The data is made available to the users via remote access. Modern facilities are investing in data post-processing and data storage systems, in order to offer to visiting researchers better on-site and off-site data access and evaluation. On-site data processing, meaning during experiment time, may influence the quality of the experiment outcomes, as it may allow adjustments of the experiments on short notice - within the constraints of the experimental methods applied, of course. Data post-processing and storage services can enhance the visiting researchers' experiment evaluation capabilities. A further aspect is the public accessibility of data generated using public funds, which may be an increasingly important requirement in the future. Modern research facilities strive for supporting visiting researchers more and more for the entire experiment-related process from the researcher's point of view. This means that the facility starts to support already with the submission of applications, throughout the experiment customisation and execution, until the experimental data evaluation. The general direction is that research facilities will provide dedicated systems that support research groups to generate and manage the research applications and from there on guide through the various steps of the whole experiment process.

Success measurement. The achievement of the Research Support Process is hard to quantify, as knowledge and the relevance it unfolds over time is difficult to measure. Sometimes the success of research facilities is estimated by using as an indicator the number of peer-reviewed publications that are based on experiments at a particular facility.

3.6.2 The Facility Creation Process

Realising the Research Enabling Process requires a research facility organisation to own a facility, including buildings, accelerator machinery and experiments, in the first place. Research facilities as a whole cannot be ordered from commercial providers, as their nature does not suggest that the commercial production of research facilities could be a successful business model. This means that research facility organisations have to execute the Facility Creation Process themselves. In respect of this process, research facilities resemble Engineering, Procurement and Construction (EPC) companies, even though their projects are in comparison, few or even singular.

The main purpose of the Facility Creation Process is to deliver the operational facility as a whole. The Facility Creation Process comprises essentially the recursive application of the system life cycles to the research facility as a system. Over a facility's lifetime, often there are further upgrades realised (e.g. increase of beam energy, addition of further experimental stations, etc.), in which case the Facility Creation Process is evoked too. The customer of the Facility Creation Process is the research facility organisation in the role of the facility operator. The Facility Creation Process is consumer of the generic products or product designs provided by the Generic Development Process, which is another process internal to the research facility organisation.

While the main output of the Facility Creation Process is, in a technical and tangible sense, the facility and its systems, this process also needs to create the corresponding information entities and information processing systems. Technical information on the created systems for their different life cycle stages need to be generated and maintained in a controlled way, including e.g. requirements, design documentation, integration documentation, operation and maintenance manuals, etc. The increasingly adopted approach is to utilise and customise Product Life Cycle Management tools (see 4.9).

The roles within a facility creation process arise from responsibility types (operational managerial, technical, relevance for research support) and from responsibility granularity (whole facility, major systems, subsystems, components). The managerial responsibility here means the balancing of specification (function and quality), budget and time. The technical responsibility here refers to technical development and engineering methodology, i.e. performing the technical processes of a system life cycle. Figure 19 outlines how these responsibilities at different system levels are typically associated to organisational roles (directorates, technical groups, etc.). Note that the structure, responsibility allocation and naming of organisational units differ significantly between research facility organisations, but a general approximation can be given here which can typically be found at synchrotron light and neutron science user facilities.

	managerial	technical	research support
research facility (for some organisations, several facilities)	Technical directorate Science directorate	Technical directorate Science directorate	Science directorate
Major systems, sub-systems (multi-disciplinary)	Accelerator systems: mixed groups, typically lead by senior discipline engineers/scientists Instruments: Lead Instrument Scientists and Lead Instrument Engineers	Accelerator systems: shared among senior engineers and accelerator scientists Instruments: Lead Instrument Scientists and Lead Instrument Engineers	Senior engineers/scientists for each instrument: Lead Instrument Scientists Lead Instrument Engineers
low-level systems components, (mono-disciplinary)	Technical groups, discipline engineers Lead Instrument Scientists Lead Instrument Engineers	Technical groups, discipline engineers Lead Instrument Scientists Lead Instrument Engineers	Technical groups, discipline engineers Lead Instrument Scientists Lead Instrument Engineers

Figure 19: Roles in the Facility Creation Process

3.6.3 The Generic Developments Process

Research facilities are commonly characterized by a certain degree of technical uniqueness that requires highly customized or unique equipment. Oftentimes, such equipment cannot be ordered as commercial product, but requires in-house customisation. In other cases, equipment is designed from scratch. For example, proton beam measurement equipment or radiofrequency systems usually require a significant development effort within the utilising research facility, even though some of the used components may be deliverable by the industry. If such a development result in a generic system type, which can be used several times within the facility (or potentially, other facilities), this development is conducted as part of the Generic Developments Process. This process differs from the Facility Creation Process in that it focuses on technology development, with the output being a generic system design and/or a technical in-house standard, such as a customised communication protocol in a facility-tailored networked system (e.g. high speed timing). As particular technology developments are often motivated by a sole facility project, such the resulting designs are typically produced only in small quantities. Clarity over this distinction is however beneficial for the SE management, as these two major processes operate on different information structures and life cycle models, with implications on the technical information management (see 4.9).

	managerial	technical	facility integration
complex generic systems (multi-disciplinary)	Mixed groups, typically lead by lead discipline engineers/ scientists, e.g. - senior controls engineer - senior accelerator scientist - senior experimental scientist	shared among senior engineers in different disciplines.	case-dependent, typically lead by Facility Creation Process roles
systems, components (mono-disciplinary)	typically managed within technical groups or divisions	typically a discipline expert or team of experts	case-dependent, typically lead by Facility Creation Process roles

Figure 20: Roles in the Generic Developments Process

3.6.4 Policy and Planning Process

The overall transformation of resources into executing processes - according to financers' expectations and user needs for a research facility - is the aim of the Policy and Planning Process. Here, usually a 'programme' is defined and managed that can span years or decades. Typical external coordination entities include (named differently from case to case):

- A *financers' steering group* represents the interests of typically governmental stakeholders and delegates domain specific evaluations to the expert committees listed in the following.
- A *machine' advisory committee* focuses on the accelerator systems, typically advising on the Facility Creation Process in system function and quality, but also in management questions (e.g. staffing recommendations).
- A *scientific advisory committee* determines key drivers and needs in the experimental science domain; usually giving recommendations for the direction of the Research Enabling Process and Facility Creation Process in regard to experimental capabilities and research support services (e.g. data processing and storage services).
- A *safety focused committee* is required in particular at research facilities that introduce risks to the public, e.g. radiation or emission of radiated materials. Also personnel safety requires to be addressed.

Internally, research facilities typically establish various forms of 'forums' (regularly meeting groups) that reflect the organisation's hierarchical decision-making process. These forums may also reflect major systems, or address a temporary need (e.g. a venue that develops the commissioning and operation plans). The internal organisation of the Policy and Planning Process can be understood as often influenced by an organisation's structure, traditions, maturity, size, intra-political situation and hence needs to be understood case by case.

Outcomes of the Policy and Planning Process include budget allocations and roadmaps for the other major facility processes.

3.6.5 Top Management Process

The top management process within a research facility organisation provides the necessary environment for the other processes to be activated, e.g. it provides the human capabilities (line management), manages the project portfolio (possibly spanning several research facilities operated within the organisation), and thereby balances the Facility Creation Process, Generic Development Process and Research Enabling Process. The Top Management Process is typically executed on the Directorate level, and to an extent delegated to discipline divisions; e.g. the definition and development of in-house technology standards in the computing and control systems area is typically performed mainly by the corresponding controls group or division. This delegation is necessitated by the domain knowledge required for successful standardisation (e.g. PLC, FPGA, SCADA technology etc.).

Research facility organisations are typically structured into domain-oriented organisational units (typically called divisions or groups), such as accelerator technology and physics, control and computing systems, experimental science, etc. The developed systems are often crossing the boundaries of these organisational units, as they require multi-disciplinary engineering competencies. Thus the top management process needs to facilitate the coordinated multi-disciplinary engineering activities, meaning it needs to facilitate *shared or commensurable*[20] *information models for engineering information* being utilised by the organisational units. As the facilitation of these information models is a core activity of Systems Engineering Management, it can be seen as an extension of the Top Management Process. In practice, it can be seen that this aspect of Systems Engineering Management is often not performed by "directorate staff", but delegated according to the particular organisation's capabilities and monitored from the directorate more or less from distance. *Incommensurabilities* between information models of organisational units can occur that lead to problems, e.g. regarding design consistency or integration planning. If such problems cannot be resolved by the organisational units themselves, the problem escalation path leads eventually to the directorate level; consequently, a directorate needs to be aware of such issues and be able to realise their resolution. This aspect ties into the technical information management process that is outlined in 4.9.

3.6.6 Main process interplay and problems

In the daily practice, tasks with an engineering character appear in the Facility Creation Process, the Generic Development Process, and to some extent in the Research Enabling Process. If such tasks of these different main processes concern the same facility system or technology, they are often performed by the same people. E.g. it is common that staff responsible for the engineering of specific subsystems in a particular facility (Facility Creation Process) also is the developer of the generic system design, the base technology (Generic

[20] Commensurable information models allow for consistency when transferring data among each other.

Development Process). In regard to roles, such an engineer alternates between the roles of *facility developer* and *generic technology developer*. In this case, the engineer delivers a new generic system design to him/herself, in order to be used in the facility design.

It is also common that developers of experiment installations become supporters of visiting research groups for equipment customisation, adjusting for specific experiment setups. This has obvious advantages, as the creators of these systems are most familiar with the designs, capabilities, history and customisation options of these systems. In this case, the engineer or scientist assumes the role of a *service provider* (Research Enabling Process).

This widespread practice also introduces a peculiar Systems Engineering Management problem: The separation of the roles according to the major processes blur. This has consequences:

The different roles and corresponding processes may become unbalanced, when one role dominates a person's (or group's) actions, setting back the proper, full execution of another role and its process. Typically, this is likely determined by the personal backgrounds, e.g. a software developer, used to think with a technology developer mind set, may underestimate the relevance of daily service provision during facility operation. Conversely, a scientist aiming to work in the conduction of experiments is more like to value the quality of research service provision. Alas, the scientist may disregard the value of proper technology development, including its life cycle management and technology standardisation - for him/her, the experimental problems dominate the mind set. This may result in hard-to-maintain systems and technologies.

Hand-overs between the processes that are executed in personal union tend to be done informally (one person handing over to oneself). This invites to skip definitions of requirements, skip design clarifications, or to relax the quality control. This becomes easily a problem in the case of excessive focus on resolving short-term problems. For example, in the *service provider* or *facility developer* role an engineer may be pressed to achieve a short-term goal. To resolve the problem quickly, this engineer who at the same time acting as the *technology developer* may now choose to implement short cuts that are verified in a fashion limited to the problem at hand. Instead of developing a well-defined, encapsulated, standardised solution, a parochial solution may be adopted. Documentation of the technology changes may be skipped altogether. This phenomenon, the accumulation of technical debt, may lead to long-term problems, such as hardly maintainable systems and technologies. This kind of technical debt in research facilities is a relatively widely accepted fact of life in informal discussions, but not a preferred topic of open presentation, as it equates the admission of deficiencies. While the problem is to a degree intuitively understood by many practitioners, it is not necessarily understood that it has its roots in the incomplete awareness and execution of the different main roles and processes as outlined in this chapter.

This pattern of technical debt accumulation can also emerge between the service provider and facility operator role, respectively the corresponding main processes.

Technical information structuring, as facilitated by Systems Engineering management, is a way to create the awareness and facilitate the proper execution of these major processes. If the SE management promotes the clear distinction of *facility specific information* (plant architecture, etc.) and *generic system development information* (technology development), a separation of concerns can be achieved, e.g. technology standardisation issues can be addressed in more clarity.

If SE management is unable to promote this, a likely consequence is that technical information tends to be structured inconsistently according to personal preferences. These might mirror the organisational structure, ownership scopes, projects or work packages, locations or any other ad-hoc decision on clustering. This again is likely to lead to a generally deteriorating overview on technical matters.

These sorts of problems are less likely to occur in projects or environments where already the organisational level implies clear separation of the major roles, as is the case if one company is the operator, another company the EPC, and additional companies act as suppliers and base technology developers.

3.7 Organisational structures in Research Facilities

The organisational structures of research facility organisations may take different forms, sometimes significantly, reflecting different sizes (number of staff members), purposes, specialisations, and certainly also the organisations traditions and history. There is however a rough pattern visible, which is the formation of primary organisational units (called directorates, divisions or groups) according to discipline. At accelerator facilities, there is typically an organisational unit focused on

- particle acceleration technology
- scientific support (experiment development and execution support)
- one or several units focusing on engineering, such as
    - electrical engineering
    - controls, computing systems,
    - civil engineering
    - cryogenics
    - vacuum systems,
    - cooling systems,
- administration.

However, already from this level on the organisational hierarchies begin to differ significantly between organisations, and have to be studied case by case. The dividing principle however, to divide and subdivide units by scientific or engineering discipline, is commonplace. It follows the idea to create centres of competencies in technical or scientific domains.

The constructed systems, accelerators, experiments, etc. are of course highly interdisciplinary. This introduces a common challenge to these organisations: the problem of integrating the various organisational units in regard to the systems and their life cycles.

As the involvement differs significantly over time - development and construction phases require forms of involvement that differ significantly from continuous operation - the research facility organisations often struggle with establishing effective forms.

One way of establishing focal points for system development is the definitions of *projects*. A project is here understood as a sum of interrelated tasks with the aim of development and/or delivery of systems utilising allocated financial and labour resources. For example, the construction of an accelerator, and experiment or on a smaller scale, a magnet system, a beam position monitoring system, etc. would be an obvious choice for a project. This approach would follow the idea of the matrix organisation.

In practice, this approach is not always clearly implemented, for various, typically facility-specific reasons. In the case study facility, the ESS, the main projects have been defined along the scopes of organisational units rather than technical systems. As a result, cohesive technical systems are developed in different projects run by different organisational units. In particular, *controlling* equipment and its related *controlled* equipment, which form together *one functional system*, are typically developed in different projects by different organisational units. This practice, which is opposed to Systems Thinking, has led in many cases to a lack of definition of the overall functional system. It introduces a certain degree of unclarity of responsibilities and scopes that have to be resolved by negotiations of the involved stakeholders. As for such negotiations no guiding Systems Thinking approach is realised, these negotiations rely primarily on the arbitrary problem awareness and prioritisation of the involved personnel.

The allocation of resources in the case study facility is primarily done by the projects, which are on the higher levels defined as equivalents to organisational units (divisions, groups). Again, this is to be seen as in opposition to an approach that would allocate resources to actual technical systems. Hence, the observed approach caters to some degree for protectionism or parochialism, which can make negotiations on system scopes, design responsibilities and decision making difficult. It can be seen as a questionable approach.

4 Systems Engineering at Research Facilities

This chapter introduces Systems Engineering in general and outlines its application. Further, the relevance of Systems Engineering and related fields for the research facility domain is described. The chapter moreover highlights notable SE aspects in regard to controls and computing systems.

For centuries, approaches to the development of novel, advanced systems have been characterised by the personal expertise of personnel in charge, rather than on theoretically described concepts. In the mid 20th's century[21], this approach met its boundaries in the development of systems that were exceeding a certain complexity threshold - complexity in regard to technical aspects, information management, stakeholder composition, locally distributed engineering and versatility of involved professions. Sets of distinct methods for generating and executing engineering activities, and capturing information related to these activities emerged and were bundled under the term "Systems Engineering", with the goal of defining consistent, over-arching approaches to the management of engineering of highly complex systems. The originating domains were the telecommunication, defence and aerospace industries in the United States. A widely recognised milestone project for the successful application of Systems Engineering has been the Apollo program.

Systems Engineering has been defined in a number of ways, some of which are quoted here in their most compact form:

"Systems Engineering is an interdisciplinary approach and means to enable the realization of successful systems."
- ISO/IEC/IEEE 15288: Systems and software engineering - System life cycle processes. (ISO 15288, 2015)

"*Systems engineering is a methodical, disciplined approach for the design, realization, technical management, operations, and retirement of a system.*"
- NASA Systems Engineering Handbook. (NASA, 2007)

"*The function of systems engineering is to guide the engineering of complex systems.*"

[21] The INCOSE Handbook (INCOSE SE Handbook, 2015) has an overview on the origins of SE as a discipline. Also he SEBoK has a page on the historical perspective of SE. http://sebokwiki.org/wiki/Systems_Engineering:_Historic_and_Future_Challenges

- (Kossiakoff, Sweet, Seymour, & Biemer, 2011)

"*Systems Engineering is about creating effective solutions to problems, and managing the technical complexity of the resulting developments.*"
- (Stevens, Brook, Jackson, & Arnold, 1998)

"Systems Engineering is the application of Systems Thinking to real world systems problems in the field of engineering in order to achieve successful solutions to such problems."
- (Pidd, 2004)

"*Systems engineering is an interdisciplinary approach and means to enable the full life cycle of successful systems, including problem formulation, solution development and operational sustainment and use."*
- (SEBoK authors, 2016)

These and other definitions commonly emphasize

- the holistic aspect of SE: systems are addressed as a whole, not only a sum of parts, relating to Systems Thinking[22],
- the development-over-time aspect: the genesis and evolution of a system as an iterative process, the system life cycle,
- the multi-disciplinary aspect, the multitude of involved professions and stakeholders in the development, and the guiding and bridging character of SE for these disciplines,
- the pragmatic benefit of SE usage.

In summary, Systems Engineering adds a methodical approach to complex problem-solving processes that rely on engineering. It helps its users to cope with some of the engineering problems coming from the human condition: our limited capabilities to retain and communicate massive amounts of information, our individually limited professional perspectives on the world, our difficulties in synchronising our work activities with our fellow beings around us. SE does not guarantee any success in problem solving on its own, but complements other success factors such as financial or human resources, competences, or external/environmental factors in a widest range.

In the remainder of this chapter, different aspects of SE are introduced and related to accelerator research facilities, in particular the controls and computing systems. A reference model is presented in section 4.1, which is intended to help SE managers, coordinators or other facilitators in the accelerator computing systems domain in the consideration of SE aspects. It is

[22] A variety of publications explain System Thinking in broad terms, see (Boardman & Sauser) (Senge, Kleiner, Roberts, Ross, & Smith, 1994) (Lawson, 2010) (Checkland, 1999). Specifically for SE, see (Haberfellner, Fricke, Weck, & Vössner, 2015), (Haberfellner, 2002).

built on the experience of this work, the role of a general-purpose SE facilitator in a control system division, and theoretically founded in the studies of SE flavours that relate in different ways to this domain. Section 4.2 discusses the underlying concept of SE, Systems Thinking, and focuses on its particular application and relevance in the studied engineering domain. The following section 4.3 introduces another fundamental concept, viewpoints and viewpoint management. With this base, the foundations are laid to take a turn to the more ‘technical systems’ oriented aspects: systems life cycle management is outlined in 4.4, and system life cycle processes are introduced in 4.5. Some more specialised SE (or SE related) approaches, which are relevant to the controls domain at particle accelerators, are described in 4.6. Research facilities are complex socio-technical systems. Coping with this complexity is a challenge for which Systems of Systems Engineering appears to be a viable approach, as is introduced in 4.7. The role of safety critical engineering for the controls domain is outlined 4.8. Technical information management at research facilities is characterised in 4.9. Finally, the role of in-house standardisation and technology management is presented in 4.10.

The sections in this chapter are meant to give an introductory overview on the multiple facets of SE and closely related fields in the domain. For further details on concepts or approaches, the sections link to the attached papers or other literature.

