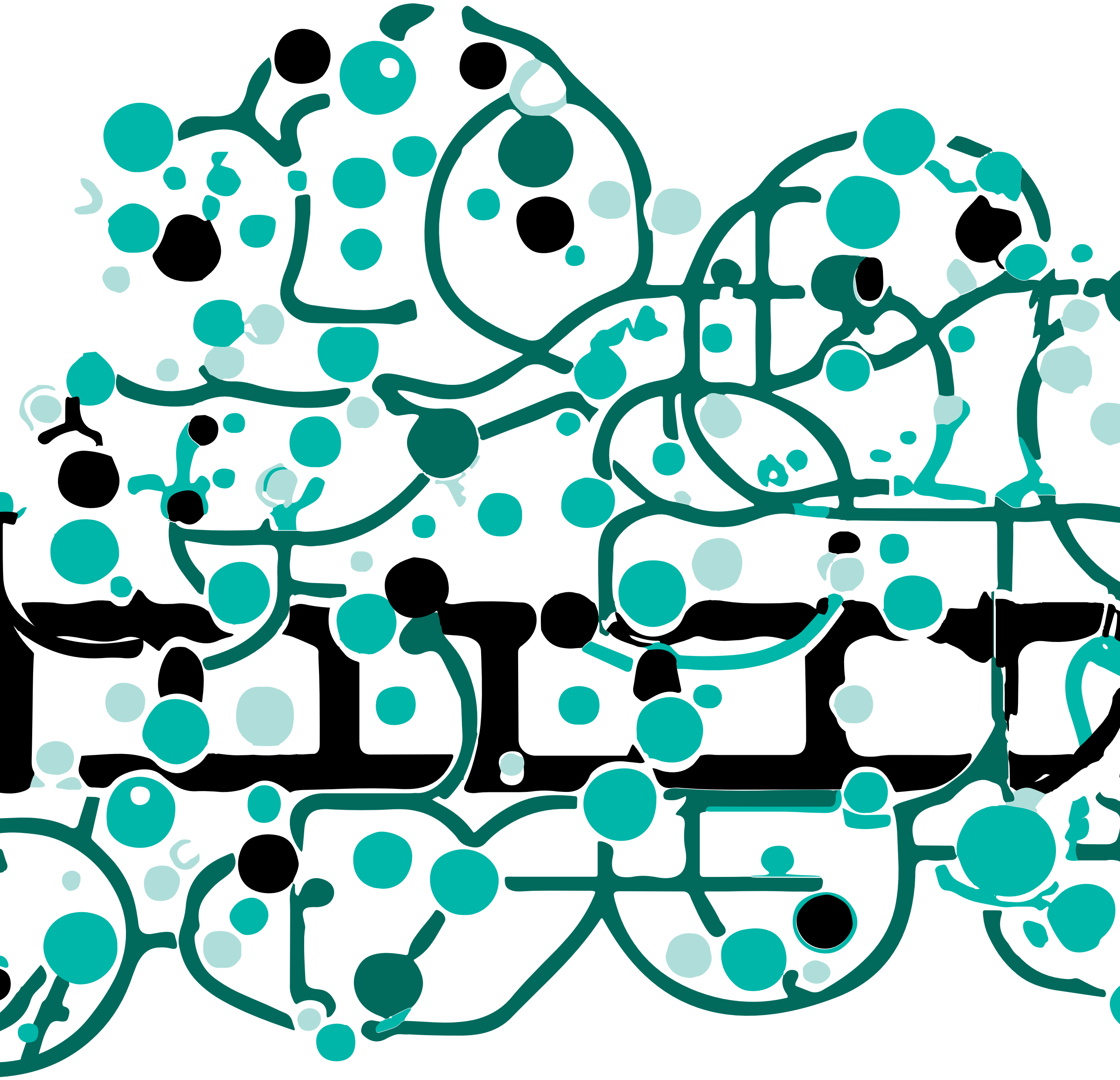
ENABLING INTER-ORGANIZATIONAL CHANGE INTEGRATION IN SOCIOTECHNICAL SYSTEMS:

SYSTEMS THINKING APPLIED IN THE DUTCH RAILWAY SYSTEM



Merishna Ramtahalsing

ENABLING INTER-ORGANIZATIONAL CHANGE INTEGRATION IN SOCIOTECHNICAL SYSTEMS:

SYSTEMS THINKING APPLIED IN THE DUTCH RAILWAY SYSTEM

Merishna Merilyn Ramtahalsing

ENABLING INTER-ORGANIZATIONAL CHANGE INTEGRATION IN SOCIOTECHNICAL SYSTEMS:

SYSTEMS THINKING APPLIED IN THE DUTCH RAILWAY SYSTEM

DISSERTATION

to obtain

the degree of doctor at the University of Twente,

on the authority of the rector magnificus,

prof.dr.ir. A. Veldkamp,

on account of the decision of the Doctorate Board

to be publicly defended

on Thursday the 26th of October 2023 at 16.45 hours

by

Merishna Merilyn Ramtahalsing

born on the 1st of November, 1993

in Paramaribo, Suriname

This dissertation has been approved by:

Promotors

prof.dr.ir. L.A.M. van Dongen
dr. A.J.J. Braaksma

Co-promotor

dr.ir. W. Haanstra

Cover design: AI generated by DALL·E 2, edited by Alexander Jansen

Printed by: Ipskamp Printing

Lay-out: Merishna Ramtahalsing and Alexander Jansen

ISBN (print): 978-90-365-5829-7

ISBN (digital): 978-90-365-5830-3

URL: https://doi.org/10.3990/1.9789036558303

Graduation Committee:

Chair / secretary:	prof.dr.ir. H.F.J.M. Koopman
Promotors:	prof.dr.ir. L.A.M. van Dongen University of Twente, ET, Asset Management & Maintenance Engineering
	dr. A.J.J. Braaksma University of Twente, ET, Asset Management & Maintenance Engineering
Co-promotor:	dr.ir. W. Haanstra University of Twente, ET, Asset Management & Maintenance Engineering
Committee Members:	prof.dr.ir. G.M. Bonnema University of Twente, ET, Systems Engineering & Multidisciplinary Design
	prof.dr.ir. J.I.M. Halman University of Twente, ET, Market Dynamics
	prof.dr.ir. J. Henseler University of Twente, ET, Product–Market Relations
	prof.dr.ir. R.P.B.J. Dollevoet Delft University of Technology
	prof.dr. N. Olsson Norwegian University of Science and Technology
	prof.mr.dr.ir. S.C. Santema Delft University of Technology

“If you change the way you look at things, the things you look at change.”

-Wayne Dyer

Table of Contents

Summary (English)

People, organizations, and societies around the globe rely on the proper functioning of numerous systems to sustain day-to-day life as we know it. These include for example power grids, water supply, internet, and transportation systems. Oftentimes, the existence of these systems is taken for granted, unless something unexpected happens, such as train delays or power outages.

In such systems, like, for example, the transportation system, there is a constant demand for increased capacity and efficiency, whether by air, road, sea, or rail. In railway systems, there is a continuous request for improvement, enabling faster, safer, more reliable, and higher-capacity transport, preferably at low costs. In order to achieve these improvements, changes of various kinds, scales, and complexities are constantly emerging, all of which need to be integrated into the existing railway system context in order to attain the desired system-level qualities.

Despite the apparent advantages of these developments, countless examples indicate that such integration does not always go as smoothly as expected, sometimes resulting in financial losses, decreased productivity, damaged reputation, or even casualties.

One reason such errors occur is related to the context in which such changes are to be integrated. Railway systems are sociotechnical and inter-organizational in nature and thus characterized by multiple domains such as processes, personnel, technical systems, rules and regulations, with numerous interfaces and interdependencies between those. Additionally, involved organizations and inherent business units, employees, and experts often have diverse views, skills, responsibilities, objectives, and interests, and information and knowledge are dispersed among them. As such, it is challenging to have a mutual holistic view of the railway system and the changes to be integrated in this context. In short, this indicates that there appears to be a limit to the improvements that can be achieved if included actors cannot work together effectively.

In addition to this, technological advances are also increasing in size, in complexity, and in their interdependence with other systems that have preceded them. As such, the foreseen changes and the projects that strive to realize them are increasing in scope, and consequently in systemic impacts. Designing a change to one part of the system without considering how this might affect or require a change in the other aspects of the system will limit effectiveness.

A way to overcome these challenges is by applying systems thinking: understanding how different components of a system are interconnected and how changes to one component could affect the entire system. However, systems thinking appears not to be as self-evidently applied in practice. There seems to be a gap in translating theoretical methods to pragmatic practices in inter-organizational sociotechnical railway systems.

In the Dutch railway system, advances like automatic train operation are to be integrated, the impacts of which tend to affect multiple organizations, often responsible for different aspects of the system, such as infrastructure, operations, and maintenance. These need to effectively work together to achieve this integration. As such, this dissertation aims to answer the research question:

How can systems thinking support inter-organizational change integration in the Dutch railway system?

Next to a scientific contribution, this dissertation also aims to make an empirical contribution and provide pragmatic insights and tools to practitioners. To accomplish this, this dissertation uses design science research, which is reflected in the research topics associated with this dissertation.

Firstly, we aim to understand the integration challenges and associated needs encountered in the Dutch railway system. The results show that in the event of a change, the investigated integration challenges mainly concern: (1) effectively determining what is being changed, (2) the scope and impacts of this change, and (3) how the change would fit within the existing railway system context, all of which pointed towards systems thinking.

Secondly, we aim to identify to what extent well-known systems thinking practices currently support integration in the Dutch railway system. By testing postulates and case study research, several factors emerged: a clear goal, inclusion of multiple experts, synthesizing expertise to obtain mutual integral insights, and focus on managing interfaces. Moreover, the research shows that hard systems thinking approaches which are prevalent in the railway context, do not sufficiently accommodate the various perceptions of reality and the needs of all actors to be included in inter-organizational change integration.

Thirdly, the abovementioned factors form the basis of the designed artifacts, which apply systems thinking in the complex sociotechnical railway system: (1) to facilitate scope definition enabling inter-organizational change integration; (2) to changes in system environments with external influences like climate change; and (3) to aid interface management in inter-organizational projects.