4.1 A reference model for Systems Engineering facilitators in the domain

This chapter presents a reference model for facilitators of Systems Engineering in the domain. It is intended to provide a quick reference model of Systems Engineering Management aspects that support a facilitator’s daily work in the holistic analysis and intervention planning.

A method or “tool” that helps an SE facilitator with the identification of significant aspects for a given SE management concern is hence desirable. To meet this need, a “Systems Engineering Management Reference Model” is presented here, which is meant to work as a guideline for quick yet encompassing estimations of Systems Engineering Management (SEM) aspects in the daily SEM practitioner’s work. It is at some points tailored to the controls/research facility domain.

Such a reference model is presented in the following. First, a visual map is presented, which is intended to help a user of the reference model to maintain overview on SEM aspects, e.g. in assessment discussions with engineers and managers. Here, the SEM aspects are presented as memorable key words. Then, the aspects key words are structured and related to example questions. The model can allow the user/SE facilitator to steer discussions to different areas, for example, in the exploration of existing SE problems or for the anticipatory exploration of SE improvement proposals.

4.1.1 Visualization of the SEM reference model

Figure 21 shows a visualisation of the SEM reference model presented in a 'mind map' style: At the centre is a given SE Management concern, which is connected to aspects detailed further. Each node is connected to at approx. 3-5 closely related nodes that outline a path to more specific analysis aspect. Using the model, the SE facilitator can now traverse the nodes and check the central problem against the outlined node.

The model is intended to have as use cases,

- the examination of a given SE issue, or
- the validation of an SE improvement proposal.

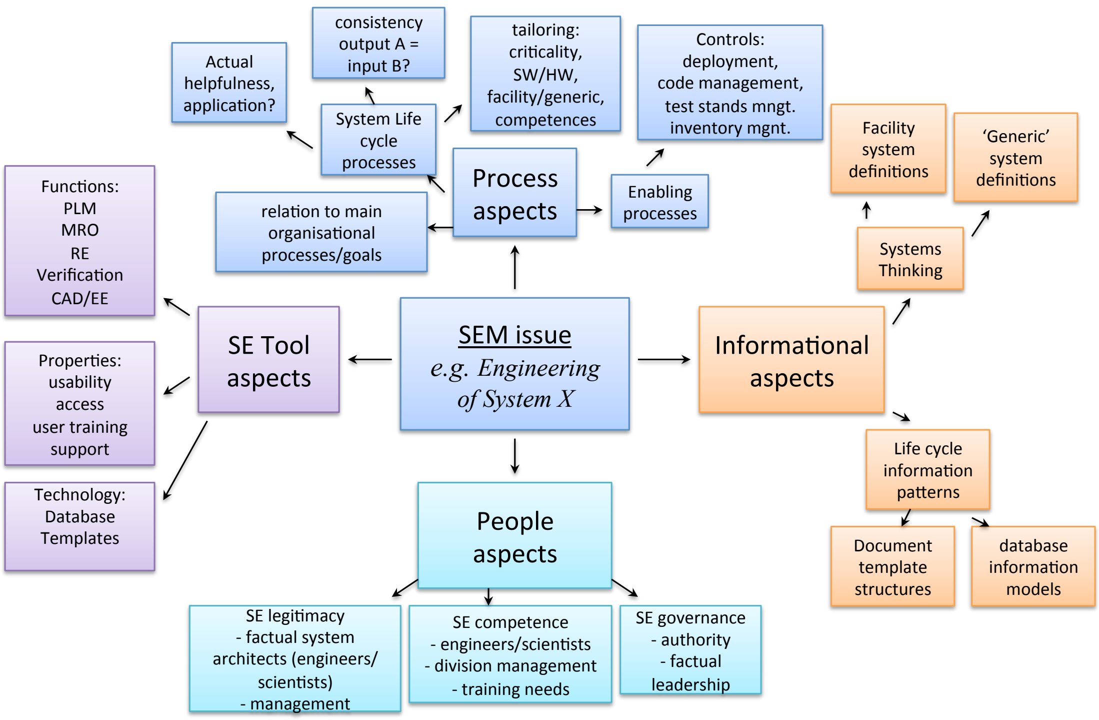


Figure 21: Visualisation of the SEM reference model

During an examination, the SE facilitator can now structure the problem exploration by a traverse of the model in order to create visibility for potential problems. This can occur during a discussion with stakeholders, or when writing a management report on the issue. Using this model should result in a reasonably encompassing presentation of the issue, and possibly initiate more detailed examinations.

During the validation of an SE improvement proposal, the SE facilitator can traverse the model and inspire reality checks (validation). For example, if asked to guide the application of SE for a sample conditioning system[23], the model can guide to the "question":

"For the sample conditioning system X (SEM issue), is System Thinking applied correctly, more precisely, are system definition are correct as 'Facility system' definitions?"

A more detailed level of "question generation" can be achieved by adding a second iteration. Refining the previous example question, it can be extended as this:

"For the sample conditioning system X (SEM issue), for the System Thinking/Facility system definitions thereof (1st model iteration), is the SE competence of the involved experimental scientists (2nd iteration) sufficient?"

Or, varying the 2nd iteration:

"For the sample conditioning system X (SEM issue), for the System Thinking/Facility system definitions thereof (1st model iteration), are the tools for documenting the facility breakdown structure readily available and useable to the experimental scientists? (2nd iteration)?"

Using the model for validating SE management actions can in this way guide to a relatively broad spectrum of relevant considerations.

4.1.2 Outline of aspect part of the SEM model

The success of using an abstract model is eventually determined by the correct interpretation of the outlined aspects for each application case. The model view in Figure 21 gives only key words, or catchwords, for each node.

For this reason, this section presents the SEM reference model in another view: The visual mind-map style is transposed to a tree structure. This allows adding textual descriptions or questions to each node, which is more suitable for explaining the node.

Aspects of the SEM reference model:

1. Informational aspects: "What information is needed and what is actually processed?"

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[23] Sample conditioning system: A subsystem of an experiment installation. It conditions a studied material sample according to the needs of an experiment. Typical 'conditioning' includes exposing a material sample to ultra-high vacuum, magnetic fields, electric currents, laser light or temperature.

- 1.1. Systems Thinking: "How is (how should) be Systems Thinking (be) applied in the information structure?
  - 1.1.1. Facility breakdown structure: "How is the facility structure partitioned and managed?"
  - 1.1.2. Generic systems: "How are generic system structures partitioned and managed?"
- 1.2. Life cycle information patterns: "What information patterns are needed by/exist for system life cycle processes?"
  - 1.2.1. Document template structure: "How should document templates be structured in the context of the SEM issue?"
  - 1.2.2. Database information models: "What information model should be applied to databases concerning the SEM issue?"

2. Process aspects: "How are human processes defined and managed?"
   - 2.1. System life cycle processes: How are system life cycle processes defined, managed and executed?"
     - 2.1.1. Consistency: "Are the outputs and inputs of the processes consistent and suitable?"
     - 2.1.2. Helpfulness: "Are the specified processes a) actually executed and b) considered helpful?"
     - 2.1.3. Tailoring: "Are the processes tailored to the SEM issue demands, and in what respect (criticality, technology, ...)?"
   - 2.2. Organisational main processes: "How does the SEM issue relate to the organisation's main processes?"
   - 2.3. Enabling processes: "What enabling processes need to be considered for the SEM issue? (acquisition, software deployment, ...)"
3. SE Tool aspects: "What SE tools are relevant for the SEM issue?"
   - 3.1. Information management tools: "What information management functions are of relevance to the SEM issue?"
   - 3.2. Suitability: "How suitable are the available SE tools for the SEM issue?"
   - 3.3. Tool technology: "What are available technical means to realise required databases, templates, etc.?"
4. People - "The human domain: communication, mandates, competences, cultures."
   - 4.1. SE legitimacy: "What standing does SE have among the involved engineers? the management? How does it impact the success of SE implementation?"
   - 4.2. SE competence: "What degree of SE competence is among the involved engineers? What training or explanation is needed? What educational improvement is realistic to achieve?"
   - 4.3. SE governance: "Who has the formal mandate to determine SE practices? Who has the factual leadership?"

4.1.3 Customisation of the SEM reference model

In its presented fixed way, the SEM reference model is limited to a certain depth, to a certain context and determined to the contents (nodes) that the author deemed appropriate. This is most likely not optimal for all users and situations. For this reason, the presented SEM reference model should be seen as *open* in its content, meant to be further refined by its users. This can be envisioned in various ways:

- Personal refinements: For a SEM practitioner with a defined scope, personal refinements to this scope should yield best results.
- Organisational refinements: A group of SEM practitioners may find a commonly shared model beneficial in order to communicate efficiently and clarify among each other their personal views and priority estimations, when discussing the content of their customised model.
- SE topic refinements: Topic refinements could result in a set of SEM reference models, which are easier to apply in certain problem cases. E.g. an 'experiment data acquisition' SEM model could exclude some nodes and introduces others that are typical for the development of neutron or synchrotron light source data acquisition systems. A customisation of the terminology might also be helpful in such cases, if the model is intended to be used by more than few people.

Generally, the model traverse is intended to stimulate the identification of SE aspects early and quickly - it is not meant to claim completeness in the analysis or guarantee sufficient depth. A decent customisation however should enhance its problem identification power.

4.1.4 Purpose and application of the SEM reference model

The idea of a quick reference model is to present in a *memorable* way

- the different aspects for which a Systems Engineering facilitator needs to *analyse* a given Systems Engineering situation, and
- the aspects for which the Systems Engineering facilitator needs to *validate* an improvement of SE practices.

The work of a Systems Engineering facilitator at a research facility requires to maintain overview of all Systems Engineering relevant aspects and propose SE improvements that in order to work need to be viable in all these influencing aspects. Maintaining this overview constitutes a base contribution to engineering coordination, and is essential for successful introduction of SE improvements. The successful introduction of SE changes requires a good anticipation of the effects it has the engineering practices. This concerns to equal parts SE processes; information conventions on the kinds of information that is to be generated, how it is structured, etc.; supporting tools and artefacts; and the relation all of this has on people, e.g. regarding mandates, competence development, acceptance of SE change proposals, etc. Also, the pressure, e.g.

time and resource wise, may lead to "shortcuts" being taken (promoting short term delivery, but neglecting longer term crucial aspects).

Furthermore, all SE standards and guideline literature have the problem of positioning themselves in a field of tension between general applicability - " ... all man-made systems ... " (INCOSE SE Handbook, 2015) - and domain specificity. An example for a domain-specific book that can be seen as a SE guideline including project management and information management aspects is the Oil & Gas Engineering Guide (Baron, 2015), even though it does not make the claim explicitly. High domain specificity can have the advantage of being easier useable by experts in the domain who dislike abstract engineering methodology, but prefer concrete advise.

In order to give this SEM reference model a chance to increase its usability, the evolutionary component is emphasized here. It could perhaps best be introduced to an organisation by an intrinsically interested 'champion', who adjusts the model to the concerns and terminology. With improved suitability for its intended environment, it should find easier acceptance among other SEM practitioners.

4.1.5 Validity of the SEM reference model

The presented model represents a condensation of the knowledge on aspects encountered in the course of the activity threads outlined in 2.4.2, which repeatedly created communication situations where the author had the need to maintain overview over the many aspects and facets of SE management. A precursor to the presented model is the included in paper A, on process implementation for Requirements Engineering. The model here constitutes a generalised and expanded form of guidance for SEM. As the model as presented has been formalised in the late phase of this thesis work, it has not been continuously applied in its present form. However, retrospective estimations indicate it would have been beneficial in some situations, where relevant aspects were identified only after problems emerged (not previously anticipated). The SEM reference model certainly requires dedicated validation, and can presumably benefit from further refinement.

4.2 Systems and Thinking

It is worth to reflect on one of the core terms' of this thesis, "system", before delving into its utilisation in the specific engineering domain. Differences in its interpretation have repeatedly been experienced in SE discussions during this thesis work, effectively sneaking in subtle misunderstandings leading to derailing engineering coordination. The following train of thought is influenced by Constructivism in philosophy of science (Glaserfeld, 1997) and by the Theory of Communicative Systems' (Luhmann, 1984). It focuses on a usually underrepresented aspect of Systems Thinking, but importance in engineering contexts. Hence this section is meant to complement existing works, general Systems Thinking literature (Boardman & Sauser) (Senge, Kleiner, Roberts, Ross, & Smith, 1994) as well as engineering focused literature (Haberfellner, 2015), (Haberfellner, 2002). Checkland approaches the issue described in the following, which concerns the definition of "one or more particular systems, which will be part of a hierarchy of systems, [..] being defined as *relevant to problem-solving*." (Checkland, 1999)

The word system has ancient Greek origins: "*σύστημα* whole composed of several parts or members, literary composition, organized body or association, group of men or animals, series of musical intervals, scale" (OED Online, 2016). The word's origin hints at the basic characteristics that distinguish a system from other abstraction patterns: A system is a whole in its own right, and this determines its boundary. A system comprises of distinct, constituting entities. These constituting entities have relationships that are meaningful to the wholeness. While the constituting entities are defined, a degree of dynamics is also present, (distinguishing systems from mere structures), manifesting in the interplay between the constituting entities and possibly the outside world. Representing the world in this fashion is called *Systems Thinking*.

The representation of the world as *systems* requires an entity that hosts the representation. This entity shall be called the *observer*. It is notable that the relation of the observer's representation, the system, and the physical world is *contingent*, meaning, it is not necessary for the thought system to have an equivalent in the physical world (the observer can think fictional systems).

In this constructivist view on the observer-system couple, systems represent and structure the world (real or imagined) for an observer. This capability empowers the observer. First, it enables to build an understanding of dynamics of a framed set of real-world entities. Second, it allows for complex, purposeful manipulations of the world. The imaginary thinking of systems preceding real-world actions allows anticipating the real-world behaviour of a system before its physical production. This allows the optimisation of the system according to the observer's interests.

So we see, the act of representing parts of the world as systems is *motivated* by the observer. The mental act of thinking in systems has an intent, such as the *intent of study* or the *intent of shaping* the world.

The *intent of study* is the typically driving motivation for thinking in systems in the natural sciences. Systems thinking is here applied to identify the dynamic aspects of previously identified elements, for examples stars and plants / solar system, cells/organs/body, atoms/molecules, etc. The choice of delimiting the studied system is determined by the observer's investigation interest. Systems created for the intent of study are *descriptive*. Their measure of merit is the success by which they describe the world - with further details being negotiated in the discourse of philosophy of science.

In contrast, the dominating motivation of thinking in systems in the engineering sciences is the *intent of shaping*: engineering means creating systems for a purpose. It is this purpose that in Systems Engineering is called the system's *function*. This function is what primarily determines the boundary, the constituting elements and the behaviour of the system; in short, the architecture. Systems thought with the intent of shaping are *prescriptive*.

Nonetheless the engineering sciences extensively apply systems thinking for the intent of study, too - in so far, as it is suitable to determine whether a system's structure and behaviour actually realises the system's function. Hence, Systems Thinking with the intent of study is in engineering sciences and practices usually subordinate to *Systems Thinking* with the intent of shaping.

It is this *difference in intent* that distinguishes Systems Thinking in the natural and engineering sciences. This distinction is the base for the formation of intellectual habits within the according communities, natural scientists and engineers (in particular, system engineers). Members of these communities may speak to each other of systems in the accustomed sense of their own community, not noticing these system conceptions may differ in intent. This introduces potential for hard-to-identify misunderstandings, misconceptions, poorly understood 'culture' clashes and engineering problems.

Research facility environments are typically comprised of a mix of people with a natural science mind set and an engineering mind set, so this basic difference in applying Systems Thinking is reflected in daily practices. During the course of this thesis work this issue has been identified as a deeply rooted, persistent hindrance in the application of Systems Engineering. Hence the awareness of the issue is seen as a key to successful SE management in the domain.

Barriers to the introduction of System Thinking. As a main barrier to the successful introduction of Systems Thinking in the domain, *confusion of systems for the intent of study and for the intent of shaping* has been described in the previous section. It is a barrier that is pronounced for the accelerator engineering domain due to the dominance of natural scientists in leading engineering functions, which is atypical for other plant construction industries. Further barriers that have been encountered in the course of this work include other types of confusions related to the systems term. These are easier to identify, as they are based on more common category mistakes: Equipment that is located in defined spatial positions or areas (e.g. an accelerator section) is sometimes called a 'system'. This can be a *confusion of systems and spatially aggregated groups of equipment.*

Another confusion can arise from the aggregation of certain types of equipment under the term system, even though they are functionally separated and have no interfaces. In this case there is a *confusion of systems and classes.*

Organisational ownership scopes of technical equipment have also been found to be declared systems. In these cases, the motivation of the proponents may be to regulate or control the ownership of equipment. This phenomenon clashed with the aim to define systems as functional units, comprised of subsystems that are contributions from different organisational units. It is a *confusion of systems and equipment ownership*.

It should be noted that this outline of confusion types is not always as clear-cut as presented here - in fact, it is the nature of confusions to be blurry and ambiguous. In practice, different types of confusions may overlap and reinforce each other, making it difficult for an SE manager to entangle the underlying confusions and motivate the need for implementing SE-guided Systems Thinking. It is however needed in order to create and populate the different breakdown structures for technical information (system breakdown, work breakdown, location breakdown) in a consistent manner. The roles of these are further outlined in paper D.

4.3 Viewpoint management

Complex systems such as found in particle accelerator research facilities have architectures that can and need to be described from different perspectives. The perspectives needed are determined by the various interests of the stakeholders involved in the system development and operation. These interests can pertain e.g. to system structure or behaviour descriptions for construction or operation purposes.

To enable successful communication between the stakeholders, it is hence desirable to achieve clarity about the *conventions* of the various descriptions; e.g. clarification of languages or model kinds that are to be used for the description of the developed systems. In the case of accelerator facility systems, this is of relevance to e.g. avoid misunderstandings, ambiguities etc. between different departments or between a facility design team and suppliers such as in-kind contributors or industrial suppliers of customised equipment. The clarification of conventions for system descriptions is especially relevant for the information exchange between automated information processing systems (e.g. information that defines control system configurations). Further, conventions are highly desirable for the integration of information from various sources in formalised information management systems (e.g. PLM systems). These are intended to make human created information (drawings, texts such as requirement specifications) available in a consistent fashion by themselves, or semi-automated by other information systems (e.g. on request from an alarm system GUI, control GUI, etc.). In the control and computing systems domain at research facilities, common technical perspectives on systems include software architecture, software behaviour, hardware architecture, system connectivity, data models, control flows, network topologies and security measures, electrical engineering or mechanical aspects.

A set of conventions that defines how information of certain stakeholder concerns is expressed is called a *viewpoint*. The coordinated definition of viewpoints for a project or organisation is called *viewpoint management*.

The international standard ISO/IEC 42010 Systems and software engineering - Architecture descriptions (ISO 42010, 2011) describes a set of terms and concepts that are useful as meta-concept for the discussion of viewpoint management. The usage of viewpoints for integration on the levels of people, formal models and information processing tools for cyber-physical systems has been described in (Törngren, 2014).

The relevance of viewpoints and their management in the engineering processes in the studied domain is given in the attached paper B, in particular in view of the often informal communication practices typical for the domain. Further relations are outlined for Requirements Engineering (paper A) and System Integration (paper C). A dedicated management of viewpoints is also desirable for the application of a Systems of Systems Engineering approach, as described in paper D, which involves the coordination of a particularly versatile stakeholder composition.

4.4 System life cycle management

Systems Thinking is applied for defining a system and iteratively its sub-systems that are to be engineered. *System life cycle stages* are used to describe the development status of a system over its life time. The possible life cycle stages are defined in a life cycle stage model.

System life cycle processes are methods that can be evoked in order to advance the life cycle stage of a system. Life cycle processes are executed by humans on a given system and on the information available for a system. The definition and application of system life cycle stages and processes is called *system life cycle management*.

System life cycle stages need to reflect the character and parent process of the produced system. For example, the different main processes (section 3.6) determine different system life cycle stages, as developments in the Facility Creation Process should include in some form production/assembly/installation/commissioning/ stages, while generic system developments (a controller *type*, a sensor system *type*) finalises after the successful prototype verification and validation. The newly developed type can then be used in several places and instances the Facility Creation Process. The applied engineering method can further determine applicable life cycle stages, in particular for various degree of criticality: mission critical/high reliability systems, personnel safety systems and nuclear safety systems may require different definitions. Also, software may be described with other life cycle stages, depending on release cycles or development approach.

A generic framework for system life cycle management is given by (ISO 15288, 2015) and based on this standard, by the (INCOSE SE Handbook, 2015). NASA promotes a comparable handbook (NASA, 2007).

A discussion of life cycle processes oriented at (ISO 15288, 2015) in the control and computing systems domain at synchrotron light sources are presented in (Friedrich, 2013).

4.5 System life cycle processes in the domain

This chapter outlines the major systems life cycle processes as encountered in the controls and computing domain at particle accelerator research facilities. Note that the life cycle processes in this chapter are outlined slightly differently than in the afore presented frameworks, which use different process definitions among each other. The standards' processes can also differ in versions, e.g. ISO 15288 started in the 2015 version to distinguish between Architecture definition process and Design definition process, which has been a single Architectural Design process in the previous versions of 2002 and 2008.

The following subchapters describe the general purpose of a life cycle process and relate them to domain-specific aspects. The domain specific aspects are typical concerns for research facilities in the tailoring of the generic process to their particular systems and organisational situations.

4.5.1 Requirements Engineering Process.

The analytical and descriptive activities that identify for a given system the stakeholders and their interests, demands, needs and expectations are called Requirements Engineering.

This thesis work encompassed as part of the Action Research activities work on the establishment of requirements engineering practices in the case study environment. The activities and their guiding approach are described in the attached paper A, "Requirements Engineering for Control and Computing Systems at large research facilities: Process Implementation and a case study." The paper focuses on the implementation of requirements engineering as a process.

4.5.2 Architectural Design Process.

The specification of systems and their functions, the composition of constituting subsystems, the definition of interfaces, the specification of the system behaviour and the system qualities is called the architectural design. The specification of architectures is preceded by the identification and evaluation of architectural alternatives (trade-off analysis). Architectures are iteratively refined towards a detailed design. The increasingly stabilising architectural description has to be sufficiently detailed in order to guide the implementation of the system with the means of implementing discipline-specific methods (software development, hardware development, etc.). The purpose of architectural design is to ensure that the properties of the eventually implemented system correspond to the needs and drivers of the system stakeholders.

Architectural design activities at research facilities occur in practice in a variety of sometimes more, sometimes less SE guided forms. A wide-spread practice is the production of design descriptions within specialist teams with significant experience in a certain field, e.g. magnet design, RF systems, or a certain experimental technique. This approach has the inherent risk of underestimating aspects of controls and computing systems: Either the involved discipline experts have little personal expertise in the controls and computing systems area, and simply do not consider the related potential issues. Or, if a notable practical amount of experience in practical development of electronics and software is given, which is often the case among experimental physicists, this experience is often very problem-area-specific, and does not take into consideration technology management and standardisation concerns. A controls group, tasked with the maintenance of n-thousand electronic components, has naturally a much higher interest in standardised technologies, remote inspection means, deployment procedures, etc. than the developer of a singular controller prototype may be concerned with. For these reasons, it is generally advisable to have specialised controls developers involved early in system designs, and for a controls division, to have a well-defined and communicated set of technological standards as guidelines for the architectural design activities of distributed control systems.

This thesis work highlighted as special aspect of architectural design at large accelerator facilities the System-of-systems characteristic, and exemplified the implications in a case study fashion in the design of the Machine Protection System-of-System at the ESS. In this case, the SoS approach is additionally influenced by its application in a critical system, utilising functional safety standards (IEC 61508, IEC 61511 based tailoring). The attached paper D presents the approach in detail.

The introduction of sufficiently well-structured SE approaches and formal information exchange is a continuous challenge for SE facilitators in this domain. Nevertheless, it is also difficult, but highly desirable to reach a high degree of clarity and efficiency in human, informal communication. Typically, a large amount of explanation of engineering motivations and decisions is communicated over informal ways in the research facility environments. An approach to get a scientific hold on the problem has been described in the attached paper C, on Conceptual Reasoning.

4.5.3 Integration

What is integration? A review of basic concepts is presented in paper C, which draws upon definitions of (INCOSE SE Handbook, 2015) (Grady) (Muller, 2012) (Langford, 2012) (NASA, 2007). For the understanding of this section, we shall consider integration activities as following:

Purpose of Systems Integration. The purpose of integration activities in a research facility project is to enable the aspired research support service within the project's schedule and budget constraints. The goals of integration activities include:

a) The *identification of critical aspects as early as possible*, including technical issues (e.g. interface compatibility, emergent system behaviour, enabling systems) and external dependencies (organisational and other preconditions, e.g. human access to installation rooms), for the purpose of enabling corresponding actions or measures.
b) The *identification of sequential dependencies of the system synthesis activities* that transform subsystems to the finally delivered system, for the purpose of managing them over time.
c) The successful execution of *implementation, assembly, installation, verification and validation activities.*

The attached paper C describes and reflects on the development of an Integration strategy for the controls and computing systems at a research facility. It is exemplified by a case study of the Integration group in ICS division at the ESS. As a tool for generating the required information and managing integration, the paper describes the document type "Systems Integration Management Plan", its contents and advisable diagram types.

Integration activities in the domain. Figure 22 shows from an integration perspective the typical integration-related activities for the control and computing systems domain in a research facility project. To the left (purple), activities are visible that are typically part of the generic developments process. Technical in-house standards are defined (commercial-of-the-shelf components, PLC types, standard electronics, software technologies, protocols, etc.). Also coordinative standards relevant to integration are defined, such as for documentation and procedures. The outcomes of the in-house standardisation are inputs to system design and prototyping, which still is part of the generic development process. For example, common platforms for distributed controllers are defined, developed and tested that merge various COTS components, operating systems, domain-specific control software (e.g. based on EPICS or TANGO) and possibly facility-specific software. The overall system may be tailored to e.g. beam monitoring tasks in the facility. In the facility creation process, the system or its components must be acquired and installed according to the previously done design. To the right of Figure 22 (cyan) are the activities that are related to the Facility Creation Process. The acquisition includes the incorporation of the components into the organisation's operational flows (in regard to finance, logistics, quality control and acceptance, storage, registration in databases). The installation includes system assembly (e.g. subsystems that are assembled in workshops or off-site), on-site assembly (e.g. in the accelerator tunnel, in the experiment hutch), verification (such as function tests), early operation (possibly staged, ramping up to full performances over time, in coordination with other systems), and finally validation of the full operational capability.

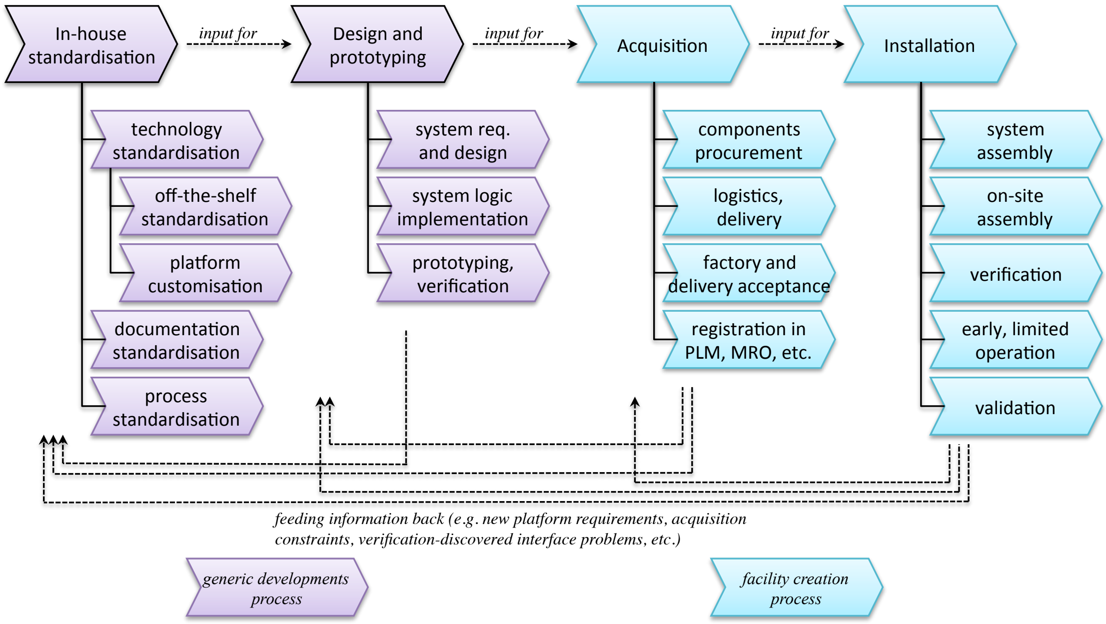

Figure 22: Typical integration activities in the domain

Integration of control systems in a research facility. The role of controls as a mediating layer in research facilities in the chain between humans and physical processes has been outlined in 3.3. Figure 23 shows, in a block-diagram oriented fashion, integration scopes of a neutron experiment, as it is relevant for the facility creation process (compare 3.6.2). Working from the bottom up, localised integration, beginning with a "sample magnetization system", is followed by higher level integration, "sample conditioning system". For understandability, Figure 23 shows a simplified pattern, not a concrete facility. In the example, we can see a sample magnetization system, used for exposing sample materials to magnetic fields in-situ. The sample magnetization system is a 'multi-disciplinary' system in the sense that it is composed from subsystems or components from different groups or divisions within an accelerator facility organisation. The subsystems or components designs and implementation responsibilities would depend on the organisational structure, and could be e.g.

- sample electromagnet: Magnet group
- power supply: Electrical engineering group
- power supply controller: Hardware integration group
- Magnet configuration graphic user interface: Hardware integration group

In any organisational setup, the sample magnetization system as a whole would equate to an integration scope. The sample magnetization system then would need to be integrated with other systems that together form the sample conditioning system. Depending on the experiment, this may allow to regulate the temperature of the sample, vacuum conditions, electric currents, etc. The sample conditioning system would also include a controller dedicated to the overall conditioning, possibly including feedback loop processing. In facilities utilising EPICS, this is typically realised by an EPICS Input-Output Controller (IOC). The sample conditioning system would thus constitute another integration scope. The execution of an experiment would need a way for experimenters to configure the sample conditioning system as well as other parameters of the experiment, e.g. neutron beam parameters such flux, angles or temporal resolution. For this, the experiment has an experiment master GUI, which provides a mean for central configuration of the experiment. The sample conditioning system, the experiment master GUI and additional systems not shown in the diagram would constitute the overall neutron experiment integration scope.

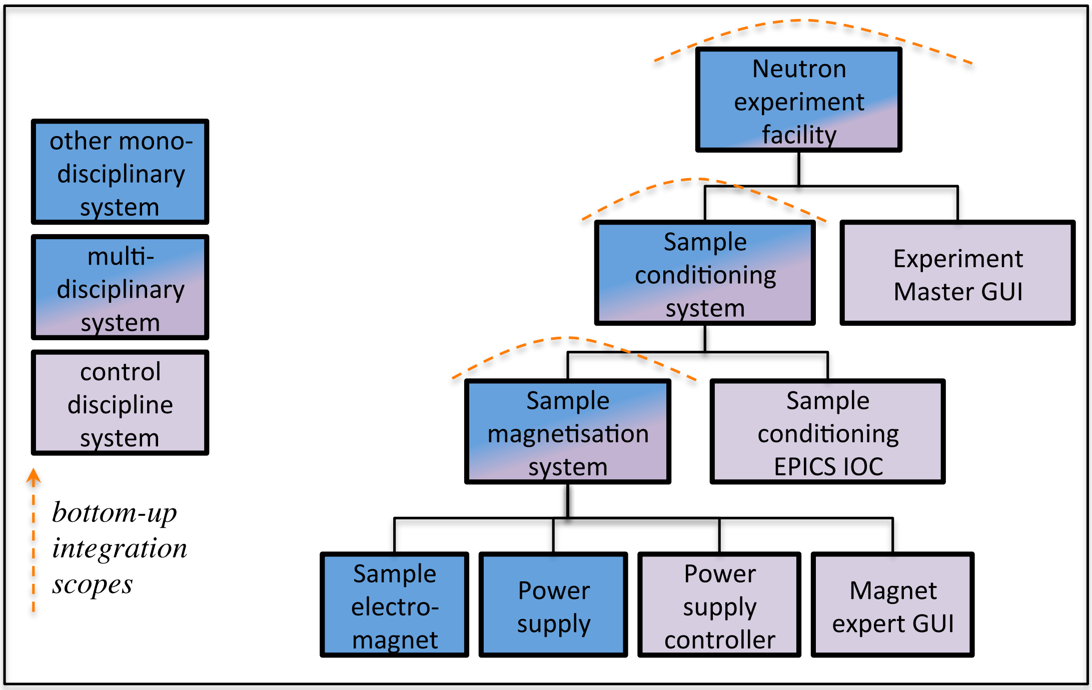

Figure 23: Bottom-up integration of controls and other system types

The example shows that multi-disciplinary integration work is involved on many system levels. Comparable patterns apply to all parts of a particle accelerator research facility, such as the beam steering systems, cooling systems, site-wide electrical systems, door access systems etc. This emphasizes the relevance of integration activities for a controls and computing systems group, and outlines the special role that this groups play for the integration of an entire facility.

This universality of the issue of integration is for no other engineering group than a controls and computing systems group equally tangible and pervasive. Understanding this further underlines the relevance of a functional-systems oriented approach for this specific discipline. It also indicates why other monodiscipline groups are more likely to dismiss the importance of consistent systems thinking and system definitions: As they typically angle the problems from the physical processes, it appears less relevant for their primary domain-specific topics and the personal interests of their members. This corresponds to the repeatedly reported observation of control system practitioners, who claim that controls integration is an often neglected topic in the design of research facilities, and that to a large extent integration problems and their resolution occurs during installation and early operation ("commissioning").

4.5.4 Verification and Validation

The integration of research enabling systems is commonly accompanied by activities that confirm the system's correct behaviour and benefit for the intended user. These activities are typically invoked by the bottom-up integration, and can refer to the component level (a singular power supply, controller, etc.) as well as any higher-level system (a beam acceleration system, and experiment, an entire neutron source), depending on the integrated system.

Activities that confirm whether system functions correspond to defined system requirements are commonly called verification. Verification of control systems in research facilities can use various methods or techniques, such as tests, inspections, analyses, proof, demonstration and simulation. In the Generic Development Process, component prototypes are often tested in lab environments, analysed by experts, and artificial demonstrations are performed. In the Facility Creation Process (on-site), the actually installed control components (electronics, deployed software, cabling, etc.) are tested for their base functionality (e.g. connectivity tests), or implicitly by tests of parent systems (e.g. field strengths measurements for complex magnet systems, or beam behaviour measurements).

Activities that confirm the degree by which the system supports stakeholders in their mission are called validation. Compared to test results, validation results tend to be acquired and captured quite informally in research facilities. Validation results that require follow-up engineering efforts are often not explicitly documented in system validation reports; instead, they initiate upgrades, system changes etc. usually directly from informal discussions.

In the practice of commissioning complex systems such as accelerator installations, which can take months or more, depending on definitions of having reached 'operation', it is not uncommon that integration, verification, validation, and late on-the-fly design/function adjustments blur heavily in the perception of accelerator construction personnel. The controls and computing systems domain is responding and preparing for this by designing the control system infrastructure for high degree of configuration and system behaviour flexibility, e.g. by providing tools such as scripting environments.

4.5.5 Operation, Maintenance and Upgrades

The usage of a system for providing its intended service is called operation, and part of the Research Enabling Process of the research facility (see main processes in 3.6). Activities that aim at sustaining the system's ability to provide its intended service are referred to as maintenance. Upgrades are activities that intend to improve the operational capabilities, i.e. the quality of the Research Enabling Process. Typical upgrades of accelerators improve beam properties, parameterised as higher beam energies, better emittance, better beam stability etc. Upgrades of experimental facilities can focus on physical properties and performance parameters (detector resolution, beam properties, physical sample conditioning), or on the effectiveness of experiment execution (sample handling, in-situ analyses, reliability and availability improvements). Maintenance and upgrade activities are part of the Facility Creation Process. Operation, maintenance and upgrades can occur simultaneously within the same system in the sense that systems and subsystems on different levels can be considered as 'in operation', 'in maintenance', or 'under construction/upgrade': E.g. for beam studies during 'accelerator maintenance', still most accelerator subsystems are in operation. Conversely, during facility operation some sub-systems may be 'in maintenance', if they are not critical for the overall facility operation by function or due to redundancy.

4.6 Engineering coordination approaches and the accelerator controls domain

This chapter introduces to software and Systems Engineering related approaches that have gained relevance in the accelerator construction domain.

A certain amount of work at a controls and computing systems group in a research facility is dedicated to classical software development rather than the development of controllers that steer physical processes. This applies to the development and tailoring of data processing services including archives, data evaluation and visualisation, managing of configuration settings, databases for inventory management, graphic user interfaces, web services. For the coordination of such development projects, *Agile* (Beck, Grenning, & Martin, 2001) approaches have become increasingly popular in the research facility domain, e.g. the application of *Scrum* (Sutherland & Schwaber, 2013). Agile methods emphasize human communication among the developers; short, incremental development cycles; continuous, close customer inclusion in the development process and short response times to change demands. Scrum is a development framework that defines roles, information conventions and work processes that realise the Agile principles.

Scrum has become a popular framework among software development focused groups in the particle accelerator domain, as it suited the naturally close relation between these groups and its customers, mostly in-house developers and operators of accelerator machinery and experiments. It has the advantage of giving structure to the work processes and roles, whilst emphasizing responsiveness to varying degrees of urgencies of issues that appear during the Facility Creation Process, e.g. during commissioning of accelerator and experiment installations.

For a controls group in a research facility, the Facility Creation Process is characterised by repeated changes of the produced system on various scales: small bug fixes or major upgrades; urgent, short term interventions or long term planned improvements with any intermediate levels can occur at any time in the facility life cycle, typically with many such activities being done in parallel. Hence, a controls group needs to establish a reliable process that allows for *Continuous Delivery* (Humble & Farley, 2010), which means the production, release and distribution of software on varying timescales anywhere in the facility. A software building and deployment pipeline needs to be established, spanning across a software *tool chain*, which realises the various software production and deployment steps. These tools include source code repositories, code quality assurance tools, building tools, configuration tools regarding the facility's specific settings and physical distribution tools for distributed software deployment in the facility.