This led to the iterative design and development of three respective artifacts, Management of Sociotechnical and Inter-organizational Change Integration (MOSAIC) analysis, a Climate Change Adaptation (CCA) framework, and a proposed Interface Management (IM) process.

These research topics are implemented and evaluated through multiple case studies conducted within the Dutch railway system. These case studies are characterized by inter-organizational projects with a broad scope, involving diverse departments across the infrastructure managing-, and main railway operating organization, dispersed information, fragmented knowledge, involvement of numerous multidisciplinary actors with different perspectives, and in general lack of shared understanding. These projects consist of various interfaces, which needed to be identified and managed to enhance coordination across departmental- and organizational boundaries.

By applying and evaluating the developed artifacts in various case studies, several generalizable design principles emerged: (1) making the objectives of a change explicit to facilitate focused discussions, (2) using and synchronizing dispersed expert knowledge to gain holistic integral insight into the impacts and scope of change(s), (3) taking a multidomain perspective to organize the collection of information, (4) making inter-organizational interfaces transparent, and (5) condensing interface information by aggregating and visualizing information concerning critical interfaces.

In order to accommodate the subjective interpretation in understanding systems and changes, the design research gravitated toward stakeholder engagement and emphasized the importance of learning, especially in the context of inter-organizational collaboration, on top of existing more technical approaches.

This dissertation concludes by providing professionals and empirical researchers with the means to apply systems thinking to address integration challenges in a more fitting manner.

Samenvatting (Nederlands)

Mensen, organisaties en samenlevingen over de hele wereld vertrouwen op de feilloze werking van talloze systemen om het dagelijks leven zoals wij dat kennen in stand te houden. Dit zijn bijvoorbeeld elektriciteitsnetten, watervoorziening, internet, en transportsystemen. Vaak wordt het bestaan van deze systemen als vanzelfsprekend beschouwd, tenzij er iets onverwachts gebeurt, zoals bijvoorbeeld treinvertragingen of stroomuitval.

In zulke systemen, zoals bijvoorbeeld het transportsysteem, is er een continue vraag naar hogere capaciteit en efficiëntie, of het om transport via de lucht, over de weg, over zee, of per spoor gaat. In spoorwegsystemen is er een voortdurende vraag naar verbetering, zodat vervoer sneller, veiliger, betrouwbaarder en met een hogere capaciteit kan plaatsvinden, bij voorkeur tegen lage kosten. Om deze verbeteringen te realiseren, komen voortdurend verschillende soorten veranderingen tot stand, van uiteenlopende groottes en complexiteiten, die allemaal geïntegreerd moeten worden in het bestaande spoorwegsysteem om de gewenste systeemkwaliteiten te bereiken.

Ondanks de ogenschijnlijke voordelen van deze ontwikkelingen, blijkt uit talloze voorbeelden dat dergelijke integratie niet altijd zo soepel verloopt als verwacht, met soms financiële schade, verminderde productiviteit, reputatieschade of zelfs slachtoffers tot gevolg.

Een van de redenen waarom zulke fouten optreden, heeft te maken met de context waarin dergelijke veranderingen moeten worden geïntegreerd. Spoorwegsystemen zijn sociotechnisch en interorganisatorisch van aard, en worden dus gekenmerkt door meerdere domeinen zoals processen, personeel, technische systemen, regels en voorschriften, met talrijke interfaces en onderlinge afhankelijkheden daartussen. Bovendien hebben de betrokken organisaties en inherente afdelingen, werknemers en experts vaak uiteenlopende visies, vaardigheden, verantwoordelijkheden, doelstellingen en belangen, en zijn informatie en kennis verspreid. Hierdoor is het een uitdaging om een gemeenschappelijk holistische blik te hebben op het spoorwegsysteem en de veranderingen die in deze context moeten worden geïntegreerd. Kortom, dit geeft aan dat er een limit lijkt te zijn aan de verbeteringen die kunnen worden bereikt, als de betrokken actoren niet effectief kunnen samenwerken.

Hiernaast nemen de technologische ontwikkelingen ook toe in omvang, complexiteit en onderlinge afhankelijkheid met andere systemen die eraan vooraf zijn gegaan.

Als gevolg hiervan nemen deze veranderingen en de projecten die ernaar streven om ze te realiseren toe in omvang, en dus ook in systemische impacts. Het initiëren van een verandering in één deel van het systeem, zonder er rekening mee te houden hoe dit een verandering in de andere onderdelen van het systeem zou kunnen beïnvloeden of vereisen, zal de effectiviteit beperken.

Een manier om met deze uitdagingen om te gaan, is door systeemdenken toe te passen: begrijpen hoe verschillende onderdelen van een systeem met elkaar verbonden zijn, en hoe veranderingen in één onderdeel het hele systeem zouden kunnen beïnvloeden. Systeemdenken blijkt echter niet zo vanzelfsprekend te worden toegepast in de praktijk. Er lijkt een gap te zijn in het vertalen van bestaande theoretische methoden naar de praktijk in interorganisationele sociotechnische spoorwegsystemen.

In het Nederlandse spoorwegsysteem moeten verscheidene ontwikkelingen zoals bijvoorbeeld automatische treinbesturing worden geïntegreerd. Echter hebben deze ontwikkelingen impacts op meerdere organisaties, die vaak verantwoordelijk zijn voor verschillende aspecten van het systeem, zoals bijvoorbeeld de infrastructuur, de exploitatie, en het onderhoud. Deze organisaties moeten dus effectief samenwerken om de integratie te bereiken. Derhalve heeft dit proefschrift als doel de onderzoeksvraag te beantwoorden:

Hoe kan systeemdenken integratie gerelateerd aan interorganisatorische veranderingen in het Nederlandse spoorwegsysteem ondersteunen?

Naast een wetenschappelijke bijdrage beoogt dit proefschrift ook een empirische bijdrage te leveren en pragmatische inzichten en hulpmiddelen te bieden aan de praktijk. Om dit te bereiken maakt dit proefschrift gebruik van ontwerpend onderzoek, wat wordt weerspiegeld in de onderzoeksonderwerpen die bij dit proefschrift horen.

Ten eerste willen we de integratie uitdagingen en bijbehorende behoeften in het Nederlandse spoorwegsysteem begrijpen. De resultaten laten zien dat in het geval van een verandering, de onderzochte integratie uitdagingen voornamelijk betrekking hebben op: (1) effectief bepalen wat er wordt veranderd, (2) de reikwijdte en gevolgen van deze verandering, en (3) hoe de verandering past binnen de bestaande spoorwegsysteem. Dit wijst allemaal in de richting van systeemdenken.

Ten tweede willen we vaststellen in hoeverre integratie van veranderingen momenteel ondersteunt wordt door bekende methodes voor systeemdenken in het Nederlandse spoorwegsysteem. Door het testen van postulaten en casestudy onderzoek kwamen verschillende factoren naar voren.

Een duidelijk doel, het betrekken van meerdere experts, het synthetiseren van expertise om wederzijdse integrale inzichten te verkrijgen, en focus op het managen van interfaces. Bovendien toont het onderzoek aan dat harde systeembenaderingen, die gangbaar zijn in de spoorwegcontext, onvoldoende tegemoet komen aan de verschillende percepties van de werkelijkheid en de behoeften van alle actoren in interorganisationele integratie van veranderingen.

Ten derde vormen de bovengenoemde factoren de basis van de ontworpen artefacten, die systeemdenken toepassen in het complexe sociotechnische spoorwegsysteem: (1) om het definiëren van de scope van veranderingen te faciliteren waardoor interorganisationele integratie mogelijk gemaakt kan worden; (2) om veranderingen in systeemomgevingen met externe invloeden zoals klimaatverandering te vergemakkelijken; en (3) om interface management in interorganisationele projecten te ondersteunen.

Dit leidde tot het iteratieve ontwerp en de ontwikkeling van drie respectievelijke artefacten: Management of Sociotechnical and Inter-organizational Change Integration (MOSAIC) analyse, een raamwerk voor aanpassing aan klimaatverandering (CCA) en het voorgestelde Interface Management (IM) proces.

Deze onderzoeksonderwerpen worden geïmplementeerd en geëvalueerd aan de hand van meerdere casestudies binnen het Nederlandse spoorwegsysteem. Deze casussen worden gekenmerkt door interorganisatorische projecten met een brede reikwijdte, waarbij verschillende afdelingen van de infrastructuurbeheerder en de grootste spoorwegvervoerder betrokken zijn, verspreide informatie, gefragmenteerde kennis, betrokkenheid van talloze multidisciplinaire actoren met verschillende perspectieven, en een algemeen gebrek aan gedeeld begrip. Deze projecten bestaan uit verschillende interfaces, die geïdentificeerd en beheerd moesten worden om de coördinatie over afdelings- en organisatiegrenzen heen te verbeteren.

Door artefacten toe te passen en te evalueren in verschillende casussen, kwamen verschillende generaliseerbare ontwerpprincipes naar voren: (1) het expliciet maken van de doelstellingen gerelateerd aan een verandering om gerichte discussies te faciliteren, (2) het gebruiken en synchroniseren van verspreide expertkennis om holistisch integraal inzicht te krijgen in de impact en reikwijdte van verandering(en), (3) het hanteren van een multidomein perspectief om het verzamelen van informatie te organiseren, (4) het transparant maken van inter-organisatorische interfaces, en (5) het condenseren van interface-informatie door informatie over kritieke interfaces samen te voegen en te visualiseren.

Om tegemoet te komen aan de subjectieve interpretatie in het begrijpen van systemen en veranderingen, richtte het ontwerponderzoek zich op de betrokkenheid van belanghebbenden en benadrukte het het belang van leren, vooral in de context van interorganisatorische samenwerking, bovenop de bestaande meer technische benaderingen.

Dit proefschrift sluit af door professionals en empirische onderzoekers te voorzien van de middelen om systeemdenken toe te passen om integratie-uitdagingen op een passendere manier aan te pakken.