The implementation of such a tool chain from development to operational production systems (in our domain, beam production and experiment conduction) requires beyond the integration of the tool level also a corresponding organisational environment, which can be a challenge in organisations where development, IT operations and quality control are relatively divided in regard to culture, organisational units or location. The DevOps (Kim, Humble,, Debois, & Willis, 2016) (Kim, Behr, & Spafford, The Phoenix Project: A Novel about IT, DevOps, and Helping Your Business Win, 2014) movement, which has emerged in recent years, aims at facilitating the communication and collaboration between the involved stakeholders. This involves the adoption of Systems Thinking, establishing feedback loops with quick responsiveness and promoting a culture of practice by repetition. Translated to the accelerator research facility domain, the involved stakeholders include control system developers for distributed control software and control configuration data, software developers who produce operating systems and drivers for distributed control platforms (PLCs, mTCA systems, etc.); network, server and tool administrators, and the various testers of distributed systems.

4.7 Systems of Systems engineering

Systems of Systems (SoS) engineering is a trend in SE that responds to increasing difficulties of applying ‘classical', traditional SE (define) to increasingly complex systems. Traditional SE assumes a relative clarity the purpose of the engineered systems, a hierarchical functional system structure, and overall clear stakeholder and management relations. With complex socio-technical systems, this clarity can diminish, and we may identify, re-phrasing (Maier, 1998) slightly, that system components fulfil valid purposes in their own right and continue to operate to fulfil those purposes dissembled from the overall systems, and the system components are managed (at least in part) for their own purposes rather than the purpose of the whole. Maier defines thereby central criteria for Systems of Systems.

This characteristics are further expanded and detailed in the (SE Guide for SoS, 2008). As criteria are included here aspects of operational and managerial independence of constituting systems, meaning the stakeholders may have competing or conflicting interests, and the constituent systems may to varying degrees be operated for other goals than the SoS goal. An evolutionary, incremental development process has to be applied, which can make system acquisition, integration, verification and validation difficult to coordinate across multiple system life cycles and can continue during SoS operation. The boundaries and expected functions or capabilities of the SoS are not necessarily stable during operation; it is open to changes. The criteria for an evaluation of the SoS performance may not be clearly specifiable, as they differ for varying stakeholders and may require balancing between the constituent systems.

The attached paper D introduces further to SoS Engineering and explains the suitability of the approach for the particle accelerator domain. The paper outlines the application of SoS engineering in a case study that is the engineering approach for the Machine Protection System-of-systems (MP-SoS) at the ESS. Special consideration is given to the aspect of functional safety engineering, as the MP-SoS is a mission-critical system for the ESS.

The case study describes how the following generalisable benefits are achieved by applying a SoS Engineering approach in the construction of particle accelerator research facilities:

- The SoS Engineering approach enables the *application of functional Systems Thinking for a large system structure* characterised by complex functional dependencies. Particle accelerators expose a high degree of entanglement of functions among their systems. High-level properties of particle accelerator research facilities are emergent behaviours that require functional system views that go beyond a tree/top-down structure. The SoS Engineering approach enables a more appropriate approach to the description of these emergent properties, while also enabling their decomposition towards lower level constituent systems.
- Among such high level properties of research facilities are the reliability and availability of particle accelerator facilities or structures. A SoS Engineering coordination approach allows for SE tailoring towards high *reliability and availability* on the SoS level based on functional safety engineering approaches.
- A SoS Engineering approach accommodates for the *openness* characteristic of the research facilities. In particular for user facilities, the SE approach needs to prepare for frequent but in detail no entirely

predictable changes of constituting systems over the whole facility life cycle. These occur e.g. for performance improvements or for enabling new experimental techniques, which can entail small or large system additions, removals or alterations to new functions. For example, accelerator structures with diminishing scientific value can sometimes be (partially) recycled pre-accelerators for new accelerator structures.

- SoS Engineering enables a systematic approach for managing a *high diversity in SE maturity among development teams*. It is not uncommon for experts in the various technical domains to have little or no general SE experience, and in particular, experience with functional safety standards.
- The SoS Engineering approach can help to *clarify organisational responsibilities or mandates*. Paper D describes that the establishment of the SoS perspective on Machine Protection at ESS has been used to define and assign the corresponding mandate to an organisational unit.
- The SoS perspective gives a common frame for *facilitating negotiations* among the stakeholders of the constituent systems and the overall SoS. Such negotiations can be of managerial as well as technical nature.

The case study is furthermore of interest for the SoS Engineering community as an example for aspect- or quality-driven application - in this case, the reliability and availability of a System of Systems of considerable complexity. In the case of the ESS, the involved stakeholders consider the SoS an *acknowledged System of Systems*, following the classification in (SE Guide for SoS, 2008)

As a relatively young branch in Systems Engineering, SoS Engineering is still a developing field. Standardisation efforts and clarification to existing SE standards are on-going. An overview on standardisation efforts in the ISO and IEC domain has been elaborated by (Dahmann & Roedler, 2016), which presents SoS areas (for example, Security) and current standards for application or revision. High reliability, high availability or functional safety as SoS areas are not explicitly mentioned, but one could consider these as relevant SoS area aspects and relate the to the standard (IEC 61511, 2004) or the (IEC 61508, 2010) standard family. For this, our case study described in paper D could serve as example for a SoS Engineering approach for high reliability and availability based on (or at least, inspired by) these functional safety standards.

Another aspect of interest could be multi-level modeling of SoS, which is a background subject of paper D as we see particle accelerator facilities as SoS on different levels ("whole facility"-SoS, therein the Machine Protection SoS).

4.8 Functional safety engineering

Functional safety engineering is generally the realisation of system functions that achieve freedom of unacceptable risks. Particle accelerator based research facilities usually encompass a variety of systems with serious risks for the facility personnel or the environment. Dealing with these risks often involves dynamics and automation, which is why typically all accelerator control groups spend a notable effort on the development of safety critical systems. The criticality levels typically found in research facilities can (but don't have to) encompass the following:

- nuclear safety critical systems, (e.g. reactors)
- personnel safety critical systems, (human injury)
- mission critical systems, (protection of critical machine parts)
- other systems.

The former two are typically subject to approval from regulation authorities according to the national law. It is common practice to design dedicated safety-critical systems for certain purposes, e.g. for human access to controlled environments (buildings containing accelerator machinery, laser hutches). Other application areas can concern radiation, oxygen deficiency, containment of chemicals, high voltage, etc. These systems are typically referred to as personnel safety systems, and interlocked to parts of the accelerator machinery. Among the many national and international standards that are applied in the domain, used in accelerator facilities is for example the IEC 61508 standard family (IEC 61508, 2010).

In this thesis, paper D presents an engineering approach for realising a mission critical system for the European Spallation Source, the Machine Protection System of Systems. The approach is heavily oriented at (IEC 61511, 2004), and applies it in a Systems of Systems Engineering fashion.

4.9 Technical Information Management

Technical concerns and their representation play a central role in all technical processes at a research facility. The generation, storage, processing and provision of technical information are called Technical Information Management. It affects external research facility stakeholders with technical interests, including users of the experimental facilities, as well as technically involved staff within the research facility organisation. Technical information management is a significant factor for the effectiveness and efficiency of the Facility Creation Process, the Generic Developments Process and also the Research Enabling Process as outlined in chapter 3.6.

Figure 24 shows the main information producers and consumers for a research facility's technical information management during the development. Grouped according to the interest in detail the parties are shown (left side), the character of the related content (mid) and the typically used information processing tools (right side).

Facility stakeholders such as experiment users, as well as the research facility's top management, are primarily concerned with technical aspects on a high level of abstraction, omitting technical details. In their discussions, the focus includes some figures of merit and functionalities that indicate adequate support for aspired experimental methods. Due to the diversity of communication reasons, events and involved people the communication media are primarily based on common office applications or otherwise widespread, easily accessible technologies. Formalisation is usually low, consistency not a necessity.

Facility architects and integrators transform content from the top-level into specifications, plans and models of higher-level systems. These higher-level systems are multi-disciplinary by nature, typically requiring cooperation of at least one expert group (accelerator physics, experiment physics, cryo, vacuum, etc.) and the controls group. The engineering content for multi-disciplinary systems can include e.g. requirements specifications, design specifications, verification plans, risk registers - depending on the engineering approach that is applied to the particular system. The trend in this field at research facilities is to adopt supporting tools from comparable industries. For example, the overall technical information for a research facility can be hosted in a *product life cycle management system* (PLM), as it is common practice for industrial facilities. System-describing content can be generated and maintained by requirements engineering tools, verification management tools, risk management tools, - all of which also operate on a multi-disciplinary level. In industrial contexts the use of model based systems engineering (MBSE) based system modeling languages (e.g. SysML) has gained certain traction. While in principle this approach is well applicable for the research facility domain, few examples exist so far, such as (Karban, Hauber, & Weilkiens, 2015) for a telescope, for facility level systems. Reasons for this are the unfamiliarity of research facility staff with the approach, respectively the average SE maturity of research facility organisations, and barriers inherent to the approach and tools.

System architectures and specifications are translated into detailed design utilising domain-specific tools on the mono-disciplinary level. Technical drawings are generated in Computer-Aided Design (CAD) tools, which maintain the spatial information in a 3D model of the entire facility. Electrical engineering tools are used to describe the electrical layout, also based on databases. Physics calculations are performed in dedicated simulation tools, e.g. for beam orbit layouts and beam trajectory calculations. Code repositories and related software build and deployment systems store information that is needed to realise the facility's control and configuration capabilities.

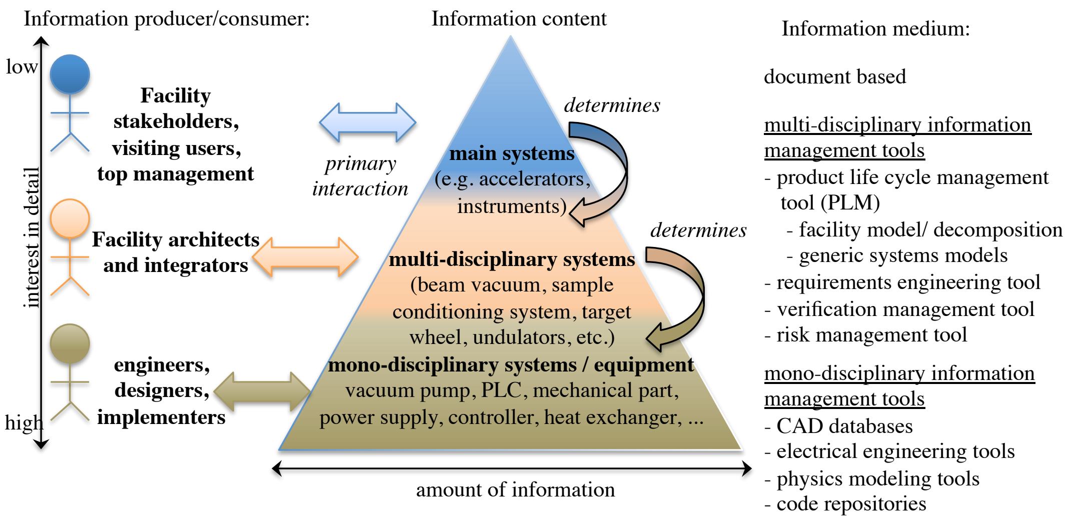

Figure 24: Technical Information Management

The *Technical Information Management Process* as discussed here addresses the definition and provision of concepts, methods and tools for managing technical information in the organisation. Within the research facility process model described in 3.6, it can be seen as part of the Top Management Process.

It should be noted that e.g. ISO 15288 defines Information Management as a system life cycle process. This is complementary to the Technical Information Management process outlined here, as it approaches the information management problem from the perspective of a concrete system development. In a system development, system stakeholders commonly require or welcome support for their system information management based on organisation's information management.

Systems Engineering management for a research facility is hence well advised to participate in both *system life cycle management processes* as well as in the *technical information management process* of the organisation. Thus system engineering management practitioners can identify the information management needs of the various, disparate system developments, and give feedback to the party realising the technical information management process and tools. Conversely, system engineering management practitioners can educate the end users (system developers, engineers, scientists) about the concepts and services provided for information management by the organisation. This education is likely to go hand in hand with education about systems engineering methods, as these often motivate outcomes (specifications, plans, reports, etc.) that are informational by nature. The characterisation of typical research facilities, their project and staff structure (section 3.5, 3.6) pointed out the often temporary aggregation of staff for a facility construction project. This characterisation renders significant educational efforts in information management practically a necessity for any large research facility project.

Insufficient success in the elaboration of the technical information management process and the required staff education can impact the effectiveness and efficiency of the research facility organisation, or the quality of the produced systems, and eventually, the quality of the research enabling services. Practical problems can include

- incomplete, delayed, or cumbersome access to technical information,
- unnoticed diverging engineering efforts,
- unnoticed overlap of engineering efforts,
- ambiguity on the current status (valid version).

Such problems are to a good extent “normal” in given the character of research facility projects, and have to be accepted as part of the challenge. If unaddressed however, they can seriously impact the goals of a construction project and also pertain into the operations phase. If, for example, a comprehensive, consistent information model is not realised, a likely consequence is that the management of inventories and design information will be cumbersome and inefficient during maintenance, repair, overhaul and upgrades.

In the course of this thesis work, participation was pursued in both system life cycle management and technical information management on the ESS level (in section 2.4.3, this corresponds to *AR_ESS-M_SLC1* and *AR_ESS-M_INF1*). It revealed a widespread divergence of efforts, concepts and tool developments in the descriptive study phases. This led to interventions in succeeding prescriptive phases aiming at alignment between various ESS divisions. The success was mixed, due to significant, but only partial increases of problem awareness among the involved parties. However, initiatives to resolve the unsatisfactory aspects of the situation have been triggered or at least influenced. Yet at the time of writing the long-term repercussions are impossible to forecast.

4.10 Technology management and standardisation

This section describes technology standardisation in the controls and computing systems domain, referring to the managed introduction, development and utilisation of technologies.

Technology standardisation crosses and connects the Facility Creation Process and the Generic Development Process in research facilities in both directions. In the Facility Creation Process, multitudes of functions are identified. In the Generic Development Process, these functions are analysed for commonalities, which allow the utilisation of the same system type to fulfil the requirements of a group of similar functions. Accordingly, generic systems are specified and declared to be preferred technology for certain technical functions (“in-house standardisation”). The control system in-house standards at research facilities often include a significant degree of development for customising commercial off-the-shelf components (COTS) for integration with other in-house standards. This practice results in a lowered number of systems types that are used in a facility, helping to reduce the variance of knowledge and competences that are required for maintaining the facility systems. Further, this approach focuses the improvement efforts on few base systems, the generic in-house standards, and allows making these systems more reliable or feature-rich. Finally, batch acquisitions can help to reduce hardware costs.

To give an example for technology standardisation in practice: The ESS machine and experiments require a few thousand distributed control units which range widely in performance and reliability parameters. In principle, in-house system developers and in-kind contributors could be encouraged to use any hardware control technology of their preference to enable their local functions. This would however result in a technology variety that would be difficult and costly to maintain, e.g. due to the need of maintaining the expert knowledge in ESS. Not all the controls hardware at the ESS project is owned by the ICS project. However, this division will provide the majority of the software and code development effort. Also, this division will provide the infrastructure for the deployment and maintenance of the whole controls infrastructure at ESS.

To cope with the long-term maintenance of the ESS control infrastructure, the ICS division has defined a hardware strategy based on the different types of distributed control system functions expected in the ESS project. According to these premises ICS has standardized three different types of hardware technologies for distributed process control:

- fast, real-time signal processing (MHz range) shall be realised using mTCA systems,
- middle-range I/O (KHz range) shall be realised using EtherCAT technology,
- Industrial I/O (slow control) shall be realised using SiemensPLC technology.

Each of these technological standards has been refined further in regard to the utilised operating systems, drivers, EPICS (SCADA) integration, facility timing system and the build and deployment process. The resulting standardised base systems are the ICS-preferred technologies to be used in the Facility Creation Process by all technical divisions and in-kind contributors.

Other typical example for technology standardisation at research facilities concerns the usage of operating systems for servers and distributed controllers, the usage of programming languages, and the choices for field bus systems (Friedrich, 2013).

Technological in-house standardisation can easily become a matter of open or tacit conflicts in the creation of research facilities. The following aspects of technology management or standardisation management have been identified as relevant:

- *Roles*. For any in-house standard, is a responsible defined? Is the mandate clarified?

- *Standard selection:* Is there an analysis method applied for the standardisation decision? Are all stakeholders actually considered and do these stakeholder see themselves appropriately considered in the standardisation process? Is an open-ended investigation actually wanted or supported by the stakeholders?
- *Documentation:* Is the standard communicated actively into the organisation? Is it motivated? Is information material available?
- *Procedures:* For given technical standards, are related procedures or guidelines defined? E.g. for a PLC technology standard: Are viewpoints for interface description defined? Are programming guidelines defined? Is a procedure for equipment selection (modules) defined?
- *Revisions:* Are versions/revisions of in-house standards well defined? Are upgrades appropriately based on standard user needs? Is deprecation clearly declared for out-dated versions?
- *Portfolio management:* Is the overall in-house technology standard portfolio and roadmap sufficiently elaborated and accessible? Is the portfolio of one division systematically checked for consistency (gaps, overlaps) with the developments in other divisions?

5 Discussions and Reflections

This chapter revisits the research goals and questions (5.1) and then reflects on the research approach (5.2). For a better understanding for the genesis of this thesis, a retrospective characterisation of the author's research situation is given (5.3). On this base, an evaluation of the overall validity of the findings (5.4) is presented. Some over-arching findings that apply to the thesis work as a whole are discussed (5.5 to 5.8). The chapter closes with an evaluation of the research field (5.9).

5.1 Revisiting the Research Questions and Goals

Revisiting the Research Questions. In the course of this research work, a number of research questions (2.2) emerged that concretised the more programmatic research goals (see 2.1). In the following, the research questions are revisited and related to the research contributions.

Q1: *What characterises Systems Engineering at accelerator based research facilities? What operational and organisational factors influence the currently predominant approaches to SE?*

A systematic analysis of the organisational and process context of SE in the construction and operation of research facilities has been presented (chapter 3). Further references to the accelerator environment are given in detailed discussions of SE concepts, spread out over the thesis.

Q2: *What standards and frameworks exist for Systems Engineering at accelerator based research facilities?*

SE and its application in particle accelerator facilities has been presented from various sides in chapter 4, including SE standards and more controls and computing system related engineering approaches (4.6).

Q3: *What are characteristic challenges for the Systems Engineering Management in the control systems and computing systems domain at accelerator based research facilities? How can SEM issues be approached?*

A reference framework for SE management has been presented in section 4.1. It guides the SE manager to considerations of the various SE aspects further outlined in chapter 4, where these aspects are further related to the controls and computing systems domain in particular. Typical over-arching problems, the 'SE awareness paradox', the introduction of improvements and barriers to SE application have been further discussed in sections 5.5 - 5.7. Section 5.8 discusses the role of informal and semi-formal communication for SE in the domain, and paper B proposes a concept for SE managers to enhance this role.

Q4: *What are the relevant aspects for the implementation of Requirements Engineering in the control systems and computing systems domain at accelerator based research facilities?*

With paper A, an analysis of relevant aspects for the implementation of Requirements Engineering in the domain has been presented, and an approach proposed to the implementation of an RE process. While unfortunately this case study is on hold in the case study environment due to a variety of reasons, the case study could reveal further related barriers to the successful implementation. This led to further analyses, notably of the role of Systems Thinking (see section 4.2) and the role of SE competences and communicative factors (5.5 to 5.8).

Q5: *How can the SE-related communication among stakeholders be improved in environments with largely immature SE practices?*

A concept for guiding improvements of SE related communication in every-day practices among engineers, developers, scientists, etc. has been presented with paper B. Educational aspects and communication aspects have been discussed in (5.5 to 5.8). This includes potential improvement strategies for SE facilitators to improve the situation, e.g. by reflections on the SE management style (authoritative vs. democratic SEM), or on a smaller scale, the introduction of user story for the analysis of accelerator operations.

Q6: *How can Integration be facilitated in the control systems and computing systems domain at accelerator based research facilities?*

A case study has been presented on the introduction of an Integration Strategy for the ICS integration group, which at the time of writing appears to find promising acceptance and is iteratively refined. This has been described in paper C.

Q7: *How can Machine Protection (high reliability and availability goals) be realised at large, complex accelerator facilities with Systems of Systems characteristics?*

An Systems of Systems Engineering approach for the development of a Machine Protection System of Systems has been presented, which is expected to realise high reliability and availability of the neutron beam production at the ESS. It implements the main concepts of the functional safety engineering standard (IEC 61511, 2004) on a systems of systems level, and accommodates for system of systems properties such as stakeholder diversity, system openness and operational independence of systems and organisations; hence it is considered to be well transferable to comparable accelerator based research facilities.

Q8: *What is the state of research on SE for large research facilities? What are relevant future trends and research topics for Systems Engineering in the particle accelerator domain?*

Based on reviews of the state of the art of SE for large research facilities (see 2.3.1), a characterisation of the research field has been given (5.9) and a number of promising future research topics have been described (6). These future research topics reflect the multiple angles on SE in this domain, and range over methodical, educational, communicative aspects to philosophy of science questions.

Q9: *What methodological problems for Systems Engineering research in the domain exist, and how can they be addressed?*

The research method for this thesis has been presented in depth in section 2.3, where the different problems are explained that led to the methodological choices. Theoretical reflections on the application of the approach have been presented in 5.2, and complemented with their practical side in this course of this work in 5.3. The overall validity of the results that this approach, applied in this thesis, yielded is discussed in 5.4. Both the approach and the methodological research problems it addresses are formulated on a theoretical level and kept separate from its concrete application in this thesis work. This should allow for its application in future research on SE in the domain, at least in its main bearings, be it at ESS, MAX IV, or other comparable research facilities.

Relation of contributions to research goals. The research questions and contributions have been guided by the more far-reaching, programmatic research goals described in 2.1. As these aim beyond the scope of a single PhD thesis, it is worth to revisit them and see how the contributions outlined 2.2.1 in relate to the research goals, and to identify still existing gaps towards the goals.

1. To obtain an understanding of the relation of state-of-the-art technologies used in the domain and their relation to the Systems Engineering practices.

While the investigations on technologies used in the controls and computing systems domain for particle accelerators has been more in focus for the previous Licentiate work (Friedrich, 2013), this thesis work contributed by to this goal more from the side of Systems Engineering practices. *Contribution III - Integration Strategy* focuses on the area SE for 'industrial control' integration, as opposed to e.g. software technology related SE (which would roughly correspond to software engineering approaches). *Contribution IV - Systems of Systems (SoS) Engineering* has a technology related aspect due to the rather particular Machine Protection technology.

Systems Engineering with a notable technology-tailoring for safety critical systems, for SCADA software development or for a facility network infrastructure has not been investigated, and may be interesting as future research.

2. To obtain an understanding of the best practices in Systems Engineering and related fields for computing systems at accelerator based research facilities.

Chapter 4 gives an introduction on SE used in the computing systems domain at research facilities.

More detailed descriptions could be elaborated for the various life cycle processes and their implementation. In particular, the system verification and validation processes have not gained much attention in this thesis due to the overall life cycle of the studied facilities, which were in early or mid design phases.

A practical implementation approach for viewpoint management and its facilitation in formal and informal engineering communication could be elaborated, which should accommodate for the cultural properties of the research facility community.

3. To gain an overview on the state-of-the-art methods of Systems Engineering that are compatible, or applicable, to accelerator based research facilities. Criteria for compatibility, or applicability, include Systems Engineering management aspects as well as technological and organisational properties. The purpose of this goal is to inspire methodological cross-fertilisation.

A base for compatibility and transferability considerations is presented by *Contribution I*, an analysis of the organisational and process context of SE. More concrete inspirations taken from other domains, e.g. by the adoption of standards, are described in their application; e.g. the incorporation of the SE Handbook (paper A and C), the SE guide for SoS Engineering (paper D), ISO 61511 (paper D).

The transferability of SE approaches with certain industry sector backgrounds from and towards the particle accelerator domain is discussed in the context of validity (section 5.4). However, a dedicated overview on SE transferability, and a methodical approach for the appropriate choice and adoption of 'foreign' SE approaches has not been described for the research facility domain. It should be a worthy future contribution.

4. To develop a body of knowledge on Systems Engineering Management for the studied domain, computing systems at accelerator based research facilities. This includes

a. A comprehensive overview on the core and related disciplines and their relations.

b. A collection of method frameworks suitable to the domain, including system life

cycle approaches.

c. An information model suitable for the domain.

d. Application in practice: tools, training, management.

Regarding 4a, core SE aspects and related disciplines have been described in chapter 4. Frameworks of methods and concepts are presented, both concerning life cycle management or SE aspects in a more domain oriented form (Functional safety engineering, software development specific, etc.), adding towards 4b.

As a future contribution to 4c, a generic information model for the typically established controls-related information systems might be elaborated based on surveys across several facilities. This has not been done in this work, and the idea is explained in more detail in chapter 6. In addition to this, a generic information model for information systems at particle accelerator facilities (not so much specific to controls, but general information management including acquisition, documentation and management information) would be a contribution to SE in the research facility domain in general. This should likely help for future green-field projects to avoid parochial developments that are difficult to integrate.

This thesis has presented various contributions to 4d, SE management in practice, including *Contribution II* on Requirements Engineering implementation, *Contribution III* - An Integration Strategy, *Contribution IV* as far as it shows how a SoS approach is accommodates SE coordination in complex development situations, *Contribution VI* with domain-specific reflections, *Contribution VII* with a support concept called Conceptual Reasoning, and *Contribution VIII* - A reference model for Systems Engineering Management, which can give an SE manager or facilitator some guidance in the identification of relevant SEM aspects in practical situations.

5. To develop the domain as a research field. This includes guidance and reflections on research methodology and validity. It also leads towards a map of uncharted territory, i.e. topics for future research in the domain.

A transferable, guiding research approach based on Action Research for SE investigations in the domain has been presented, together with validity considerations from various sides (RQ 9). This approach gave the frame for the more detailed "spot-light" contributions. Further research topics, where this approach could be applied, have been outlined (RQ 8).

To strengthen the epistemological foundation of Systems Engineering research, it could be interesting to study its relation to more recent developments in philosophy of science, social or communication related sciences (see chapter 6).

Contributions to communities. As a main beneficiary of this work, the *accelerator construction community* has been in mind in the conceptualisation of this research work. This community has now a set of contributions at its disposal, which range thematically from technology-linked engineering aspects to cultural and communicative practices, and include SE application and improvement proposals ranging from high-level, facility-wide SE management to enhancements of daily-work engineering communication among the practitioners in the field. In the eyes of the author, an increase of the average SE competence of the accelerator facility community, or generalised, the research facility construction community, is a necessity, if it wishes to optimise the scientific value of its investments, and avoid the risk of lighthouse projects crashing dramatically.

But also the *SE community* has a chance to benefit from this work. The relative uniqueness of the accelerator domain, and the apparent huge barriers to the successful, broad application of SE can help to identify general barriers of SE application, if the barrier-inducing properties are identified. The trend to use SE in more and more complex, networked, multi-stakeholder contexts with widely differing SE competences and ontologies renders a good understanding of the related SE barriers quite desirable. In this sense, the study of "SE at accelerators" may give some insights into the world of SE application problems that will characterise the 21st century.

For the *controls and computing systems community* this thesis presents insights into the application of its technologies in an 'industry' sector with distinct properties. Besides the technical aspects, this thesis emphasizes the challenges in the development processes typical for this domain from various angles, for example in regard to SE management for the overall cyber-physical systems.

After this discussion of the outcomes of this research work, we continue with the discussion of the 'how', the research approach.

5.2 Reflections on the Research Approach

The results of this thesis have been acquired by a research approach that builds heavily on participation and intervention in representative engineering environment, complemented with general studies of the domain. The approach has been presented in 2.3. This section presents retrospective reflections on the approach.

The *Action Research* approach - active participation and intervention in problem solving processes - in this work has been fundamental for the research contribution. Aspects derived from the Action Research activities in this thesis work are discussed in the following.

Given the arguments presented in section 2.3, we here further elaborate why *active participation* in *SE problem solving* is essential for acquiring personal insights into the Systems Engineering Management situation in the domain. The engineering of accelerator facilities as a whole, including their controls and computing systems, exhibits domain characteristics that are in their combination rather unique (see chapter 3), even though partial overlap or similarities to other domains exist. SE researchers not familiar with the domain have a risk of missing relevant aspects, which can be mitigated by active participation. It might be indicative that experienced experts from other industry sectors usually need a long time to acclimatise in the research facility domain.

'Testing' tailored SE concepts and methods requires realistic environments. As properly simulated environments are hardly conceivable for this domain, real environments need to be utilised for "SE experiments", (such as using a Systems of Systems Engineering approach etc.). Conducting SE experiments solemnly for the purpose of SE advancement however is not in the scope of research facility organisations (they are built for serving natural sciences). Managements of research facilities may be reluctant to expose their organisations to the risk of disturbances by engineering methodology researchers. The Action Research approach allows SE researchers to propose the conduction of "SE experiments" convincingly, as it emphasizes the benefits for the host organisation (for this work, outlined as 'impact' in 2.4).

Finally, improved or tailored SE concepts and methods need to be transferred to other research facilities and applied in order to realise the benefit that motivated their research. Their relevance can be communicated by referencing real life problems and their suitability can be convincingly communicated by referencing real life problem solving. Both are facilitated by an Action research approach, which hence creates legitimacy for the research effort and its results.

The structuring of research interventions in *descriptive and prescriptive study cycles* as outlined in chapter 2.3.3 describes a pattern that naturally fitted the flow of tasks and involvement opportunities that emerged in the course of the thesis work. It gave a reflective frame that enabled the identification of research relevance in activities that were 'normal engineering' or management activities in the role as ICS division's "System and standardisation engineer". The iterative relation between descriptive and prescriptive study phases is a realistic representation of the research practice, which sometimes involved re-calibration, or re-adjustments of the intervention goals based on intermediate results. For the correct interpretation of the intervention it is helpful to cultivate the *ethnographical stance or attitude* described in 2.3.4. It reduces researcher bias (see 2.3.5) in favour of a proposed intervention, as it helps to pay due attention to 'soft' factors in the engineering environment, such as the involved person's professional culture, organisation traditions or habits, decision making structure, prioritisation changes, etc. One has to consider that these factors may overrule methodological improvements that were the aim of an intervention part of Action Research.

Participation and intervention however needs to be complemented by studies of the engineering methodology and the technical domain disciplines. In the course of this thesis work, literature studies have been conducted, and university courses have been attended in the fields of Systems Engineering, accelerator technology and experimental methods and philosophy of science. These activities build a fundament for understanding and evaluating the state of practice encountered in the 'field studies'. Further, the studies inspired the introduction of concepts and methods to the studied engineering domain.

A certain degree of reflection on the epistemological base of this work has been carried out, too. SE research in this domain (as generally SE research on socio-technical systems) deals with abstract structures, processes and communication involving humans. The form of discussions and evaluations of the findings is eventually qualitative. The scientific validity of such research therefore builds on arguments rather than statistical analyses. The abductive[24] reasoning approach "Inference to the best explanation" (Lipton, 2004) has been found to be suitable to describe the chosen approach: Phenomena are observed, and among a multitude of potential rules that lead to the observation, the "best" is inferred to as true (or at least, closest to a correct, full description of the world). "Best explanation" in this SE research domain means that relevant pre-conditions are identified, which together with coherent, logical rules allow to predict the emergence of the observed phenomena (explaining it).

To give a quite practical example: The complex phenomenon "ESS engineering groups are quite segregated." figuratively speaking "... sitting in their own silos" can be explained by many pre-conditions and rules. It might be interpreted such that a lot of ESS staff is quite malicious, ego-centric and un-communicative. A (hopefully) better, more appropriate explanation has been identified in this research work: The pre-condition - ESS lacks multi-disciplinary systems definitions due to a general lack of systems thinking - causes to a large degree the observed diverging engineering efforts, as systems have not been developed as commonly shared architectural entities. This made it probably for the spread out development teams to be unaware of other team's efforts, plans and concepts. The lack of commonly shared architectural entities

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[24] On the definition of *abductive reasoning*, the Stanford Encyclopaedia of Philosophy notes "Its core idea is often said to be that explanatory considerations have confirmation-theoretic import, or that explanatory success is a (not necessarily unfailing) mark of truth." (Stan.Enc.Phil., 2011) and continues with a description of elaborated explanations in formal logic. For the purpose of understanding its role in this text, it suffices to note "that explanatory success is a (not necessarily unfailing) mark of truth".

also makes it easy to 'withdraw' into self-defined scopes. Without the notion of shared architectural entities - functional systems - it is also not possible to define 'owners' for them; consequently there is no clear ownership for systems on the meso-level. Which entails, there is no coordinated way for creating mandates for their integration, validation etc. This explanation has been 'socially tested', meaning was exposed to various people with a certain degree of SE knowledge and ESS overview, and was found to be agreeable. In the eyes of the author, this explanation is the best to explain one of the ESS SE management problems, with a reasonably strong validity.

Social tests, exposures of concepts, ideas, etc. and other forms of interactions with practitioners in the domain have accompanied the thesis continuously. This happened within the primary environments (ESS, previously MAX IV), with practitioners of other research facilities, other industries and academia. This exchange of ideas has been repeatedly found to be fruitful, in spite of obvious limitations due to the peculiar character of the thesis topic. Domain cross-fertilisation inspired investigations, adoptions of different viewpoints and generally balanced judgements. At times, it also re-affirmed the purpose of the work when SE efforts in the environment where seemingly futile.

Participative research is open to influence from the environment conditions. For this reason, we continue the discussion of this thesis with reflections on the particular action research situation.

5.3 The action research situation (at ESS/for the author)

This section is meant to enhance the reader's understanding of the advantages and challenges of the author's particular action research situation. It emphasizes the generalisable methodological aspects, hence it also allows for reflections on the participatory approach to engineering as a research method.

The ICS division enabled the participating researcher and thesis author to execute the role of the division's "Systems and Standardisation Engineer" in the daily business, while being a PhD student. The agreement implied that the participant

a) would pursue PhD studies in Systems Engineering relevant to controls and computing systems at research facilities,

b) would support the division in regard to Systems Engineering issues, and use this experience as material for the research, in an Action Research fashion.

It should be noted that the ESS understanding of 'division systems engineer' differs from the more widespread understanding of the Systems Engineer as role that 'owns' and drives the engineering process for particular systems. Instead, the ESS division systems engineers act rather as coordinators and supporters regarding the manifold systems engineering issues that appear in the construction of the ESS and in the accompanying organisation building. In the

ICS division, for example, the actual system engineering activities for specific control systems are usually performed by so-called “Integrators”, who define the specific systems’ architectures, requirements, integration plans, verification plans, etc.

This set-up has characterized the researcher and thesis author’s work in various respects:

Research focus. The heavy involvement of the researcher into a division entailed that the research focus has been largely pre-determined by the current division needs and activities. Not surprisingly, this is reflected in the paper topics that emerged during the research period: The initial concerns have been requirements and architecture related. After some time, the topic of Integration has been increasingly approached, which led to the formulation of an integration strategy that has the purpose to guide integration efforts in the future. Verification and Validation are underrepresented in this work, if compared to their relative system life cycle importance, which is a consequence of the early life cycle stage of the ESS - it is not yet daily business. So, while the Action Research approach is probably the most suitable approach for research in the field of ‘Systems Engineering for Computing Systems at Accelerator based Research Facilities’, it incurs a sense of being driven by circumstances.

System-unspecific systems engineer role. The ESS defines the role of ‘division systems engineer’ not as owner and driver of systems development, but rather in as Systems Engineering management and support. This again led the research work in its direction: The papers and this thesis are more concerned with systems engineering management aspects for a division, rather than e.g. systems engineering methods that tie to a certain type of technology or system (e.g. Scrum for software development).

First-hand experience. The role as a division’s systems engineering coordinator and supporter involved daily interaction with stakeholders in the engineering and related processes. This allowed the identification of systems engineering management aspects that from a more distant, observing viewpoint may not be easily visible, as may have been the case for a hypothetical external researcher who works mostly with e.g. interviews and documentation inspection. These aspects include the relevance of group dynamics, cognition processes or communication pragmatics. The paper on Conceptual Reasoning (paper B) is certainly inspired by a long chain of reflections on the practical communication encountered in the research environment.

Variety of contacts. The ESS personnel spans even for an accelerator facility a wide range of staff specialisations, and due to the green-field character, also a wide range of recent professional backgrounds. The researcher’s position as “division systems engineer” implied contacts with a wide span of ESS personnel, including systems engineering practitioners (integrators, developers, designers), engineers and scientists from varied disciplines, both inside and outside ICS division, general ESS engineering management personnel (e.g. QA, safety) and related service providers (e.g. for PLM toolset). This facilitated a widening scope on the issues to be engaged, and this is reflected in this thesis work. Alas, a wider view angle comes with reduced depth of vision, and meant reduced involvement e.g. in the more technical themes of ICS division.

Long-term involvement. The research engagement covered a significant and crucial time span in the design and early construction phase of the ESS and its computing systems. This allowed for many directed interventions on small, local scales. It also lead to aggregations of observations over months or years, and motivated the pursuit of improvements with project wide repercussions that can take years to realise, beyond the time frame of the thesis work. Such is the case e.g. in the long-term initiative towards the establishment of a systems-oriented approach in the ESS product (facility) life cycle management.

Double-role. The double role as ‘productive’ division systems engineer and ‘reflective’ systems engineering researcher in personal union can at times be perceived (by co-workers) as leading to conflicting interests. Perceived “pragmatism” can be juxtaposed in opposition to “too theoretical or academic approaches”, insinuating propositions are motivated only by research interests rather than organisational needs. The double role can also hinder the execution of the role of the systems engineer, if the researcher is questioned as ‘just a student’. However, compared to a fictional full-time Systems Engineer role, this probably had not too much impact overall.

Imposed limitations on interventions. The application of advanced systems engineering methods (e.g. model based systems engineering) may be desirable given the nature of the systems to be engineered, and form an interesting research topic. Such endeavour however can collide with the limitations of the research environment, such as the organisational maturity, staff competences and the management’s prioritisation decisions, - factors, which are ultimately out of the influence sphere of the participating researcher. Such limitations were certainly hard restricting factors for interventions by the author. In many cases, interventions involved time intense educational activities regarding the basic concepts of SE. These educational activities were crucial for any small progress achieved, and progress by itself, as it allowed to built a certain degree of problem awareness. These efforts were however partially hindered by some diverging interpretations (or misinterpretations) of classical SE concepts and terminology, resulting in a source of confusion of engineers and scientists that had been exposed to non-aligned use of SE terminology. As this situation could not be resolved, a questionable reputation of “SE” - the SE confusion experienced - could be observed to develop among staff unfamiliar with SE, obviously not a helpful disposition for interventions.