List of abbreviations

Abbreviation	Description
ATO	Automatic Train Operation
BU	Business Unit
CCA	Climate Change Adaptation
CEC	Conditions for Effective Control
CSM-REA	Common Safety Methods for Risk Evaluations and Assessment
DP	Design Principle
DSM	Design Structure Matrix
DSR	Design Science Research
DSRM	Design Science Research Methodology
EM	Engineering Manager
ERTMS	European Rail Traffic Management System
GoA	Grade of Automation
ILT	Inspectie Leefomgeving en Transport; Inspection for Living Environment and Transport
IM	Interface Management
MDM	Multidomain Matrix
MOSAIC	Management of Sociotechnical and Inter-organizational Change Integration
NS	Nederlandse Spoorwegen; Netherlands Railways
PHS	Programma Hoog-frequent Spoor; High-frequency Rail Program
QDA	Qualitative Data Analysis
SD	System Definition
SI	Systems Integration
SIRA	Systems Integration for Railway Advancement
SOI	System of Interest

Chapter 1 General Introduction

1.1 Introduction

People, organizations, and societies around the globe rely on the proper functioning of numerous systems to sustain day-to-day life as we know it. These include, but are not limited to, power grids, water supply, internet, and transportation systems. These large systems comprise the technological, energy, communications, and transportation infrastructures of economies (Hobday et al., 2005). They underpin progress at the wider economic and industrial levels, as well as the prosperity of each individual firm and household (Hobday et al., 2005). Often, the existence of these systems is taken for granted, unless unexpected situations, such as power outages or train delays occur (Haanstra, 2021).

In these systems, such as the transportation system, there is a constant demand for increased capacity and efficiency, whether by air, road, sea, or rail (Daouk & Leveson, 2003). For example in railway systems, there is a continuous demand for improvement; enabling faster, safer, and more reliable transport, preferably at low cost.

In order to achieve these system-level performance qualities, changes of various kinds, scales, and complexities are continuously implemented, to keep pace with ever-changing requirements. An example of such a change is the increased attention paid to automatic train operations (ATO); an advanced technology which is used to automate the operation of trains to various degrees. The higher the grade of automation, the more functionalities the technical system will take over, and the larger the influence on the existing operating staff and the passengers. For example, routine driving work could disappear, requiring the staff to become acquainted with their new roles as part of ATO. Thus, all of these changes, like ATO, need to be integrated into the existing railway system with its inherent technical structures, personnel, and rules and regulations, in order to bring about the desired outcomes, such as increased reliability.

However, numerous examples show that this does not always go as smoothly as expected, often resulting in disastrous consequences. A recent example of this occurred in Spain in February 2023, where the Spanish public railway operator, Renfe, intended to renovate the 40-year-old railway fleet in the regions of Cantabria and Asturias, which was increasingly subject to damage. To achieve this, around €258M was spent on acquiring 31 new trains. However, after the acquisition, the trains proved to be too big to fit certain tunnels along the routes (Euronews, 2023; Railway supply, 2023). In this example, an error in the sizing of the train was discovered at the design stage, which means that the trains had not yet been manufactured, and limited public expenditure was made as a result of this situation.

While this minimizes the cost of the error, a time-consuming process of redesigning will need to be undertaken, delaying the trains' production process and subsequent delivery by several years (Euronews, 2023; Railway supply, 2023).

Another example occurred in 2014, when French train operator SNCF ordered 2000 regional trains at a cost of €15 billion and discovered that they were too wide for the network's platforms. The error was caused by data from the infrastructure manager which did not account for older structures. In this case, the trains had already been manufactured and the platforms had to be rebuilt at great cost. As a consequence, the SNCF was forced to modify more than a thousand stations, after it was revealed that the 1860 newly commissioned trains were too wide for many of the country's platforms. This mistake cost SNCF Réseau over €50 million, as the operator started 'shaving' the edges of affected platforms (BBC News, 2014; The Verge, 2014). Both examples show that such errors can cause significant delays and can be very costly.

One reason such errors occur is related to the kinds of systems in which such changes are to be integrated. Railway systems are complex, sociotechnical, and inter-organizational (Bugalia et al., 2021; Milch & Laumann, 2016), which means that they are characterized by multiple domains, such as processes, personnel, technical systems, rules and regulations, and the interactions between these (Bartolomei et al., 2012). Within these systems, multiple interacting parties, complex social structures, and numerous companies and work processes are involved, requiring the collaboration of employees from different organizations (Milch & Laumann, 2016). As such, while a change itself may initially appear simple, it can turn out to be more complex when attention is paid to the context into which it must be integrated, due to the systemic impacts of such changes.

The impacts not only affect existing technologies, but also people (with varying attitudes, backgrounds, and skills) who use a range of technologies and tools, work within a physical infrastructure, operate with a specific set of cultural assumptions, and use varying sets of processes, working practices, and regulations (Davis et al., 2014). As such, practitioners may have limited access to data and information about the railway system, which can make it difficult to understand the system itself, but also to identify how changes impact it.

Additionally, technological advancements spawn system after system, each increasingly interdependent with other, preceding systems (Arnold & Wade, 2015). As such, the predicted technological changes and the projects that strive to realize these, are increasing in scope, and therefore in degree of systemic impact. All of these potential impacts need to be considered and accounted for in parallel with the change, in order to effectively integrate the change.

According to Hendrick (1997), designing a change to one part of the system without considering how this might affect, or require an adjustment in the other aspects of the system, will limit effectiveness. As such, in order to effectively integrate such changes, attention must be paid to (1) the system into which it is to be integrated, (2) the scope and impacts of the changes, including different sociotechnical domains, (3) the inter-organizational nature of the system and projects that strive to realize diverse changes, (4) existing interfaces and interdependencies in the system, and (5) interfaces which often result from project decomposition.

All of the factors mentioned above require an understanding of how different components of the railway system are interconnected, and how changes to one component can affect the system as a whole. Many researchers and experts agree that systems thinking is essential to achieving this (Arnold & Wade, 2015; Luther et al., 2023). However, currently systems thinking appears not to be as self-evidently applied in complex sociotechnical systems such as railways. There seems to be a gap in translating theoretical methods into pragmatic industrial practices in such systems. As such, a useful starting point is to have a closer look at these systems and their characteristics.

The remainder of this chapter provides an introductory overview of the research in this dissertation, specifically the various topics covered, and the research approach followed. This introduction is divided into seven sections. Section 1.2 describes the theoretical background of this thesis. Section 1.3 focuses on the practical background, the recent developments in the Dutch railway sector, and their implications for this dissertation. Subsequently, in Section 1.4, the motivation for this research is discussed. Section 1.5 then presents the research problem and the research questions addressed in this dissertation. Section 1.6 provides an overview of the research methods, and the methodologies used throughout this dissertation. Finally, the outline of this dissertation and a reading guide are provided in Section 1.7.

1.2 Theoretical background

This section deals with the theoretical background of this dissertation. It examines why applying systems thinking to facilitate change integration within a complex sociotechnical context is an interesting topic for investigation, and which aspects are particularly essential to incorporate, thus underscoring the need for this research.

1.2.1 Complex, inter-organizational, and sociotechnical systems

According to Blanchard & Fabrycky (2011), a system is *"a set of interrelated components functioning together towards some common objective(s) or purpose(s)."* Additionally, CENELEC (2015) mentions that a *"system is a set of interrelated elements considered in a defined context and separated from their environment."*

Hobday et al. (2005) developed a typology of technological systems, which attempts to describe the scope of the system and its technological novelty, as shown in Table 1.1. In this typology, scope refers to the physical nature and content of the system and, in particular, the extent and complexity of the hierarchy and interconnection contained within it (Hobday et al., 2005).

Table 1.1 Typology of technological systems provided by Hobday et al. (2005)

		Description
Scope of the system	Assembly	An assembly is usually a mass-produced stand-alone product that performs a single function and does not form part of a wider system (e.g., a shaver, calculator, or personal computer) unless it is connected by a network.
	Component/ subsystem	By contrast, a component or subsystem always performs a role in a wider system (e.g., a telephone mobile base station or an avionics unit). Some components are relatively simple, low-technology devices (e.g., resistors, capacitors, or relays). Others may be extremely high technology in nature, involving thousands of hours of design input (e.g., semiconductor components such as microprocessors).
	Product/system	A product system can be defined in terms of its components, network structure, and mechanisms of control. These are made up of various types of components (e.g., semiconductor devices and software packages), hierarchically organized to perform a common goal (e.g., an aircraft, business information system, or weapon systems). Sometimes these are called complex product systems which represent the high-technology capital goods that underpin the production of goods and services.
	Large technical system/system of system	Large technical systems or system of systems are collections of distinct but interrelated systems, each performing independent tasks but which are organized together to achieve a common goal (e.g., an airport that consists of aircraft, terminals, runways, and baggage handling systems). Large technical systems represent the technological, energy, communications, and transportation infrastructures of the economy. They underpin progress at the wider economic and industrial levels.
Technological uncertainty/novelty	Low-tech	Low-tech systems rely on well-established technologies (e.g., roads and simple buildings). These can be large or small in value, but no new technology is required at any stage.
	Medium tech	Medium-tech systems incorporate some new features, but most technology is available with new models of existing products.
	High tech	These systems consist of, mostly, recently developed technology. Examples include internet super servers, intelligent buildings, and new passenger aircraft.
	Super high tech	Such systems depend on the development of new knowledge, artifacts, skills, and materials, are fairly rare, and rely on emerging new technologies. They involve extremely high levels of uncertainty, risk, and new investment (e.g., new spacecraft and intelligent defense systems).

Following these definitions, complex systems are generally made up of many diverse subsystems and components, interconnected and interdependent via nonlinear relationships, which can lead to difficulty in understanding and predicting overall system behavior and performance (Mostashari & Sussman, 2009).

Furthermore, a sociotechnical system considers every organization to be made up of people using tools, techniques, and knowledge to produce goods or services valued by customers (who are part of the organization's external environment) (Clemson & Lowe, 1993). In such systems, various domains, such as processes, personnel, capacity, technical systems, and rules and regulations, align with existing technology (Clemson & Lowe, 1993; Geels, 2002). These domains are depicted in Figure 1.1.

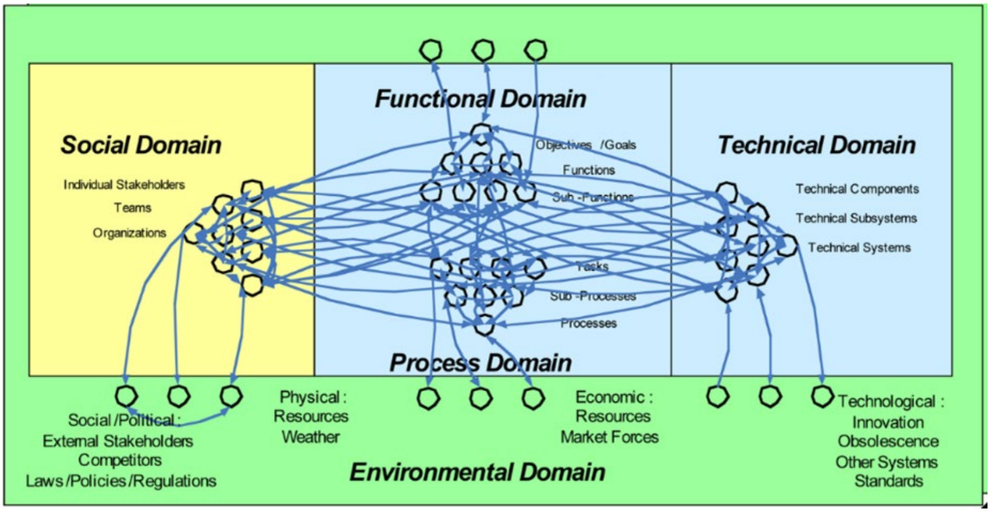


Figure 1.1: Sociotechnical domains from Bartolomei et al. (2012)

As Figure 1.1 demonstrates, complex sociotechnical systems are characterized by multiple goals (e.g., efficiency, safety, credibility, and employee wellbeing), multiple interacting parties (e.g., different technical disciplines, various tasks, and outside contractors), and complex social structures.

According to Reiman & Oedewald (2007), these structures encompass uncertainties in the tightly coupled and complex technology, and their environments (e.g., market pressures, political decisions, and regulation). Moreover, complex sociotechnical systems are dynamic.

The described contexts are often also inter-organizational. Milch & Laumann (2016) refer to inter-organizational complexity as a complex sociotechnical system that involves multiple companies and work processes, requiring the collaboration of employees from different organizations and coordination across organizational boundaries. As a result, there may be inconsistencies between the different interacting components, which are caused by people from different organizational levels, who have different roles, responsibilities, expectations, and strategies (Harvey & Stanton, 2014).

To improve the performances of these described systems, changes of different scales and complexities are continuously brought to attention. These kinds of changes can be of a technical, operational, or organizational nature, and range from small intradepartmental modifications to system-level transitions, all of which require integration into existing system structures.

1.2.2 Systems Integration

Madni & Sievers (2010) posit that systems integration (SI) is concerned with forming a coherent whole from subsystems (including humans) in order to create a mission that satisfies the needs of various stakeholders. It is an omnipresent concept involved in nearly every aspect of the engineering of large systems and systems management (Sage & Lynch, 1998). As such, integration can be defined as the process of bringing together subsystems and components into one system, ensuring that the subsystems function together as a whole (International Standardization Organization, 2015; Madni & Sievers, 2010). It is the integration of these subsystems and components that gives systems their superiority over a set of elements that do not work together without integration (Sage & Lynch, 1998).

Depending on the scope, integration can vary. For example, on the assembly level indicated in Table 1.1, integration usually takes place at the individual firm level and is a fairly simple manufacturing process (Hobday et al., 2005). In these situations, integration is an important concern for design engineers, because integration issues influence major performance indicators: cost, time, and quality (Rajabalinejad et al., 2020). On the other hand, integration at the system level usually involves many firms and other actors, including the government, regulatory agencies, users, small specialist suppliers, and other subcontractors (Hobday et al., 2005).

Unlike in the case of components or assemblies, integration here tends to be project-based, and because each change is, to some extent, tailor-made for each instance, the tasks involved in SI will differ per change (Hobday et al., 2005).

Muller (2007) complements Hobday et al. (2005), by describing integration from component- to system level. He states that by necessity, the integration of a system starts bottom-up, with the testing of individual components in a provisional component context.

The purpose of the bottom-up steps is to find problems at a scope sufficiently small to diagnose them. If thousands of components would be brought together into a system, then the system will almost certainly fail. However, it would be nearly impossible to find the source of this failure in this case, due to the multitude of unknowns, uncertainties, and possibly malfunctioning parts. Figure 1.2 shows that the focus of the integration activities shifts during the integration phase.

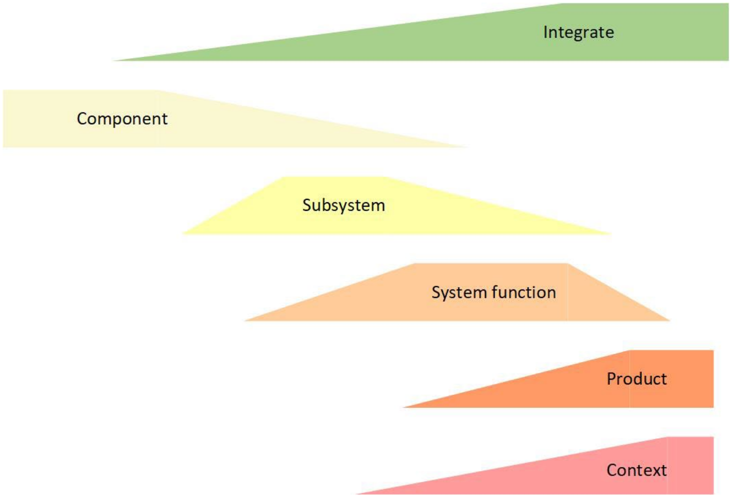


Figure 1.2: The bottom-up levels of integration over time, adapted from Muller (2007)

It is essential to integration that the higher levels of integration start before the lower levels of integration are finished (Muller, 2007). During the early stages of integration, the focus lies on functionality and the behavior of components and subsystems. Afterwards, the focus shifts to system-level functionality: do the combined subsystems operate properly? The last step in integration is focusing on the system's qualities, such as performance and reliability (Muller, 2007).

These system-level qualities can often only be tested in a context, such as other systems providing inputs or consuming outputs (Muller, 2007). The context of the system has to be realized in parallel with the system, and the system and its context are integrated step by step (Muller, 2007).

Additionally, Muller (2007) mentions systems not operating well in their context as being a typical and common integration issue. He mentions that this may be caused by a lack of, or a faulty understanding of the context, misrepresentation of the context during integration, or changes to the context during the project. This emphasizes the need to integrate with a (realistic) context as early as possible during the integration process (Muller, 2007).

The International Council on Systems Engineering (2015) refers to this as the utilization stage, where the system is operated in its intended environment in order to deliver its intended services. Possible modifications to this environment should be accounted for, to ensure smooth integration. For large, complex systems, upgrades can be substantial endeavors requiring significant efforts to integrate, equivalent to a major program (International Council on Systems Engineering, 2015).

Thus, it can be stated that integration has evolved beyond its original technical and operational tasks, cutting across technical, management, and strategic levels (Madni & Sievers, 2010). It has become a core capability of organizations responsible for coordinating large networks of suppliers involved in the design, production, and integration of interdependent parts of complex products and systems (Hobday et al., 2005; Muruganandan et al., 2022).

No matter the scope of the developed system, these need to be integrated within its context to realize the improvements and system qualities envisioned. In order to avoid ambiguous use of the term ‘system’ in this dissertation, we differentiate between changes and system context. As such, changes, which can often also be regarded as systems in their own right, can be of various scales and complexities, be of a technical, operational, or organizational nature, and range from small intradepartmental modifications to system-level transitions, all of which are required to be integrated into a specific system context.

A significant amount of literature focuses on the development and integration of these changes themselves, however, less attention is paid to the integration of these in their respective contexts. This dissertation focuses on a context that consists of multiple organizations, including their embedded departments and individuals, and multiple domains, such as technical, organizational, process, and environmental domains, with numerous interconnections and relationships between them. As a result, changes, or new technologies are often difficult to integrate and establish in such systems, as they often do not match existing sociotechnical frameworks (Geels, 2002).

In these situations, individuals from various organizations and disciplines have their own insights, (mental) models, assumptions, expectations, and approaches to describing and understanding a change and its related impacts on their field of operation and/or expertise (Danilovic & Browning, 2007). This can become increasingly challenging when a change spans across different departments and/or organizations and requires collaboration between actors from these, as well as actors with diverse engineering and non-engineering backgrounds to achieve effective change integration.

Therefore, there is an increasing need to understand the context of a change and to identify how changes, and the projects that strive to realize them, can be integrated into it (Potts et al., 2021). Depending on the change and its scope, the impacts on the system context (and vice-versa) may vary, span across different organizations, and across multiple sociotechnical domains, which increases the integration scope, and as such, the system of interest.

1.2.3 The system of interest

While a change may appear simple at first glance, this can turn out to be more complex when the context in which it must be integrated is taken into account (Ramtahalsing et al., 2022). Therefore, it is vital to determine the scope of the impacts of a change in order to set bounds on various aspects considered to be of interest: this is defined as the system of interest (SOI). The SOI is used to determine which aspects are considered to be the main subject of study and provides the opportunity to clarify which parts of the context are included in the assessment, and which parts are considered to be out-of-scope (Haanstra, 2021).

1.2.4 Project scope definition

Projects resulting from such SOIs are often complex and inter-organizational, as well because multiple organizations interact to create value together (Hass, 2008). In these cases, defining project scope using input from all stakeholders is a vital task that needs to be adequately carried out at an early stage (Dasher, 2003; Williams et al., 2019). While adequate front-end project planning with a clear project scope definition can aid in avoiding negative effects on project performance, inadequate project planning and poor scope definition can lead to expensive changes, delays, rework, cost overruns, schedule overruns, and project failure (Fageha & Aibinu, 2013).

Therefore, a well-defined scope during the front-end planning stage is crucial for successful project execution and achieving a satisfactory project outcome (Fageha & Aibinu, 2013).

To visualize this, Botchkarev & Finnigan (2015) distinguish the bottom three layers shown in Figure 1.3. This research extends this approach to production-based organizations such as railways, which derive most of their revenue and/or benefits from producing and selling products and services (Stretton, 2016). In those organizations, the projects are part of an organization itself (the internal environment).