Synergetic hybrid? Multi-disciplinary research on such rare machines is facing a continuous acceptance challenge by the traditional disciplines, as it is nowhere “at home”: It has to carry its relevance and methodological legitimacy outside traditional, widely accepted patterns of research justification. Its results cannot be discipline-deep, so it risks appearing superficial to the discipline expert. Its methodology requires tailoring to the peculiar options given by circumstance. There is no dedicated community, only more or less related (and interested) discipline communities. On an individual researcher’s personal level, this can result in a lack of orientation, and repeated adjustments of the research direction are likely to occur. Insecurity on the own work’s relevance and validity are prone to appear, and re-affirmation of one’s purpose must be obtained. The contact with members of various related communities is certainly enriching, but at times can be tiresome for also leading to repeated lack of mutual understanding. A ‘researcher identity’ can be developed, but may not be recognised by the outside world. These aspects of the multi-disciplinary researcher’s individual situation give a different flavour of challenge than more common research situations, where the research subject and purpose is intuitively easier to understand.

5.4 Validity of results

Given the applied research methods and design presented in 2.3, 2.4 and discussed in 5.2, considerations on the overall validity on the findings are outlined in this chapter.

To frame the topic “engineering of controls and computing system for particle accelerators”, the subject of “Systems Engineering” was identified early on during the work, moving to the centre of attention. This allowed comparing the encountered domain practices against the vast body of scientific knowledge produced by the Systems Engineering community. It opened the gates to a wide range of inspirations for improvements in the engineering domain, and addition provided insights for the SE community. This thesis work builds upon the foundations given by the SE body of knowledge. It has been a goal of this work to gain *validity by congruence with the existing scientific discourse on SE and related fields*.

SE literature and concepts have been studied from various angles. Systems Engineering literature, standards, concepts etc. often have a claim on far reaching applicability, but also have some ‘home domain’ where they come from and which gives them a flavour. Usually, there is some degree of some comparability relationship to the accelerator construction domain. NASA’s SE Handbook for instance (NASA, 2007) has an aerospace background, but also concerns ‘research machinery’. Oil and gas industry plants (Baron, 2015) are processing installations for large, slow material flows, but do constitute large complex facilities. More generic SE literature, (INCOSE SE Handbook, 2015) or (Muller, 2012), may have been written with primarily product development in mind, but are widely applicable to the accelerator construction domain, especially where it includes small-series developments of subsystems. Systems of Systems Engineering literature may have an e.g. defence background (SE Guide for SoS, 2008), and still has transferable aspects to the studied domain. Nuclear safety engineering may address far greater risks than those of accelerator facilities, but their engineering coordination may be partially transferable (IAEA Mngt Sys, 2006). Functional safety engineering standards (IEC 61508, 2010), (IEC 61511, 2004) may have been written for commercial systems, but are well adoptable for parts of an accelerator facility. Software Engineering approaches (Sommerville, 2007) complement the more 'physical' engineering disciplines, and plays a major role in the controls and computing systems domain at research facilities.

The findings of this thesis are presented in the net of these SE perspective considerations, which is a way of giving *external validity* to the conclusions.

These comparability relationships also work in the other direction - perhaps it is sometimes the accelerator community that can contribute a novel SE aspect to other industry domains. This has been the hope e.g. in paper D, which intends outline a way for utilising SoS Engineering in complex facility construction (which might interest the oil & gas community, defence community or functional safety community). Feedback from experts of the outlined related domains on suitability and potential transferability is also a source of external validity, and has been sought after e.g. by exposure of the developed concepts at domain-bridging SE conferences (INCOSE Symposium[25], SoSE[26], SysCon[27]).

Approaching the problem of SE for the accelerator domain from these angles is also a matter of caution against researcher bias as outlined in 2.3.5. Multiple SE perspectives enhance the abilities of the researcher to identify issues and relevant criteria for SE evaluations.

A guiding idea has been to acquire "explanations" that are comprehensive. This led to a holistic mind-set, meaning the included aspects expanded deliberately from technical aspects to informational, managerial or cultural aspects of engineering as well in order to account for a wide variety of potential influences including socio-technical aspects.

From the beginning, this work has been oriented at studying engineering practices, observable phenomena in the field, in the real engineering

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[25] INCOSE International Symposium, http://www.incose.org/newsevents/EventIS (retrieved Feb 2017)

[26] Annual Systems of Systems Engineering Conference, http://sosengineering.org/2017/ (retrieved Feb 2017)

[27] IEEE Systems Conference, http://2017.ieeesyscon.org/ (retrieved Feb 2017)

environment. The ideas of Action Research, participation and intervention have guided these studies certainly for its aspired improvements, but no less for the conviction that a credibly comprehensive understanding of the domain requires personal experience. This conviction is based on the assumption that the studied domain is relatively inapproachable in its multitude of influencing factors (technical, social, informational, organisational etc.) and all its facets. Hence, this thesis is believed to strengthen *validity by participatory observation*. Active participation, motivated by studying one aspect, can to an extent force and enable the researcher to acknowledge other aspects that he/she has not been aware of, thereby expanding the explanatory spectrum of the researcher's conclusions. In this sense, participatory research can work against researcher bias in the form of personal affinities or preferences. Conversely, the author would tend to be sceptical of SE research in the domain without a significant participatory component.

Systems Engineering discussions sometimes are carried out on a high level of abstraction. In textbooks, articles, abstract process descriptions, etc. this is of course required in order to widen the scope of applicability. Alas, this also carries the risk of creating (seemingly) logically consistent models with a large gap towards practical applicability. The risk of self-referential thinking and conceptualizing disregarding practical applicability is in particular quite high for a "Systems Engineer" that works in the role of a general SE methods facilitator. This risk has clearly been observed in the course of this work. Again, the participatory, especially the interventive approach chosen in this research work allowed to 'test' SE concepts and methods in a real engineering environment, thus learning about their practical suitability. Obstacles encountered in such efforts are valuable, too, in order to unveil inherent shortcomings and external barriers to SE improvements. This motivated the thesis work to strive for *validity by validation of SE proposals in practice*.

Norris (Norris, 1997) mentions the "reactivity of researchers with the providers and consumers of information". If we interpret here 'providers and consumers' to include the engineers and scientists who develop, integrate and operate systems in research facilities, we can consider the quality of relationship of the researcher with these most technically involved persons a strong indicator for the suitability of SE concepts. Quality of relationship is meant here in the sense of how good do the ideas, proposals, intervention goals etc. of a researcher resonate with the very technically working staff? Are the SE researcher's proposals - primarily - met with continuous suspicion and rejection, or is there at least *some* recognition of value and benefit seen (in spite of SE introducing most inconvenient documentation requests, for example)? While such reactions are of course never safe and clear measures, as they depend on the SE researchers pedagogical and social skills, the technical staff's attitudes, managerial support and other environmental factors, one can still argue that a positive baseline attitude towards the SE researchers interventions indicate at least some suitability of the SE management direction. In this light, the author of this thesis is in particular pleased about the acceptance that e.g.

the Integration strategy found, as it most clearly intervenes in the daily work of the ICS technical staff.

However, validation of SE proposals in practice is open to selection bias (see 2.3.5), both by sampling (what the researcher chooses to see) and by circumstance (what the environment plays into the foreground). To reduce selection bias, the author has tried to spread out his involvement within ICS (different system development involvements, different aspects of SE management for the division) and within ESS (involvement in ESS SE management, in various settings).

The approach of this thesis has been to outline the factors that influence the success of engineering efforts aiming at the successful development and operation of the controls and computing systems in an accelerator facility. This however cannot be done in truly exhaustive fashion, which would be neither doable nor desirable due to the amount of data. Instead, the goal has been to outline the most meaningful causal or influential relationships among the studied phenomena. Many of such relationships have been described in the outcomes of this research work, based on the application of descriptive and prescriptive study cycles. Hence this thesis aims to gain *validity by explanation of influential and causal relationships*.

Such explanations reflect of course, what the explaining mind is able to see, so they reflect the abilities, and possibly, gaps in the education of the researcher. To avoid trying to explain beyond these abilities, 'social tests' have been conducted repeatedly in the environment.

5.5 The SE awareness paradox

This chapter describes a phenomenon, called here the SE awareness paradox, which has been encountered repeatedly in the various activity threads during this research work, most notably in activities related to establishing the breakdown structures of the ESS. Due to its appearance in many discussions, it is presented in a generalised form. In spite of its relevance for introducing SE to organisations, it appears to be not well described, at least for the studied domain.

In a research facility with a low SE maturity, a typical problem for an acting SE coordinator is the discrepancy of the *actual* and the *perceived* SE maturity by the rest of the organization.

Individual engineers, scientists and managers have a certain degree of *SE competence* and thereby a certain degree of *awareness* of the actual SE situation in their work and work environment. High SE competence typically correlates with good awareness of the actual situation.

Furthermore, these individuals have a certain degree of the *confidence* in the organisation's SE approach, meaning the quality of system architectures and technical information management, the system life cycle processes, etc.

In the course of this research, a recurrent observation was that persons with a high SE competence were showing little confidence in the current SE approach, while persons with limited SE competence seemed to be relatively unconcerned. Overall, the picture emerged of inverse proportional relationship between SE competence and awareness versus confidence in the organisation's SE approach. Figure 25 illustrates this relationship in a symbolic graph, depicting a typical situation in research facility engineering environments. The graph includes some attitude expressions, which are not to be understood as literal quotations, but heuristic summaries of sub-texts that were encountered in the manifold SE discussions of this research work.

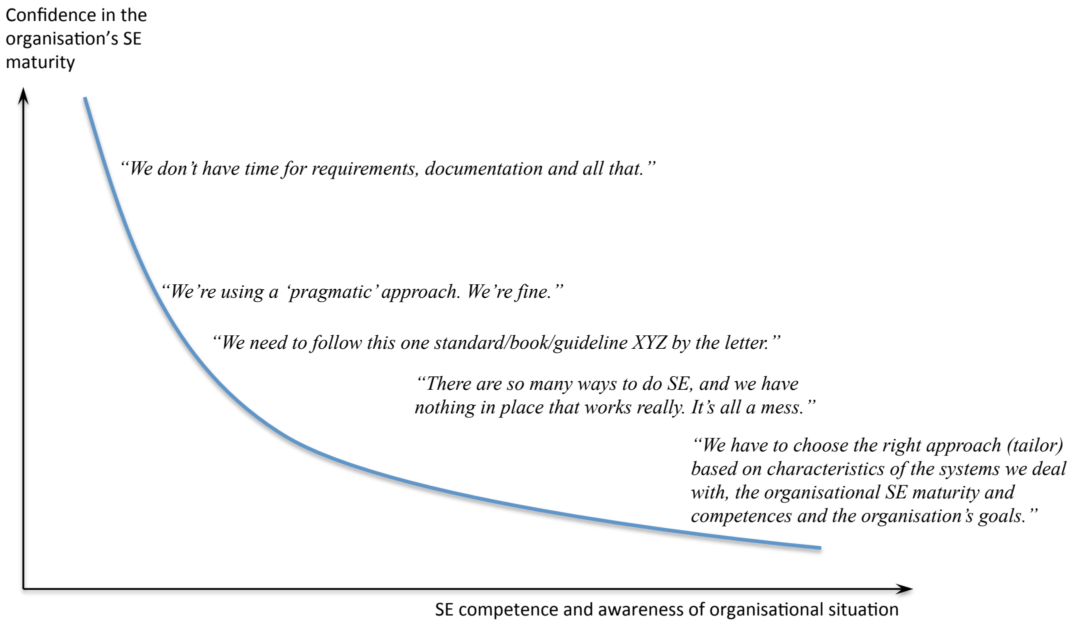

Figure 25: Typical relation between individual SE competence and awareness vs. perceived confidence in an organisation with low SE maturity

In the case of an organisation with low SE maturity, where the staff composition comprises of staff with - on average - low SE competence, this entails that a divergence develops between the actual SE maturity (which is low), and the perceived SE maturity (which is high).

The reason for this inverse relation lies in the relatively limited abilities of SE-inexperienced persons to trace technical problems back to process (architecture, integration etc.) and information management issues. For a large research facility project in an early phase, the SE process and information management issues that precedes technical work are quite abstract, and their impact on daily work and engineering practices can be difficult to anticipate. Further, in an early stage it is impossible to make detailed predictions on the technical problems that will be caused by SE shortcomings. The full causality chain leading to a problem is often simply not in the cognitive field of view, leading to over-confidence in a chosen approach. The paradoxical character of this situation for a Systems Engineering facilitator can be described this way: *A composition with factually low SE competence means that SE-related real-world problems exist, and that the SE-related reasons for these problems are* *not visible to the majority of the staff. The SE-related problems imply (as the SE expert sees) investment into improving the SE situation and the general SE competence (by education). The low visibility of SE reasons for problems however leads to a high confidence in the suitability of the factual SE approach. This high confidence discourages changes and efforts for improvements, and reinforces stagnation in the initial low SE maturity state.*

This has a serious practical consequence for the introduction of SE: An SE coordinator/ manager/ facilitator is likely lacks acceptance, and his/her role and contribution potential is not widely understood. Improvement proposals can easily be dismissed due to the prevailing high confidence in the current situation. Educational engagements are expected to require no or little effort.

In a young or quickly growing research facility organisation, this SE management problem is even aggravated by the lack of a shared mental collection of past problems that can serve as a ground stock of understandable examples with high practical relevance.

As a consequence, small-scale, situational SE-on-the-fly education is a repeatedly emerging practice. This occurs in communicative situations that often are characterised by Conceptual Reasoning (see paper B). Ideally, the SE facilitator should be able to scale SE education actions over a wide range, from discussion contributions (a few sentences) over concept explanations in focus meetings (on the scale of minutes or a few hours) to courses or workshops. In such educational actions, the SE facilitator should further be able to point out valid, meaningful benefits for the ‘student’ in order to motivate the student intrinsically to adopt the proposal. At the same time, the SE facilitator has to ensure that the spread-out SE proposals maintain an overall consistency in the large picture, for the long run.

This indicates the relevance of SE pedagogics for controlled introduction of SE methods. In fact, it can be concluded that in research facilities the educational aspect is of uttermost importance for the establishment of suitable SE practices.

For the daily work, it also indicates the relevance of understanding the communication pragmatics in Engineering Management, as presented in section 5.8.

The observation of this SE awareness paradox however also raises questions for its deeper roots. It appears to be highly dependent on the individuals’ SE competencies and familiarity with Systems Thinking for engineering purposes, which personnel brings into SE management situations. Focused, dedicated *Training in Systems Thinking* of personnel, especially in the early stages of a research facility project when the basic technical information structures are arranged may be a promising method. Such training is would also be advisable for new employees joining a project over time. A training program should cover the following points:

- enable the participants to identify the different purposes for the application of Systems Thinking as outlined in chapter 4.2 (the interest of the observer in choosing a certain perspective),

- in particular, enable the participants to distinguish a function-oriented system definition from others,
- enable the participants to understand the purposes of the different categorisations as outlined in 4.2, and understand the consequences of omitting or confusing them,
- apply the function-oriented system partitioning for their own technical domain.

Implications for general university education. Training in this sense is (to the knowledge of the author) not typical content in classical university education of students in engineering or physics. While the ‘systems’ term is of course widely used, it’s context, which is the *interest of the system observer*, remains typically somehow implied, tacit, taken for granted. And for the oftentimes domain-specific, limited, artificial examples used in teaching this works usually fine. Still, university education that claims to prepare for large, complex engineering projects (such as research facilities) should take into account the factual murkiness of human communication in highly multi-disciplinary engineering environments. Preparing students with a good understanding of the ‘system’ term, its ambiguity potential, the reasons for these ambiguities and ways to clarify such would be a beneficial addition to such education content.

Implications for Systems Engineering education. The previous paragraph is certainly applicable to SE education, too. As preparation for future system engineers, the *practical partitioning of large, complex systems* that are not obvious to ‘break down’ could play a more pronounced role. This would complement the widespread practice of using easily understandable systems for course or textbook examples. Potentially, the introduction of design patterns may be useful here, which is further outlined in chapter 6. An overview on curricula and tables of content of SE books can easily create the impression that SE is mostly about system life cycle management - conducting processes in reasonable accordance with the standards and handbooks. It is however crucial for SE facilitators to realise that any management of system life cycles can only work as good as the system partitioning is done. Without suitable system definitions, the process application is prone to run into problems. In SE education and literature, this aspect of SE application has been found to be tacitly implied as obvious or easy during the investigations of this thesis. In the engineering practice however, this posed a core problem or barrier for the successful implementation of SE in the domain.

Applicability of SE standards and SE literature. Given the prevalence of the SE awareness paradox, it might be a phenomenon that is also rooted in the applicability of SE literature and SE standards. These are necessarily written in a rather abstract way, leaving room for interpretation and misinterpretation. They are also often written in a way that on this abstract level, the ‘cogs and wheels’ grip into each other with perfect match, with no wheel being too much or not needed. Having this flavour, they provide the understanding reader with a vision of a perfect information flow resulting in an optimal system development (minor disclaimers apart). So, until the sympathetic reader meets the reality of implementing systems engineering processes.

The introduction of SE into organisations, which means, to people with limited time, cognitive preparation and little natural interest in the fascinating world of technical documentation is a subject that appears to be underrepresented in SE literature, given its relevance for establishing SE successfully. The experience of this research work as facilitator of SE indicates at least that the pedagogics of SE may at times be the major challenge for its application. It could deserve more attention in SE standards, books or conference programs.

5.6 Introduction problems of SE improvements in practice

A Systems Engineering coordinator proposes potentially unwelcome measures, such as the execution of a system definition phase, documentation thereof and system integration planning. The aversion is partially understandable on a personal level, as the addressed engineers and scientists are oftentimes more interested in discipline topics. Engineers often draw personal satisfaction from tangible system production rather than communicative products or (what appears as more) abstract project risk reduction. Also, milestone definitions of engineering projects are often defined in terms of the more obvious, easily quantifiable function achievements, which may pressure engineers into de-prioritising SE activities (e.g. analyses of qualities, maintenance procedures, cross-system workflow exploration), in spite of their relevance for operation in the long term and eventually the quality of delivered services.

Hence a situation, where a Systems Engineering coordinator intervenes in a project can be perceived as invasive by specialist engineers or scientists, and tacitly interpreted as a questioning of their competencies.

The introduction of SE improvements faces serious risks of loss of perceived legitimacy in an organisation. Mislead introductions of SE methods, techniques or information models, which do not suit the organisational maturity or system characteristics, can easily lead to a loss of reputation (informal talks about "SE is a waste of time."). This risk is quite serious in an engineering environment as the case study, where staff members from widely varying backgrounds are aggregated without a factually existing and accepted SE framework.

An SE coordinator needs to adjust the SE improvement speed to the adaptability of the changed organisation. For the SE coordinator, there is a point in self-reminders of this heuristic[28]. Slow pace of change can easily frustrate the SE coordinator, when estimating the repercussions of organisational inertia that hinders SE improvements. Such can include suboptimal system development results, unnecessary inefficiencies in the engineering processes, and also future reparations of SE practices and SE information repositories.