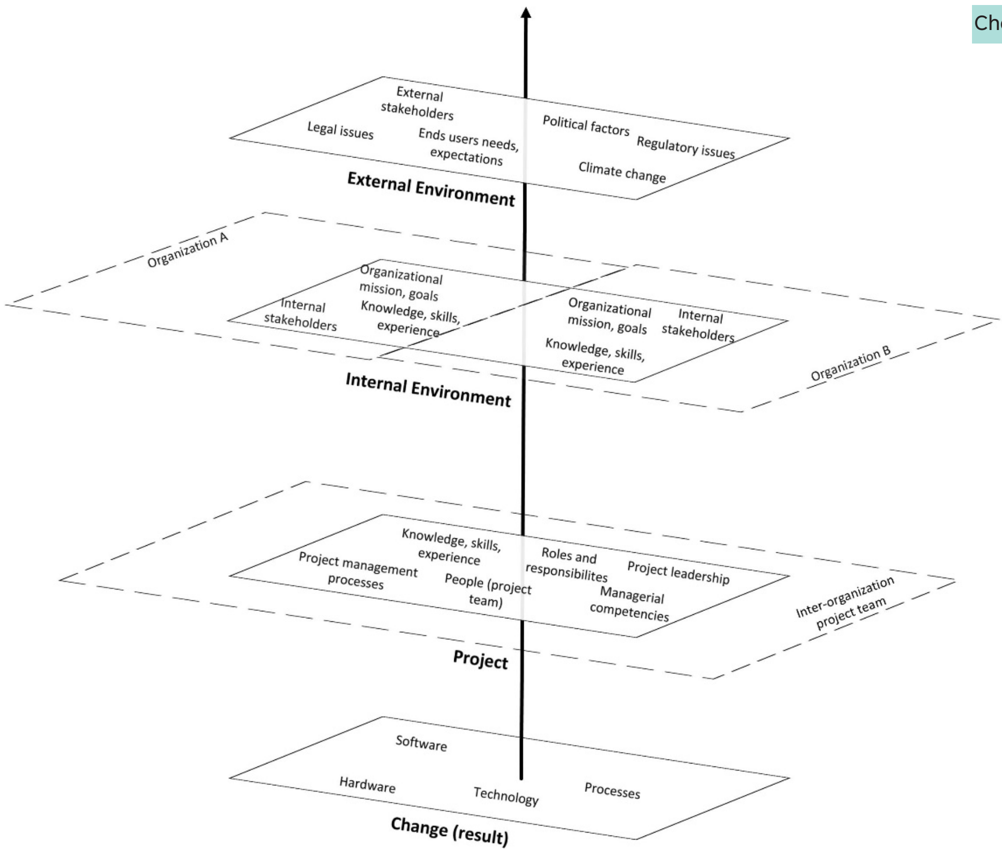


Figure 1.3: Change, project, and environment(s) adapted from Botchkarev & Finnigan (2015)

Figure 1.3 illustrates these four layers as follows:

- The first layer represents the change which is required to be implemented, and all of its components and subsystems such as software, hardware, etc.
- The second layer represents the project, which includes activities undertaken to develop or implement the change. It includes the project team and project processes.
- The third layer consists of the internal environment, which includes stakeholders internal to the company, and its mission, goals, and objectives.
- The fourth layer represents the wider external environment in which the organization operates, which can include political factors, rules and regulations, climate effects, and end users.

1.2.5 Inter-organizational projects

As previously stated, projects that aim to improve these types of systems, are often complex and inter-organizational because multiple organizations interact to create value together (Hass, 2008). As such, multiple organizations work jointly on a shared activity for a limited period of time, in order to achieve pre-specified project goals, within a pre-established time frame (Cropper et al., 2008; Scott-Young & Samson, 2008). These projects involve multiple organizational actors with disparate goals, overlapping areas of responsibility, and differing levels of expertise (Jones & Lichtenstein, 2008), as illustrated in Figure 1.3.

Furthermore, the execution of a successful inter-organizational project depends on numerous activities, individuals, teams, and organizations, as well as the relationships between them. This requires cooperation among employees from different organizations, and work processes require coordination across organizational boundaries (Browning, 2010; Milch & Laumann, 2016).

However, though this is vitally important, it can be difficult to achieve since knowledge and information are dispersed across various departments or organizations. This leads to the topic of Interface Management (IM).

1.2.6 Interface management

In order to cope with the complexities that arise from inter-organizational projects and enable effective project management (Healey, 1997), organizations often attempt to decompose a project (Davies & Mackenzie, 2014). Project decomposition results in the granulation of work into numerous diverse tasks, which are executed by diverse actors in various departments across organizations (Healey, 1997), and as a result, interfaces arise.

Lustenbergerent (2012) mentions that friction, or even failure, occurs mostly at the interfaces. No matter how the work is divided, the problem of linking the various parts remains (Healey, 1997). Moreover, according to Muller (2007), projects encounter many problems that are caused by these decomposition steps. Whenever a project is decomposed, the activities it is decomposed into usually function well on their own, however, the crosscutting of functionality and the level of quality tends to suffer because of the decomposition (Muller, 2007).

In the case of production-based organizations such as railways, projects interface with environments, both the internal one of the production-based organization itself, as well as its wider external environment. In production-based organizations, interfaces with the project’s external environment can include (Stretton, 2016): regulatory agencies, competitors, suppliers, subcontractors, and governments (Stretton, 2016). Moreover, interfaces with the rest of the organization can include top management, line management, line personnel, social contacts, personnel, and training, as depicted in Figure 1.3.

Managing these interfaces is crucial because a large number of autonomous organizations, designers, engineers, general contractors, subcontractors, vendors, consultants, and government agencies must collaborate in a harmonious way to achieve project goals (Ahn et al., 2017).

1.2.7 Systems thinking

An approach for overcoming the challenges mentioned above is applying systems thinking: understanding how different components of a system are interconnected, and how changes to one component can affect the entire system (Arnold & Wade, 2015). Systems thinking occurs through discovery, learning, diagnosis, and dialogue, which lead to sensing, modeling, and talking about the real world in order to better understand, define, and work with systems (International Council on Systems Engineering, 2015).

A systems thinker knows how changes fit into the larger context, how they behave, and how to manage them (International Council on Systems Engineering, 2015). This means that systems thinking can be regarded as a set of synergistic analytic skills which can be used to improve an individual's capability of identifying and understanding systems, and the ability to devise modifications to them in order to produce desired effects (Arnold & Wade, 2015).

Moreover, systems thinking as a practice is the ability to think abstractly in order to: (1) aid in creating an overarching perspective, (2) understand how independent elements come together into a unified overview, (3) incorporate multiple perspectives, (4) work within a space where the boundaries, scope of change, or system may be 'fuzzy', (5) understand the diverse operational contexts of the change, (6) identify inter- and intra-organizational relationships and dependencies, and (7), most importantly, predict the impact of changes to the system (Boardman & Sauser, 2008; C. Haskins & Ruud, 2017; Potts et al., 2022; Sauser & Boardman, 2015; Squires et al., 2011).

Within the railway context, hard systems approaches such as systems engineering have often been mentioned as a widely suitable approach (International Council on Systems Engineering, 2015). In this regard, Hitchins (2005) states: "*Systems engineering is the art and science of creating optimal system solutions to complex issues and problem*s." However, a disadvantage of these methods is that they are less suitable for addressing the needs of all stakeholders, especially non-engineering stakeholders (Madni et al., 2014b), and are unable to deal satisfactorily with the diversity of views and interests of involved actors (Rosenhead, 2010).

As a result, the shortcomings of these approaches and assumptions are becoming more obvious as systems become more complex (Jackson, 2003; Rajabalinejad et al., 2020).

Browning (2002) suggests that systems thinking would enhance integration by synchronizing multiple perspectives into an overview of the SOI. In these instances, a shared model can test and align participants' mental models through discussion, leading to a joint understanding of the reality of projects (Danilovic & Browning, 2007).

In addition to this, Blanchard & Fabrycky (2011) point out that system-specific knowledge is often limited at the front end, however, in this phase there is significant room for modification with limited associated costs. Contrary to this, the further a change has been developed and committed to, the more difficult and costly modifications are, as the costs of changes increase in parallel with a commitment to technology and configuration, as depicted in Figure 1.4.

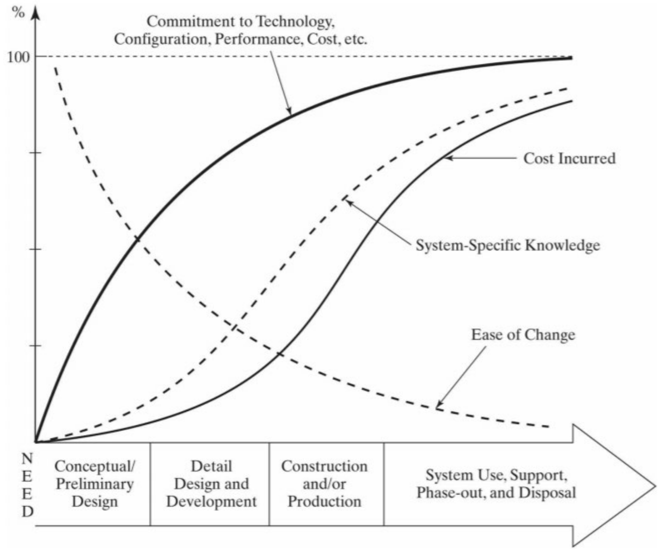


Figure 1.4: Commitment versus incurred costs and ease of change (Blanchard & Fabrycky, 1998)

The former was illustrated by the first example in the introduction, where an error in the sizing of the trains in Spain was discovered at the design stage and the trains had not yet been manufactured, minimizing the costs of the error. The latter was illustrated using the second example from France, where it was discovered that the newly acquired trains were too wide for some platforms. In this France case, the trains had already been manufactured when the error was discovered, and numerous platforms had to be rebuilt at a great cost.

These examples emphasize that suboptimal integration often leads to the redesigning and reengineering of products or services, which can become very expensive if problems are recognized too late, for example in the operational phase or at the end of a project lifecycle (Rajabalinejad et al., 2020). Thus, the earlier systems thinking is applied and the integration context is accounted for, the more system-specific knowledge can be acquired and accounted for in the design, and possible modifications can be incorporated more easily and at a lower cost.

A visual summary of the theoretical background is provided in Figure 1.5. A change of any scope or complexity is required to be integrated into the complex sociotechnical and inter-organizational system. In order to properly align it with the context, it is important to know how the change will connect to the existing system context, and whether other systemic adjustments are required (possibly across different organizations and sociotechnical domains) in order to accommodate it. This overview is referred to as the SOI and aids in determining the project scope early on, since this is the part of the project that has the greatest opportunity for creating value (Edkins et al., 2013; Fageha & Aibinu, 2014; Williams et al., 2019).

Projects that aim to improve such systems are often complex and inter-organizational, and in order to cope with this complexity, organizations often decompose the project. This results in the granulation of work into numerous diverse tasks, which are executed by diverse actors in various departments across organizations, resulting in interfaces, the management of which is vital.

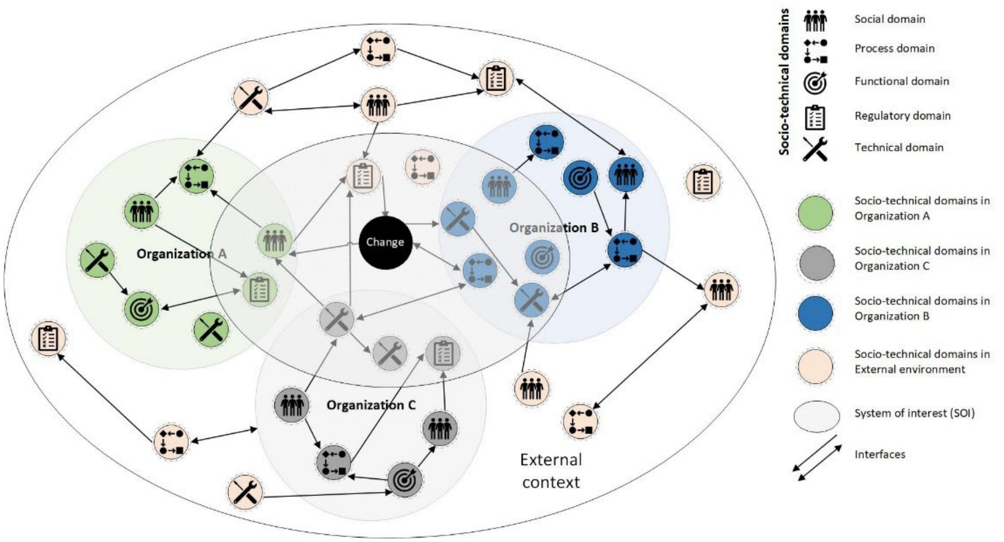


Figure 1.5: Systems thinking in complex, inter-organizational, and sociotechnical systems

Figure 1.5 illustrates how systems thinking could be applied in the described context, by systematically creating insight into, and thinking about, the SOI, in order to understand how different components are interconnected, and how changes to one component could affect the system as a whole.

1.3 Practical background

This dissertation aims to make an empirical contribution by using the industry as a laboratory, ensuring the research trajectory is properly attuned to the needs of the industry. In doing so, the dissertation aims to provide pragmatic insights and tools to railway practitioners.

1.3.1 Railway systems

Railway systems are complex, sociotechnical systems which, as stated prior, highlights the need to consider both technological and social development within an organization "*simultaneously rather than consecutively*" (Harvey & Stanton, 2014). Furthermore, depending on the social/political environment and the organizational/management structure of the railway system concerned, several actors, performing different functions, can be involved within the life cycle phases of the system. These can include railway companies, infrastructure managers, maintainers, and safety authorities (CENELEC, 2015). The number and variety of actors can differ due to social, political, or legal considerations, but also due to the size and complexity of the railway system or its subsystems (CENELEC, 2015).

1.3.2 The Dutch railway system

The Dutch railway system is an example of the type of system described above. Due to legislation by the European Union, previously nationalized railway companies have been split up into different, smaller companies. In the Netherlands, the state-owned organization ProRail is solely responsible for the infrastructure, while there are several passenger and freight operators (Huisman et al., 2005; Leijten & Koppenjan, 2010; Nakamura & Sakai, 2022). The NS (Nederlandse Spoorwegen; Dutch Railways) is by far the largest passenger railway operator (Merkus et al., 2017). Moreover, in the Dutch railway sector, governance of the railways is executed by the Dutch Ministry of I&W (Infrastructuur en Waterstaat; Infrastructure and Waterways), and oversight and control of laws that involve the safety and quality of the Dutch railways are enforced by the ILT (Inspectie Leefomgeving en Transport; Inspection for Living Environment and Transport) (S. K. Wu et al., 2019).

1.3.3 Railway system performance

All railways have the same basic targets: beyond manifesting a safe railway, they are working to maximize the capacity at which they can operate their networks, minimize passenger and freight delays, maximize the reliability of the infrastructure and rolling stock, and do all of this at minimum cost (Association of European Railway Industries, 2010).

As shown in Figure 1.3, meteorological events such as floods, droughts, heatwaves, and storms are a factor in the external environment of railway systems and can cause significant damage to railway infrastructure. As such, the existing infrastructures are required to be adapted to a changing climate (Dépoues, 2017).

Additionally, the European Union has ambitious goals for mobility and railway transport, such as establishing clear milestones for transport in reducing greenhouse gas emissions: 25% by 2030, 65% by 2040, and 100% climate-neutral transport by 2050 (Railtech, 2020b). Another example is the increased focus on seamless railway mobility across borders in Europe (Railtech, 2020a).

To reach these goals, existing railway systems are continuously being adapted, and adopting novel technologies. These changes can vary significantly, depending on their scope, the associated costs, novelty of the technology, complexity, inter- and intra-organizational natures, duration, reversibility, and impacts on the surrounding, existing system.

Hermann et al. (2016) and Xu et al. (2021) emphasize several notable characteristics in current trends regarding these changes, namely: (1) scope and system impacts (the large number of companies that are affected by these changes), (2) interconnection (the ability of machines, devices, sensors, and people to connect and communicate), (3) velocity (the exponential speed at which incumbent industries are affected), (4) interconnectivity (allowing the collection of immense amounts of data and information from all stages in the process), and (5) technical assistance (the ability of systems to assist humans in decision-making and problem-solving, as well as their ability to help humans with difficult or unsafe tasks).

Some specific examples of these changes in railway transport include but are not limited to (1) ATO, which is an advanced technology used to automate the operation of trains to various degrees, as described in Table 1.2; (2) the European railway traffic management system (ERTMS), which involves the management and interoperation of signaling systems for railways, which is to be implemented across the European Union.

This aims to replace the different national train control and command systems in the European Union; (3) High-frequency train scheduling, which involves multiple simultaneous extensive modifications to the railway infrastructure, allowing for higher frequency scheduling and increased line capacity.

Table 1.2 Grades of Automation (GoA) in Automatic Train Operation (ATO), adapted from (Lagay & Adell, 2018).

Grade of Automation		**Train control**	**Door handling**	**Stop**	**Train control in case of disruption**
GoA 0	On-sight train operation	Driving without controlling the train	Train driver or train attendant	Train driver	Train driver
GoA 1	Manual train operation	Driving with train control	Train driver or train attendant	Train driver (eventually braking system)	Train driver
GoA 2	Semi-automatic train operation	Automatic control with Train driver	Train driver or train attendant	Automatic	Train driver
GoA 3	Driverless train operation	Automatic control without Train driver	Train attendant	Automatic	Train attendant
GoA 4	Unattended train operation	Automatic control without staff	Automatic	Automatic	Automatic

No matter the type of change or development, they require integration within the existing railway system in order to improve the performance of the system as a whole (Dumolo, 2007; Guerrieri, 2022).

Currently, the operational system is comprised of train operators, infrastructure owners, and regulators, responsible for operating and delivering services to end-users (Geyer & Davies, 2000). Thus, it is important to realize that in a railway system, there are large and crucial dependencies between the network (infrastructure) and its users (transporters). As such, the importance of an integral view becomes evident, as illustrated by the following examples:

- ERTMS demonstrates that there is a very strong interconnectedness between the operational systems in the infrastructure and those in the train equipment. These systems must connect seamlessly and communicate flawlessly with each other, which is particularly crucial for safety. ERTMS can not be implemented into existing infrastructure, without simultaneously specifying exactly which compatible systems are required on the trains using that infrastructure (Spoorpro, 2023).

- The investment in 3kV voltage: In the medium term, it is necessary to increase the voltage on the overhead lines in the Netherlands, which is now at 1,5 kV, to 3 kV. This would result in more power being available, enabling more, faster, and/or longer trains, however, trains would need to be modified. Retrofitting trains is relatively expensive, but if trains are built for operation at the right voltage, the relative costs are lower (Spoorpro, 2019; Treinreiziger.nl, 2019).
- In the ATO example mentioned above, the different grades of automation show which aspect of the system (train control, door handling, stopping, train control in case of disruption), are to be automated, and to which extent. This indicates that, the higher the GoA becomes, the more functionalities are required from the technical system. Additionally, this can require significant changes to the qualifications of the operating staff (Rajabalinejad et al., 2020). For current staff, routine driving work could disappear, and the staff concerned with ATO would require extensive knowledge of all the key systems. As such, the railway staff will need to become acquainted with their new roles as part of ATO. Furthermore, ATO is subject to numerous rules, regulations, and standards in order to operate safely. Whether these are specifically Dutch or European Union regulations, they have a significant influence on the operation of ATO.
- As pointed out by van Dongen et al. (2019), the introduction of off-the-shelf trains is an increasingly complex process in which organizations, in addition to training employees, must ensure that maintenance equipment, spare parts, an appropriate maintenance program, and working methods are in place to smoothly integrate the new trains into transport organizations.

1.3.4 Practical systems integration challenges

In the Dutch railway system, processes, personnel, capacity, technical systems, rules and regulations, and their interfaces play an important role in the performance of the system as a whole, and can not be addressed separately. As such, it is important to understand the technical impacts of a change, the organizational and operational procedures, and the human actions required in case of changes.

As the above examples illustrate, a change cannot be introduced into one part of the railway system, without simultaneously understanding other required, consequential adjustments to interdependent parts. This integral view is necessary to achieve the system-level performance qualities expected from integrating the change.