5.7 Systems Engineering Management barriers

In various activity threads of this research work outlined in 2.4, a recurring question was as follows: How can conscious, guided SE be made a daily practice within the factual processes of the organisation? These discussions repeatedly exposed strongly diverging views among SE facilitators, or Systems Engineering managers, on what "implementing SE" actually means. Disparities here resulted from various sources:

- SE facilitators showed significant differences in theoretical SE competences (knowledge on SE literature, standards, etc. and their correct application).
- SE facilitators showed significant differences in the anticipation of repercussions in SEM decisions. The depth of the anticipations depended often on the individuals' professional background. (See attached paper A on 'side effects').
- SE facilitators had diverging expectations or interpretations of their formal authorities.
- Conflicting themes were visible between a central organisational unit for SE coordination and discipline-oriented organisational units, as well as between different discipline-oriented organisational units.
- SE facilitators showed to quite different degrees interest or willingness in the acknowledgment and understanding of other's SE concerns.

The commonly felt urge for moving forward paired with high confidence in a chosen approach (see section 5.5) led repeatedly to SEM decisions and actions within the secured area of influence. This led to an SE landscape with an ill-coordinated, fractured, parochial character, as SE decisions were constrained to e.g. discipline-oriented parts of the organisation. Such decisions then lacked coordination with other parts of the organisation, resulting in mutual frustration.

This leads to a question regarding SEM governance:

[28] Heuristics: Guidelines, abstractions and pragmatics generated by lessons learned from experience. (Maier & Rechtin, 2009)

When and to what extent is an *authoritative, top-down approach to SEM* is viable or advisable, and when a *discursive, democratic approach to SEM* is more likely to yield beneficial results? In a sense, the observed situation lacked both. A few patterns that could be observed are elaborated in the following.

Authoritative versus democratic SEM. An authoritative approach has sometimes been called for; expressing the vague expectation that one SE-organising entity/approach could solve all SE problems in one unifying approach for all stakeholders. Such an approach however can be in risk of imposing ill-suited SE concepts. This can take the form of over-simplification as well as overly burdening with impractical, hindering duties. The need for *tailoring* may be neglected, such as for adaptation to discipline-specific approaches (consider Software Engineering vs. civil engineering) or tailoring of a specific system's engineering approaches based on criticality properties (mission critical, personnel safety, nuclear/public safety). An authoritative, top-down approach to SE management for research facilities, in particular particle accelerators, has the following challenges:

- It would require an SE management capability of the organisation to oversee and realise all SE aspects, including the different tailoring needs, and integrating them in a consistent, overarching approach.
- The overall organisational maturity would need to be at a level that allows the factual implementation of this approach (consider management support, training of discipline engineers and physicists, supporting tool availability).
- Given the relatively underdeveloped state of literature on SE for this domain, it seems likely that the application of SE in this domain isn't sufficiently well understood to allow a predominantly authoritative approach to succeed.

A discursive, democratic approach would aim at establishing a shared, overall SE management based on active inclusion of the participants, organisational learning and improvement. Such an approach is dependent on the willingness of the participants, i.e. can easily be undermined in practice. This may happen less out of malice, but driven by factors such as short-term project tick-off expectations or a culture of negligence regarding the conservation of engineering information.

The Systems of Systems Engineering (SoS) approach, which emphasizes the role of negotiation in the development of complex systems, can be seen as an attempt to realise and structure a discursive approach to SE management. The "Systems Engineering Guide for Systems of Systems" (SE Guide for SoS, 2008) emphasizes repeatedly the role of negotiations between stakeholders. The SoS approach presented in paper D has as one motivation the creation of a common frame for facilitating negotiations between the stakeholders, in this case, ESS design teams as well as in-kind contributors.

A clear answer to the question of applicability of an authoritative vs. discursive approach is probably not viable on a methodological level alone, as the success of either approach appears to be heavily influenced by the organisation's characteristics itself. Influencing factors include the pre-existing practices (organisational traditions), average SE maturity, in particular of the main SE facilitators and also the common practices within the involved disciplines (software engineering, safety engineering, civil engineering, etc.). These contingent factors are likely also a reason for the lack of discussion of this problem in the SE literature. Finally, the question touches in practice authority, and can hence involve aspects of the 'political game'.

Acting in the role of an SE facilitator. The resulting situation experienced in this research work - characterised by lack of a consistent, also tailoring-enabling facility-wide SEM approach - raised a general question for SE facilitators: In such a situation and in sight of the best interest for the project, engineering ethics and realistic expectations on positive influence, *how should the SE coordinator/manager/facilitator act*?

A simple answer could be: to support within the assigned domain (discipline area) the defined goals for deliverables. For an SE facilitator this can be questionable, if he/she is aware of shortcomings in the quality of the goal/deliverable definitions - and this awareness should be achieved by an SE facilitator. For instance, if multi-disciplinary systems and their life cycle purposes lack analysis and definition quality, should the focus not be on improving this, instead of accepting the situation? At this point, the responsibility of the SE facilitator transcends the project goal tick-off attitude and becomes a question of engineering ethics. The responsibility towards the stakeholder (in the case of research facilities, the scientific community, or wider, society at large) here suggests to promote improvements of the overall SEM situation, rather than accepting and acting within a narrow scope.

Yet the responsibility of an SE facilitator and the factual ability to initiate improvement is limited by circumstance. Local facilitation of SE, within the small scales of the assigned discipline or domain is still viable and can be beneficial to the overall situation, if done in sight of the global problems. Engaging in systems developments can possibly be done such that explanations of the global issues are included. SE improvements can be put into practice, which later can become suitable 'building blocks' in future improvements of the global situation. More concretely, the path pursued in this research work prioritised work on multi-disciplinary system definitions with the discipline engineers, including some explanations of basic SE concepts and benefits. This approach builds on the hope for spreading the Systems Thinking with discipline engineers as multipliers, enabling the application of system life cycle management on the lower and meso-level of systems. The controls and computing domain is at research facilities exceptionally suitable for this approach due to its wide spread within the overall facility, requiring communications with all kinds of technical stakeholders, and its natural relevance to the behaviour of the distributed systems.

5.8 Pragmatics of informal and semi-formal communication

Large research facility projects are traditionally characterised by a work and communication style found in university environments, such as in research groups and laboratories. This is not surprising given that the leadership staff and the main customers of research facilities have strong ties into academia. So at research facilities, one often finds people with strong attachment and focus to a very specialised discipline, who are used to communicate with people of similar mind sets, using similar ontologies and vocabulary. On the contrary, extensive controlled and formalised communication is often perceived as bureaucratic burden due to its time and effort consuming nature. Furthermore, research facility staff is commonly not well acquainted with system engineering methodology, enterprise architecture issues - it is rarely in the personal focus of interest.

This academic parentage leads - not necessarily, but in practice often - to a lack of structure in intra-organisational communication, which is reflected by the *widespread informal and semi-formal communication practices* encountered in research facility organisations. This characteristic itself can be perceived and re-acted to in different ways. By persons who have a strong favour of well-organised processes, clear hierarchies and well-defined information flows this characteristic can easily be seen as unreasonable, counter-productive and inappropriate, given the relative complexity and magnitude of public investment in large research facility projects. And probably these persons would be quite right from their perspective.

Nevertheless, another truth is that the application of a *formal structure lacking* and *domain typical engineering approach* has de facto been able to realise working particle accelerator facilities for the research communities and significant advancements in the domain. It should be noted here that the author of this thesis started out at a smaller particle accelerator facility organisation, MAX-lab, with a very low Systems Engineering maturity (even within the domain). Yet MAX-lab operated 3 synchrotron storage rings hosting 30+ experimental stations at very low costs (for an extensive description of the policy and organisational background of MAX-lab, see (Hallonsten, 2009)). Furthermore, the old MAX-lab team has achieved to design the MAX IV facility, today a world leading synchrotron light source. To avoid wrong interpretation, the lack of SE maturity also introduced its own set of problems, which initiated the author's interest in the subject. Also, in the course of the MAX IV project, the MAX-lab team expanded and indeed introduced improvements in the Systems Engineering processes, e.g. forms of Requirements Engineering.

As a conclusion from this ambiguous picture of the domain, one can take a position that clearly promotes the application of suitable, tailored SE methods, but nevertheless recognizes the traditional communication reality in the domain, and aim at its improvement. More concretely, Systems Engineering research can try to understand how the less formal, less structured communication practices enable the development of complex systems, and introduce ways of their improvement whilst maintaining their character. In the participative part of this thesis work, it was often found that the less formal communication concerned the translation of concerns between experts of different disciplines (scientists, engineers, managers). In other words, threads of reasoning were explained, usually on some conceptual level. As the observed communication has not always been as successful and efficient as could be envisioned, this motivated the further studies and reflection on improvements of less formal communication in the domain.

Semi-formal and informal communication in the practices of engineering for controls and computing systems at research facilities is the subject of the attached paper B, "Conceptual Reasoning in the Development of Particle Accelerator Control Systems". It characterises the role, use and the interrelation of viewpoints in an engineering environment in which the engineering practices commonly lack formality.

5.8.1 Reality calibrations

A recurring topic in the characterisations of the large research facility domain is the multitude of perspectives that practitioners have to deal with. This concerns the organisational roles and main processes (section 3.5), engineering and scientific disciplines, technical aspects, and variety of backgrounds on the personal level.

The world is perceived and thought through perspectives (viewpoints). Based on the perspectives that an individual, or a group of individuals with a similar mind set, has at disposal, an overall *mental picture of reality* is formed. For the carrier of such mental picture (an individual, or a group) this mental picture constitutes (the subjectively perceived) reality.

Applied to research facility projects, we can say that for engineers, scientists, etc. their available perspectives determine their mental picture of the research facility project; and this mental picture constitutes what they perceive as the *true status of the research facility project.*

This mental picture forms the base on which the carrier forms opinions, prioritises own efforts or proposes changes, so it has strong influence on the proceedings of a project. Typically, change management methods advise to target these mental pictures early on in order to initiate change in an organisation, "creating awareness" of an issue; see e.g. (Kotter, 1996) which proposes as first of eight steps to organisational change "Creating a sense of urgency".

As these mental pictures of reality are heavily dependent on the perspectives of the carriers, they are prone to differ. This includes interpretations of the technical status of an accelerator project. Hence, *disparities in the perceptions of the technical status of large particle accelerator facilities are a common phenomenon among the engineering staff*.

A certain degree of variability in these mental pictures of reality is normal, and in fact desirable in the sense that a lot of perspectives are required within the organisation to form, collectively, a reasonable good overall picture. However, a high degree of disparity can in some cases become a problem. This applies in particular to cases where dependencies between the main processes (section 3.5) are involved.

To outline an example: controls engineers working in the Facility Creation Process can be concerned about the effectiveness and reliability of the control software deployment procedure. In large facilities, this procedure needs to enable the repeatable, controlled physical deployment of thousands of files, whilst maintaining compatibility with numerous operating system, hardware and software configurations. The procedure needs to be sufficiently flexible to address the technically highly diverse controls technology, sufficiently reliable to enable achieving the operational uptime goals, and sufficiently efficient to use, given the realistic staff size and competences. The deployment configurations need to be manageable by an appropriate toolset.

Potential concerns of controls engineers working in the Facility Creation Process can be described as disparities of the reality pictures held by them and other parties. E.g. the controls engineers may consider the status of the procedure implementation as insufficient. Further, the controls engineers may consider their superior managers executing the Top Management Process as insufficiently aware of relevance and difficulties regarding the control software deployment procedure. For this, statements such as “Management doesn’t know about the reality, they don’t understand that ...” are indicative. The controls engineers may also consider the supporting toolsets for the procedure as insufficient, e.g. not efficiently scalable for the practical workflows in the Facility Creation Process. They could explain this by the lack of understanding of these workflows by the in-house tool providers, who are often software engineers working in the Generic Development Process.

These disparities in reality perception could be further explained from the perspectives of the other parties, explaining their priorities, delimitations of efforts etc. The important point is here that these disparities can be hard to catch, as in this example of the control software deployment procedure: It involves supporting systems for storing and distributing files, etc. which are typical primary entities in the perspectives of software developers, but as a procedure also goes beyond the design of the singular supporting system. It involves workflows, executed by the group of controls engineers, who form in other perspectives judgements on the effectiveness and reliability of these workflows. A control software deployment procedure also has to accommodate expectations on the operational efficiency of the organisation in managerial perspectives, e.g. regarding the required technical in-house competences and availability. These perspectives may differ in their prioritisation and evaluation.

A control software deployment procedure requires systems that are certainly part of the 'created facility', but its contribution to the facility's goals (enabling certain types of research) is quite distant. The implementation difficulty of a solution with *long-term efficiency* can be highly opaque to most staff at a research facility.

Unearthing such disparities in the mental pictures of various stakeholders, making the problems explicit, tangible, and eventually process-able by the organisation, is a matter of Systems Engineering Management, too. The elusive character of the example given (hopefully) indicates the difficulty of identifying it, addressing it appropriately, and outlines the need of calibration of the reality pictures of involved personnel. The difficulties discussed here have been related to the overall characterisation of research facilities, and it is reasonable to assume they are domain-typical. This conclusion is also a common reflection in discussions with practitioners from various sides, be it engineers, experimental scientists, accelerator physicists, or managers.

A Systems Engineering framework for the research facility domain thus should be evaluated by the guidance it provides for analysis and treatment of disparities in the mental pictures of reality among stakeholders. To an extent, this is of course the purpose of classical requirements engineering. However, proposals for requirements engineering typically start commonly, at least implicitly, with an early conception of a given system. The characteristics of main processes, stakeholder backgrounds, etc. at large research facilities, as well as the impressions of the participative work for this thesis, indicate that the analysis and treatment of the outlined disparities of reality pictures deserve consideration in their own right.

5.8.2 Understanding the operation of a research facility

The extent of first-hand experience in the operation of a research facility can be quite varying, usually depending on the organisation's history. As for the two examples encountered in this thesis work: at MAX IV a large fraction, if not the majority, of the staff had experience in operation of a facility of the same family as the new MAX IV synchrotron light source. In contrast, at the ESS only a limited number of scientists and engineers have had first-hand experience in the operation of an accelerator facility. Among these, not all have been at 'user facilities', which are different from machines where the accelerator and the experiment are the same (such as at the LHC). Such staff may have been primarily concerned with limited, specialised engineering activities, and may not be inclined to engage in over-arching integration and overview-generating activities.

For a SE manager, such a situation poses the challenge of stipulating the analysis of the operation and maintenance of high-level systems, and the analysis of operational workflows that involve systems created by separate teams.

SE techniques that increase awareness of higher-level system issues and problems include e.g. customer key driver graphs (for an example see Figure 16) for relating basic key drivers of stakeholders to applications (procedures, workflows), system functionality and system design. A way to explore the user experience is the elaboration of user stories, see e.g. (Muller, 2012) p. 95f. A fictional example is given by Figure 6, outlining what a user story could look like that describes an instance of the famous "2 a.m. intervention" of an operator caused by broken equipment. A main point of this short story is the exploration of various information systems in order to identify use cases and interoperability demands in order to smoothen the operator's workflow.

Operator story: Mick, ESS operator, sits in the ESS control room, Tuesday 2am. He sees proton beam switch-off and an alarm popping up: 'MEBT-01:CMS-80 is unavailable'. Mick consults the synoptic GUI and understands this refers to an electromagnet system in the accelerator. He identifies that the MEBT beam steering crate (EPICS IOC) sees no magnet power supply signal.
2.05: Mick consults the system trouble-shooting procedures in the PLM and restarts the IOC, to no success.
2:15: Mick calls the the ICS on-guard support engineer, Jon, who drives to the ESS.
3.05: Jon consults the documentation (PLM) and performs checks on the IOC. He suspects a power supply's embedded controller malfunction.
3.40: Mick calls the power supply engineer, Rob, who drives to the ESS.
4.15: Rob exchanges the power supply controller and restarts the magnet system.
4.55: Mick restores the beam parameters, and beam is available at 5.10. Mick documents the incident in the ESS electronic logbook and in the maintenance, repair and overhaul system (5.30).

Figure 26: Example of a user story

SE methods or techniques that aim to explore operational aspects should have a low understandability threshold in order to find acceptance among system users.

5.9 State of the research field

Among the - more programmatic - goals of this research effort has been listed the characterization of SE for Research Facilities as a research field. While in aspects always comparable to other fields, it is the combination of characteristics that give a unique flavour to this field. After some years and academic efforts in pursuit of these goals, the author of this thesis considers it appropriate to finalize the conclusions chapter with some remarks on the state of the Systems Engineering for Research Facilities as a research field.

The accelerator based research facility domain constitutes a sector ("industry") that has a yearly turnover in the 1-2 digit billion Euro range, mostly public funding. It constitutes a research enabler and efficiency factor for a multitude of natural sciences, engineering sciences, medicine and other fields. Compared to the relevance of the produced systems for society at large, the research field appears to the author as surprisingly rudimentarily understood, which is reflected in the encountered practices.

The reasons for this are a conglomerate of social and educational facts of life, such as staff composition, typical education and lack of awareness of domain aspects of SE at research facilities. Internal engineers and scientists usually lack SE methodology oversight; external SE experts have difficulties in understanding the particular properties of SE application in the research facility domain.

The future of the research field is difficult to forecast. The lack of conscious, dedicated practitioners and miniscule number among these with research interests will likely leave it a field that is dependent on external impulses (e.g. transferable SE techniques, methodologies and tools from other sectors and industries). This always carries the risk of insufficiently suitable adaptations. An encompassing body of knowledge, as proposed in the research goals, could already profit much from a basic collaboration of a handful of practitioners worldwide, if such ever convene in this spirit. Much of the field's future is up to chance and personal engagement.

6 Future Research and Conclusions

While progress towards the over-arching research goals could be achieved, this work also left other areas unexplored and made new questions visible. This chapter suggests topics with potential for future research in the domain. As in the whole thesis, SE research for future topics of interest will be highlighted from quite different angles.

An SE framework for the entirety of a research facility. For the large research facility projects as a whole, the efficient and consistent application of SE on all levels is still an issue to be explored. The openSE framework (Bonnal, 2016) proposes an SE/project management approach on the overall project level, however an approach focusing primarily on highest, practically directorate level runs into risks of being disconnected to the meso- and low system levels and corresponding SE practices and needs. This thesis can be seen as a partial contribution to the overall SE application question for research facilities. Based on the experiences from this PhD work, a truly encompassing SE framework for the particle accelerator/research facility domain however should also include, in the eyes of the author, practically useful *tailoring and SE management advice* based on

- discipline aspects (software development, control system development, accelerator technology development, civil engineering, etc.) (see 4.6),
- system properties (simple/complex/system-of-system-complexity, degrees of criticality) (see 4.7, 4.8),
- organisational SE maturity, e.g. in regard to information management, life cycle process management, SE methods successfully applied and supported by tools (e.g. MBSE) (see 4.4, 4.5, 4.9),
- individual SE competences (see 5.5)

as any of these areas can critically impact the success of SE application.

Consequently relevant research questions include the following:
What should an encompassing SE framework for research facilities provide?
How can SE Management be successfully achieved based on the framework, on all levels?
What are SE successful strategies for tailoring towards disciplines, system characteristics, organisational and staff characteristics?
How can a consistent approach be achieved, while enabling domain specific adjustments?

To pick up on a recurrent topic of relevance here,
How can Systems of Systems Engineering (SoS) be applied and contribute to the SE Management of a large research facility?