However, the effective integration of numerous changes into the Dutch railway system faces several challenges:

- The Dutch railway system consists of various separate organizations, chief among these are the main railway operating organization (NS) and the infrastructure manager (ProRail). These organizations, and their business units, employees, and experts have different perspectives, skills, responsibilities, objectives, and interests. Moreover, this separation means that knowledge and information are dispersed across organizations, and there is a limit to the improvements that can be achieved if they cannot effectively share this information and work together.
- Within this context, there appears to be no individual or organization that has an integral overview of the entire system. Subsequently, the involved organizations and actors often do not have a mutual basis of understanding from which to grasp the coherence of distinct elements that make up the existing railway system. This complicates identifying the point of integration of a change, determining and predicting the impacts of that change on the existing railway systems, establishing the scope of the impacts of the change, as well as having a joint departure point. This becomes especially challenging in the case of inter-organizational projects.
- Individuals from various organizations and disciplines have their own insights, (mental) models, experiences, assumptions, expectations, and approaches to describing and understanding such changes and related impacts. As the scope of changes increases, more intense collaboration between people from different organizations, departments, and stakeholders from diverse engineering and non-engineering backgrounds may be needed, in order to form a shared perspective on the change and its impacts on the system.
- The increasing size of projects, advances in technology, and operations such as ATO and ERTMS, are major causes of interfaces growing in size, number, and complexity, which makes their identification and management more challenging, but also more important, especially when the interfaces are inter-organizational. In these cases, a lack of ownership, attention, and/or communication across interfaces are root causes of problems (Muller, 2007), and uncertainties, irrespective of where they originate, can be passed to parties on the other side of the interface (Sawhney, 2006).

This illustrates that the challenges concern (1) the effective determination of what exactly is being changed, (2) the scope of this change, and (3) how this change would fit within the existing railway system environment. The existence of these challenges may hinder the integration of changes into the system.

Because of these challenges and limitations, NS and ProRail are looking for pragmatic ways to support systems thinking in their complex context and to identify, where collaboration across organizational boundaries may be needed, especially for changes currently under consideration.

1.4 Research motivation

The challenges experienced by NS and ProRail appear to reflect the challenges found in the existing literature, as discussed in the previous two sections. This makes the Dutch railway sector a highly relevant and scientifically interesting environment for research:

1. In the described context, actors from different organizations tend to view the complex system differently (Hagan et al., 2011) and information is dispersed across organizations.
2. In this context, numerous changes are to be integrated in order to improve system-level performances. These are increasing in scope and system impacts.
3. In order to reap the benefits of these changes, the impacts of those changes on the system context need to be accounted for. These include impacts on various domains, such as processes, personnel, capacity, technical systems, and rules and regulations. However, the required information and knowledge are currently dispersed.
4. Involved actors can have a varied understanding of how a prospective change would impact their department(s) or their organization. This becomes more challenging when a change spans multiple organizations, and collaboration between organizations is required for its successful integration.
5. As the scope of changes increases, more organizations, suppliers, users, and processes are included: this requires more inter-organizational collaboration. However, in large projects, there can be a lack of ownership and communication across organizational boundaries (Muller, 2007; Ramtahalsing et al., 2020).
6. In such contexts, characterized by the existence of multiple multidisciplinary actors, multiple perspectives, incommensurable and/or conflicting interests, and key uncertainties (Jackson, 2003; Mingers & Rosenhead, 2004), hard systems thinking approaches such as systems engineering, seem to have shortcomings (Jackson, 2003).
7. Many tasks to be conducted within the inter-organizational project do not have neat and easily identified interfaces to project participants (business units), as a result, the interfaces can be ‘hidden’, or easily overlooked.

1.5 Research questions

Both a theoretical and practical gap currently exist concerning how systems thinking can be pragmatically applied, in order to facilitate change integration in the complex sociotechnical railway context. As such, the main question that guides the research of this dissertation is the following:

How can systems thinking support inter-organizational change integration in the Dutch railway system?

In order to answer the main research question, research sub-questions have been formulated:

RQ1. What are currently the main systems integration challenges in the Dutch railway system?

RQ2. To what extent do existing systems thinking practices support change integration in the Dutch railway system currently?

RQ3. a. How can systems thinking be applied to facilitate scope definition in order to enable inter-organizational change integration in the complex sociotechnical railway system?

b. How can systems thinking be applied in case of changing system environments: external influences like climate change on the Dutch railway system?

RQ4. How to facilitate interface management within inter-organizational projects with the aim of achieving focused coordination in the railway context?

Climate change (RQ3b) is an increasingly relevant issue within the railway sector and can be regarded as an unavoidable factor influencing the system externally, in contrast to the internal changes mentioned thus far. As such, a part of this PhD project was devoted to this topic, however, it is not part of the main focus of the dissertation. As such, less attention is paid to this topic than the other RQs in the introduction, as well as the discussion and conclusion chapter of this dissertation.

1.6 Methodology

1.6.1 Design science research

This section explains the research approach used to investigate the identified research questions. As stated in the previous sections, in addition to a scientific contribution, this dissertation aims to make an empirical contribution and provide pragmatic insights and tools to practitioners. In order to do so, this dissertation uses the design science research (DSR) methodology.

DSR has been conceptualized as a research strategy, aimed at creating knowledge that can be used in an instrumental way to design and implement actions, processes, or systems to address unsolved problems (Hevner & Chatterjee, 2010) and achieve desired outcomes in practice (J. van Aken et al., 2016). Moreover, DSR is driven by field problems or opportunities; instrumental knowledge is developed by deep engagement with these real-life problems or opportunities (Hevner et al., 2004; J. van Aken et al., 2016).

When applying DSR, academic research objectives are of a more pragmatic nature. It is solution-oriented, with the ultimate objective to produce knowledge that can be used in designing solutions to field problems (J. E. Van Aken, 2005). Furthermore, DSR takes the perspective of involved actors seeking to improve matters, such as an engineer designing a bridge (J. van Aken et al., 2016). Therefore, the artifacts which result from a DSR process can take a variety of forms.

DSR involves a rigorous process for designing artifacts to solve observed problems, make research contributions, evaluate designs, and communicate results to appropriate audience members (Peffers et al., 2007). It constitutes a systematic but flexible methodology that aims to improve practices through iterative analysis, design, development, and implementation based on collaboration among researchers and practitioners in real-world settings, leading to context-sensitive design principles and theories (Wang & Hannafin, 2005), and ultimately results in the creation of new knowledge and artifacts. As such, the research conducted throughout this dissertation is a result of problem-centered initiation. Peffers et al. (2007) designed a commonly accepted framework for carrying out DSR, which is depicted in Figure 1.6.

In order to explain how the different DSR steps correspond to the research conducted throughout this dissertation, the mapping is represented in Figure 1.7. This figure depicts, from left to right: (1) the DSR methodology steps, (2) the corresponding research questions, and (3) the corresponding chapters in this dissertation, addressing the research sub-questions.

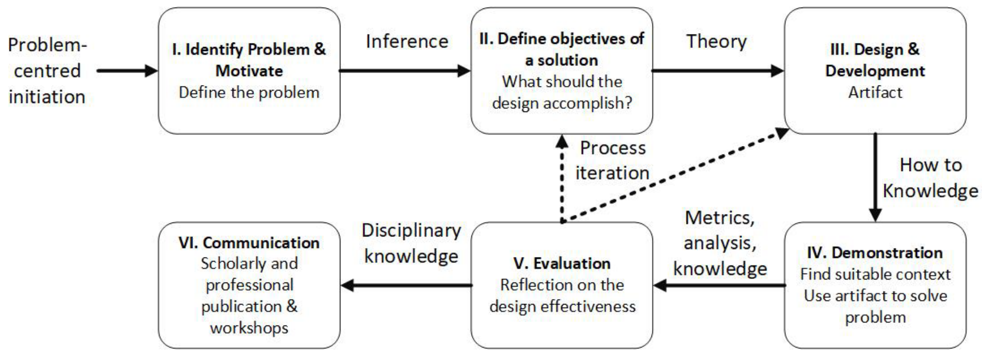


Figure 1.6: DSR methodology adapted from Peffers et al. (2007)

1.6.2 Research methods

In addition to Section 1.6.1 explaining the overarching methodology applied in this dissertation, this section discusses the research methodologies and associated methods used to investigate the research questions per chapter, as summarized in Table 1.3.

Generally, case studies are the preferred strategy when 'how' or 'why' questions are posed, when the investigator has little control over events, and when the focus is on contemporary phenomena within a real-life context (Yin, 2003). The use of case studies allows investigators to retain the holistic and meaningful characteristics of real-life events (Yin, 2003).

Considering the exploratory nature of RQ1, a case study was deemed a suitable choice for identifying the main integration challenges faced in the Dutch railway system, as this allows for a holistic overview of a certain phenomenon to be obtained (Noor, 2008).

RQ2 is used to examine to what extent existing systems thinking practices currently support change integration in the Dutch railway system. The corresponding Chapter 3 investigates whether a number of assumptions found in the literature are supported by empirical evidence, as well as explores possible reasons for organizations to deviate from what is generally assumed in current literature. Case studies attempt to highlight why certain decisions were made, why these were implemented, and with what results (Yin, 2003). Furthermore, they benefit from the prior development of theoretical propositions in order to guide data collection and analysis (Yin, 2003). In order to do so, this chapter makes use of 13 case studies in combination with postulates. These postulates refer to a commonly accepted truth, which serves as a starting point for deducing and inferring other (theory-dependent) truths (Braaksma, 2012). These postulates are either refuted, qualified, or elaborated on, based on the empirical findings from the case studies.

Finally, DSR was used to answer RQ3 and RQ4. J. van Aken et al. (2016) mention that DSR projects consist of two components. The first provides a solid foundation for the second by cultivating a deep understanding of the field problem for which the second component produces improvement-oriented knowledge. This allowed for the design and development of problem-solving artifacts in chapters 4, 5, and 6, and aided in the evaluation of these artifacts in practical settings.