Systems Thinking and Architecture. Diversified architectural descriptions are required from various viewpoints, but they need a common ground in order to enable successful, efficient communication on various levels:

- among the stakeholders on 'why' and 'what' it is they intend to construct,
- in architectural models of the facility and of the systems developed for the facility,
- among the tools that process and link the content of the architectural models.

A relevant research question becomes the following:
How should Systems Thinking be applied in the various engineering activities at research facilities, e.g. for partitioning and system definitions?

It has been established that research facilities exhibit a significant degree of uniqueness, yet it is also clear that on a conceptual level many of the utilised systems have commonalities in their architecture. Still, these commonalities reside primarily in expert knowledge, not in formalised, easily accessible forms. In software engineering, the application of design patterns (Gamma, 1994) has been a powerful way of teaching and communicating architectural concepts with a wide application range. Using design patterns might be a way to guide domain engineers and scientists in the application of Systems Thinking, leading to the research question:

Can the concept of ***design patterns*** *in software engineering be transferred to the accelerator research facility domain in order to guide SE appliers in the appropriate application of Systems Thinking?*

In the case of a reasonably positive answer to the previous question, this leads to the follow-up question:

How can the application of Model Based Systems Engineering support the application of design patterns in SE at research facilities? What methods, notations or tools for MBSE are suitable in what way?

SE application barriers. At various places in this thesis, especially in section 5.7, the barriers to Systems Engineering application have been described and remedies to overcome these barriers have been proposed. These barriers have often been related to 'soft' factors, including understandability of SE, competences, culture, interests of involved personnel, etc. A comprehensive analysis and summary of domain-typical SE barriers, including a research approach description on barrier identification, may be useful to make the SE problems in this domain visible, and improve the potential for finding solutions.

How can SE barriers in this domain systematically be identified?
How can successful strategies be developed and implemented for overcoming these barriers?

SE education. SE education has been identified as one of the major enablers or barriers to successful SE introduction in the domain (see 5.5), depending on how successful SE education is performed. This raises the question on the appropriate pedagogical approach in the various constellations where SE facilitators need to engage in education. These situations range from SE-teaching on-the-fly to courses or the provision of educational material or other helping artefacts. Consistently underperforming SE education efforts are furthermore pose the risk of undermining the perceived legitimacy of SE among the engineers and scientists. Relevant research questions include the following:

How can SE successfully been taught in research facility environments, considering their typical project conditions?
What are typical reasons for underperforming SE education efforts, and how can this be mitigated?

The role of the SE facilitator. The role of a dedicated SE manager, coordinator or in other form dedicated SE implementer is at research facilities relatively new and not overly common. It can be attributed to in-house staff or external consultants. For such personnel, few guiding literature exists on how to execute this role successfully. Consequently; guidance would be useful from answers to the research question:

How should a SE facilitator act in order to fulfil his/her role successfully?

Resource estimation and SE. The impact of SE on resource consumption (time, cost) in the domain is very hard to estimate, and practically 'invisible' to many practitioners. This poses a continuous legitimacy challenge for the SE facilitator, which concretises in repeated justification discussions until a point is reached, where either a sufficient intuitive understanding is reached on among both SE 'student' and SE facilitator, or one side caves in. To promote the perceived legitimacy of SE among other scientists and engineers, and to avoid or shorten SE discussions, it would be desirable to have a time-efficient way of demonstrating the resource related benefits of SE application, in particular in terms of time and cost.

Most convincing for this purpose is <u>not</u> the citation of literature or abstract examples, but the demonstration at the systems at hand. Such a method could also help the project management to estimate what a reasonable amount of resources is for Systems Engineering.

How can the resource impact of SE application for a given system development be estimated quantitatively?

SoS Engineering in the particle accelerator domain. Standardisation for SoS Engineering is an on-going objective of the SE community. An overview on standardisation efforts in the ISO and IEC domain (Dahmann & Roedler, 2016) has identified some apparent gaps in the current standard landscape, e.g. multiple levelling of SoS. High reliability, high availability or functional safety as SoS areas are not explicitly mentioned, but one could consider these as relevant SoS area aspects and relate to relevant safety standards such as (IEC 61511, 2004) or the (IEC 61508, 2010) standard family. For the validation of standardisation efforts in regard to acknowledged or directed SoS (SE Guide for SoS, 2008), particle accelerator based research facilities may pose uncommon yet still suitable case studies as socio-technical cyber-physical systems. Aspects of safety and security for such systems are being raised as prioritised areas for research on cyber-physical systems (CPSoS, 2016) (CyPhERS, 2014). At the same time, the research facility construction community may profit from the insights of the SoS Engineering field. Further research questions in this area can be envisioned, following the example described in paper D:

What emergent properties of research facilities (like high reliability and availability) can benefit from being the focal point for applying SoS Engineering? Could SoS Engineering approaches be suitable for research facilities in regards to

- *network infrastructures, data security and intrusion security,*
- *energy and mass flow systems,*
- *encompassing management of visiting researchers (experiment planning, preparation, execution, data acquisition, processing, storage and evaluation)?*

How could several SoS within an over-arching SoS be managed? Are there synergies?

Systems Engineering Research and its epistemological foundation. Few scientific disciplines interact in the theory and practice with so many others as Systems Engineering; the SE researcher, facilitator and practitioner touches on all kinds of engineering sciences, natural sciences; social and psychological sciences; legal and economic fields.

For an SE researcher, this exposure can raise questions on validity beyond the own research and render a comparison interesting regarding validity in these different fields. The discipline that traditionally deals with the question of what qualifies as scientifically valid knowledge is philosophy of science. For gaining a better understanding of the epistemological basis of Systems Engineering - and possibly strengthen it - it may be interesting to relate SE research to other contemporary, or at least recent, trends in this field. As godparent for such engagement one could see Peter Checkland, who draws some notable relations to philosophical works in (Checkland, 1999). The subject has been explored by Lipton and other in (Philosophy of Engineering, 2010). Some questions of interest may include:

What are recent trends in philosophy of science that may be summarised as "philosophy of engineering"?

How would Systems Engineering be described in by the use of the Theory of Communicative Systems (Luhmann, 1984)*?*[29]

How does Systems Engineering Research as a field that includes studies of communication in writing or speech, human activity processes, organisational or institutional contexts, epistemically relate to discourse analysis approaches (Keller, 2011)*?*

Does the advent of SoS Engineering in the SE discipline constitute a 'paradigm change' (Kuhn, 1962)*, considering its renewal of fundamental concepts and assumptions, and if so, what characterizes the paradigms?*

Are there meaningful parallels between the SoS Engineering approach, which embraces viewpoint multiplicity of stakeholders, with, for example, the multiplicity of 'grand' narratives in theories of postmodern knowledge (Lyotard, 1984) *and their intersection?*

Information management in the controls and computing systems domain at particle accelerator research facilities. In the controls and computing systems domain, *information models* have to be introduced which structure information for facility integration on the tool level. These encompass e.g. the configuration data for the facility and the representation of its components and systems in the facility control software. To various extents, this information is produced and consumed by humans, semi-automatically or automatically. Such information models usually tie into the SCADA technology applied (typically EPICS, TANGO) and also depend on decisions made within the facility.

[29] An extended description of this question in the context of SE barrier identification can be found in (Friedrich, 2013).

It might be useful to survey and analyse systematically the information models in the controls and computing systems domain at particle accelerators across a number of facilities. This may result in the identification of typical *information patterns* used in different places, their evaluations, and allow comparisons with other industrial sectors. Building on such analyses, it might be useful to elaborate a reference model for typical and useful information patterns in the domain. Such a reference model would be helpful for standardisations in domain-specific software development and for avoiding suboptimal developments, and guide in the development of software services (data archiving and analysis tools, alarm applications, configuration, maintenance and operation tools, etc.).

At the moment, there is a notable degree of collaboration between accelerator facilities that is already touching on this, but this is typically centred on software/code that has been developed in one place and then migrates to other facilities. The emphasis in the proposed approach would be the identification of information models and related needs, validated by several facilities, and then to base developments on these.

Can common information patterns for particle accelerator SCADA technology be identified, and what do these information patterns represent?

How can information patterns for particle accelerator SCADA technology be used?

Technology, innovation and standardisation management. Control and computing systems divisions in large research facilities have to manage numerous technology in-house standards over the lifetime of a research facility. This encompasses in-house standardisation decisions (commercial systems, in-house developments and mixtures), enforcement (by hard or soft means), integration into the existing in-house standard portfolio, maintenance (consecutive adaptation), and decommissioning including the physical phasing out of legacy. These concerns can in practice be competing with short-term goals. Research on successful strategies on technology management may improve the effectiveness of controls and computing systems divisions in this domain.

What are the challenges regarding technology, innovation and standardisation management in the controls and computing systems at research facilities?

What strategies, concepts or methods can be applied to cope with these challenges in sustainable ways over the typical life times of research facilities?

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In the light of the rarity of suitable study objects and their long life cycles, it becomes apparent that the goal of establishing an encompassing body of knowledge for SE at research facilities has to be seen as a long-term goal of the research facility construction community, spanning over different facilities and facility life cycle periods. It is the hope of the author that this thesis can be a stepping-stone towards this goal, by contributing some pieces of practical insights, by outlining a viable methodological frame, and by portraying the research goal, its motivation and its benefits in the larger picture.

8 Bibliography

Abduction. (2011). Stanford Encyclopaedia of Philosophy. https://plato.stanford.edu/entries/abduction/ Retrieved Feb. 2017.

Baron, H. (2015). *The Oil & Gas Engineering Guide.* Editions TECHNIP.

Beck, K., Grenning, J., & Martin, R. C. (2001). *Manifesto for Agile Software Development.* ... Retrieved from http://agilemanifesto.org (Feb. 2016).

Blessing, L. T., & Chakrabati, A. (2009). *DRM, a Design Research Methodology.* London: Springer. ISBN 978-1-84882-586-4.

Boardman, J., & Sauser, B. *Systems Thinking.* CRC Press. Taylor&Francis Group. ISBN 1-4200-5491-0.

Bonnal, P. e. (2016). *openSE: A Systems Engineering framework particularly suited to particle accelerator studies and development projects.* IPAC 2016, Busan, Korea. Conference proceedings.

Checkland, P. (1999). *Systems Thinking, Systems Practice: Includes a 30 Year Retrospective.* Wiley. ISBN-13: 978-0471986065.

CyPhERS Cyber-Physical European Roadmap & Strategy. Research Agenda and Recommendations for Action. (2014). CyPhERS - Cyber-Physical European Roadmap and Strategy (FP7 ICT programme). http://cyphers.eu/sites/default/files/d6.1+2-report.pdf Retrieved Feb. 2017.

Dahmann, J., & Roedler, G. (2016). *Systems of Systems Engineering Standards.* Insight journal. vol. 19, Issue 3, Pages 23–26. Oct 2016. .

Davison, R. M., Martinsons, M. G., & Kock, N. (2004). *Principles of Canonical Action Research.* information systems journal. vol. 14, issue 1, p.65-86.

Davison, R. M., Martinsons, M. G., & Ou, C. X. (2012). *The Roles of Theory in Canonical Action Research.* MIS Quarterly, (36:3) pp. 763-786.

Douglass, B. P. (2016). *Agile Systems Engineering.* Morgan Kaufmann Elsevier. ISBN 978-0-12-802120-0.

Fermi, E., & Lamberti, A. (Eds.). *Advances in Systems Engineering Research.* Nova Science. ISBN 978-1-62948-310-8.

Friedrich, T. (2013). *Engineering Aspects of Computing Systems for Accelerator based Light Sources* (Licentiate thesis, monograph ed.).

Stockholm: Royal Institute of Technology KTH, School of Industrial Engineering and Management (ITM), Department of Machine Design.

Gamma, E. e. (1994). *Design Patterns. Elements of Reusable Object-Oriented Software.* Addison-Wesley. ISBN-10: 0201633612.

Glaserfeld, E. (1997). *Radikaler Konstruktivismus: Ideen Ergebnisse, Probleme.* Suhrkamp wissenschaft. (German) ISBN 3-518-58230-5.

Grady, J. O. *System Integration.* CRC Press, Taylor and Francis Group. ISBN 9780849378317.

Haberfellner, R. (2015). *Systems Engineering. Grundlagen und Anwendung.* orell füssli Verlag. ISBN 978-3-280-04068-3.

Haberfellner, R. (2002). *Systems Engineering. Methodik und Praxis.* Verlag Industrielle Organisation. Zürich, 11te Auflage. ISBN 3-85743-998-X.

Hallonsten, O. (2009). *Small science on big machines. Politics and practices of synchrotron radiation laboratories.* Research Policy Institute, Lund University, Sweden. PhD thesis. ISBN 978-91-628-7790-3.

Herr, K., & Anderson, G. L. (2015). *The Action Research Dissertation.* Sage publications. ISBN 978-1-4833+3310+6.

Humble, J., & Farley, D. (2010). *Continuous Delivery: Reliable Software Releases Through Build, Test and Deployment Automation.* Addison-Wesley. ISBN 978-0-321-60191-9.

IAEA Safety Standards - The Management System for Facilities and Activities. (2006). International Atomic Energy Agency.

IEC 61508: Functional safety of electrical/electronic/programmable electronic safety-related systems. Part 1-7. (2010).

IEC 61511: Functional safety - Safety instrumented systems for the process industry sector. (2004).

ISO/IEC 42010: Systems and software engineering - Architecture description. (2011).

ISO/IEC/IEEE 15288: Systems and software engineering - Systems life cycle processes. (2015).

Jenny, J. (2010). *Modern Methods of Systems Engineering.* Amazon Distribution.

Karban, R., Hauber, R., & Weilkiens, T. (2015). *MBSE in Telescope Modeling.* INSIGHT, vol 12, issue 4.

Keller, R. (2011). *The Sociology of Knowledge Approach to Discourse.* Human Studies 34:43–65. doi:10.1007/s10746-011-9175-z .

Kim, G., Behr, K., & Spafford, G. (2014). *The Phoenix Project: A Novel about IT, DevOps, and Helping Your Business Win.* IT Revolution Press. ISBN 978-0-9882625-0-8.

Kim, G., Humble,, J., Debois, P., & Willis, J. (2016). *The DevOps Handbook.* IT Revolution Press. ISBN 978-1942788003.

Korhonen, T. e. (2015). *Status of the European Spallation Soure Control System.* ICALEPCS 2015, Melbourne, Australia. Conference Proceedings. .

Kossiakoff, A., Sweet, W. N., Seymour, J. S., & Biemer, M. S. (2011). *Systems Engineering Principles and Practices.* John Wiley & Sons. ISBN 978-0-470-40548-2.

Kotter, J. P. (1996). *Leading Change.* Boston: Harvard Business School Press.

Kuhn, T. S. (1962). *The Structure of Scientific Revolutions.* University of Chicago Press. ISBN 9780226458113.

Langford, G. O. (2012). *Engineering Systems Integration. Theory, Metrics and Methods.* CRC Press.

Lauesen, S. (2002). *Software Requirements. Styles and Techniques.* Addison-Wesley. ISBN 0-201-74570-4.

Lawson, H. '. (2010). *A Journey Through the Systems Landscape.* College Publications. ISBN 9-781848-900103.

Lencioni, P. *The Five Disfunctions of a Team. A Leadership Fable.* Jossey-Bass. Wiley. ISBN 978-0-7879-6075-9.

Lewin, K. (1946). *Action Research and Minority Problems.* Journal of Social Issues, vol 2, issue 4, p. 34-46.

Lipton, P. (2004). *Inference to the Best Explanation* (Second ed.). Routledge, Taylor&Francis Group. ISBN 0-415-24203-7.

Luhmann, N. (1984). *Soziale Systeme. Grundriss einer allgemeinen Theorie.* . Suhrkamp. ISBN: 978-3-518-28266-3. (English translation: Social Systems, Stanford: Stanford University Press, 1995).

Luzeaux, D., & Ruault, J.-R. (2010). *Systems of Systems.* ISTE Ltd, John Wiley & Sons Inc. ISBN 9781848211643.

Lyotard, J.-F. (1984). *The Postmodern Condition: A Report on Knowledge.* Manchester University Press. ISBN 0-7190-1450-6. (Frz 1979).

Maier, M. W. (1998). *Architecting Principles for Systems-of-Systems.* Systems Engineering. John Wiley & Sons. 1 (4): 267-284.

Maier, M. W., & Rechtin, E. (2009). *The Art of Systems Architecting* (3rd ed.). CRC Press, Taylor&Francis Group.

MAX-lab. (2010). *Detailed Design Report. The MAX IV Facility.* MAX-lab (www.maxlab.lu.se), today MAX IV Laboratory.

Muller, G. (2012). *Systems Architecting - A Business Perspective.* CRC Press, Taylor&Francis Group. ISBN 9781439847626.

NASA. (2007). *Systems Engineering Handbook.* Washington, D.C.: National Aeronautics and Space Administration. NASA/SP-2007-6105 Rev1.

Norris, N. (1997). *Error, Bias and Validity in Qualitative Research.* Educational Action Research, vol 5, no.1.

OED Online. (2016). Oxford University Press. Retrieved Feb 2017.

Philosophy of Engineering. (2010). The Royal Academy of Engineering. ISBN 1-903496-38-1.

Pidd, M. (Ed.). (2004). *Systems modelling: Theory and Practice.* John Wiley & Sons, Ltd. ISBN 0-470-86731-0.

Proposal of a European Research and Innovation Agenda on Cyber-Physical Systems of Systems 2016-2025. (2016). CPSoS Project (FP7 ICT programme). http://www.cpsos.eu/roadmap/ Retrieved Feb 2017.

Scientific Realism. (2011). Stanford Encyclopaedia of Philosophy. https://plato.stanford.edu/entries/scientific-realism/ Retrieved Feb. 2017.

SEBoK authors. (2016). *Guide to the Systems Engineering Body of Knowledge (SEBoK).* Hoboken, NJ: The Trustees of the Stevens Institute of Technology.

Senge, P., Kleiner, A., Roberts, C., Ross, R. B., & Smith, B. J. (1994). *The Fifth Discipline Fieldbook. Strategies and Tools for Building a Learning Organization.* Currency Doubleday. ISBN 0-385-47256-0.

Sharp, H., & Robinson, H. (2004). *An Ethnographical Study of XP Practice.* Empirical Software Engineering, vol. 9: 353-375.

Sommerville, I. (2007). *Software Engineering* (8th ed.). Addison-Wesley. ISBN 0-321-313-79-8.

Stevens, R., Brook, P., Jackson, K., & Arnold, S. (1998). *Systems Engineering. Coping with Complexity.* Pearson Education Ltd. ISBN 0-13-095085-8.

Sutherland, J., & Schwaber, K. (2013). *Scrum Guides.* Retrieved from http://www.scrumguides.org (Feb 2016).

Systems Engineering Guide for Systems of Systems. (2008). Office of the Deputy Under Secretary of Defense for Acquisition and Technology, Systems and Software Engineering.Version 1.0 Washington, DC: ODUSD (A&T)SSE.

Systems Engineering Handbook. A guide for system life cycle processes and activities. (Fourth edition ed.). (2015). International Council on Systems Engineering (INCOSE).

Törngren, M. e. (2014). *Integrating viewpoints in the development of mechatronic products.* (T. e. al., Ed.) Mechatronics, vol 24, issue 7. http://dx.doi.org/10.1016/j.mechatronics.2013.11.013.

Weilkiens, T. (2007). *Systems Engineering with SysML/UML. Modeling, Analysis, Design.* Morgan Kaufmann Publishers. ISBN 978-0-12-374274-2.