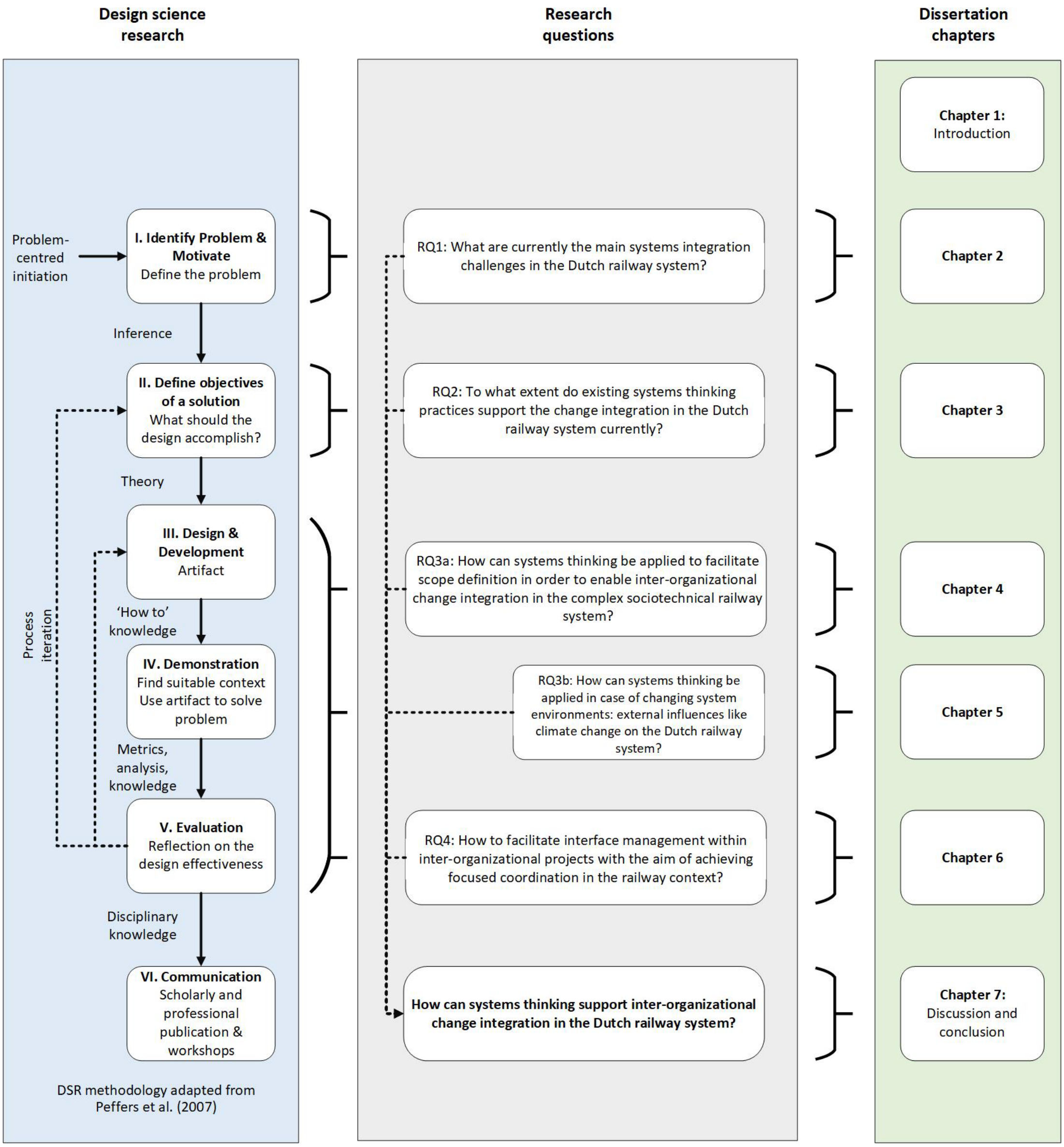


Figure 1.7: Research mapping and dissertation structure

Additionally, demonstrating the usefulness of the developed artifacts for solving one or more instances of the problem, has been done by means of their application to various case studies. Moreover, because DSR encourages the exchange between science and practice by directly implementing theoretical concepts in real-world cases (J. E. Van Aken, 2005), the feedback of practitioners was incorporated into the design iterations as well, further closing the gap between science and practice.

Table 1.3 provides an overview of the applied research methodology and methods employed to answer each research question. The main empirical inputs for the various research questions and chapters are case studies. In instances where the case studies were an integral part of answering the research question, these are also mentioned.

Table 1.3: Research methodology and methods used per research question

Research question	Research methodology	Research method	Case studies
RQ1	Exploratory case study	43 semi-structured interviews Qualitative data analysis (ATLAS.ti)	The Dutch railway system
RQ2	Postulates Case study research	Literature review Structured interviews Qualitative data analysis (ATLAS.ti) Triangulation (survey, observation, archival research)	ATO ERTMS Train introduction High-frequency scheduling Train modernization Train-towing vehicle Signaling systems within railway infrastructures Modification of train seats LED lights Modification of storage tanks Train speaker sound levels Train cockpit power outlets
RQ3a	DSR Case study research	Structured Interviews Workshops Triangulation (interviews, observation of industrial expert sessions, archival research)	The inter-organizational implementation of a multipurpose train-towing vehicle
RQ3b	DSR Case study research	Exploratory and semi-structured interviews Literature review Archival research	Dutch railway infrastructure managing organization
RQ4	DSR Case study research	Structured interviews Workshops Triangulation (interviews, observation of industrial expert sessions, archival research)	The construction and implementation of a new train stabling yard

Furthermore, Gregor & Hevner (2013) mention that artifacts that can be explained at a high level of abstraction are more easily transferred to other application domains, especially when its rules are expressed as generalizable statements. Thus, the results of this dissertation do not only discuss the developed artifacts, but also encompass a reflection on the underlying generalizable design principles.

1.7 Reading guide

During the PhD research, a publication strategy that aimed to publish and present the core academic findings of the research in conference proceedings and through publications was adopted. Consequently, the dissertation consists of a collection of individual publications that each have a specific focus, contributing to the research questions as formerly described.

An overview of the thesis outline, including the research focus per chapter, the respective research questions, and their relationships to the DSR process is provided in Figure 1.7. Together with this introduction, and the discussion and conclusion chapters, these form the main structure of this dissertation. Moreover, Chapters 2 through 6 can also be read as stand-alone pieces of research as these are a result of scientific publications. The following section provides a brief overview of their content:

Chapter 2: Systems Control in Railway Transport, Challenges Towards Managing Integration

This chapter is focused on understanding the main integration challenges faced in the Dutch railway system. To do this, semi-structured exploratory interviews were conducted in the Dutch railway system. Based on qualitative data analysis, challenges are analyzed using two frameworks taking a systems perspective. This chapter reveals numerous challenges faced in this context, as well as pinpoints the key factors that could enable more effective SI, all of which point toward systems thinking as a solution to the identified challenges.

Chapter 3: Application of System Definitions as a Foundation for Risk Assessments: A Multiple Case Study in the Dutch Railway System

This chapter aims to identify to what extent well-known systems thinking practices currently support integration in the Dutch railway system. Existing literature emphasizes that system definitions (SDs) appropriately describing changes to be integrated, are critical prerequisites for successful risk assessment and safe integration, requiring systems thinking. Moreover, due to existing rules and regulations in the railway sector, SDs and their development, are mandatory by law, and thus quite well-known in the Dutch railway sector. Although current literature sufficiently addresses the content of such SDs, direct and thorough comparisons between theoretical best practices, and examples of actual practices in the industry are scarce. To fill this gap, this chapter condenses the most prominent descriptions and assumptions present in the literature concerning SDs into five postulates. These postulates are then compared to industrial practice using a multiple case study conducted in the Dutch railway system. The results of this chapter form the basis of several systems thinking features to be included in the designed artifacts, linking it to the next chapter of this dissertation.

Chapter 4: MOSAIC: Design of a Structured Multidisciplinary Approach for Managing Integration of Inter-Organizational Change

A crucial aspect enabling integration is to define the scope of the changes, referred to as the SOI. By employing DSR, this chapter proposes an analysis that supports engineering managers in managing sociotechnical and inter-organizational change integration (MOSAIC) by facilitating a structured, multidisciplinary assessment of system impacts and interdependencies. This artifact is evaluated by application to a case study concerning the inter-organizational implementation of a multipurpose train-towing vehicle.

Chapter 5: Climate Change in Dutch Railway Infrastructure: Towards a Framework for Adaptation Strategies

Climate change is an increasingly relevant issue within the railway sector and can be seen as an unavoidable factor influencing the system externally, in contrast to the internal changes mentioned earlier. As such, a relatively small part of this PhD project was devoted to the topic in this chapter. Due to climate change, the need to adapt assets in order to deal with a changing climate has been receiving increasing attention from both a practical and theoretical perspective over the past decade. While existing literature pays attention to, for example, risk identification and management in the described context, other essential aspects such as the inclusion of synergetic opportunities and integrality are not currently considered for managing climate change adaptation (CCA). In order to address this gap, this chapter aims to develop a framework that effectively takes into account, the identified theoretical aspects and limitations for managing CCA.

Chapter 6: Interface Management in Inter-Organizational Projects: A Process Approach Towards Mutual Integral Insight and Coordination

The results from Chapter 4 emphasize that understanding and managing interfaces is vital in inter-organizational projects. By employing DSR, this chapter proposes a structured, continuous, five-step process aimed at gathering, organizing, integrating, and analyzing information to support IM within inter-organizational projects. The approach aims to enable the identification, understanding, awareness, and maintenance of a large number of interfaces, as demonstrated through its application to an inter-organizational project in the Dutch railway sector.

Chapter 2 Systems Control in Railway Transport, Challenges Towards Managing Integration

Abstract:

The growing demand for optimal rail mobility requires an efficient and well-integrated railway system, one which can cope with technical, logistical, and environmental constraints, to enable sustainable growth. This demand has led to numerous (proposed) changes in railways, including in the Dutch railway system. Because of this, managing systems integration is currently a trending topic. Besides technology, systems integration involves humans, organizations, processes, and information sharing. Hence, challenges related to systems integration can be manifold. In order to get insight into these integration challenges in practice, 43 semi-structured exploratory interviews are conducted in the Dutch railway context. In our qualitative data analysis, challenges are analyzed from two frameworks taking a systems perspective. This research reveals numerous challenges faced in this context, most dominant here is the desire to effectively manage changes. Specifically, our analysis and subsequent mapping on systems control theory show that many of these challenges revolve around effective control in the railway system. Finally, our research shows that future research should be aimed at gaining early insight and models on changes to be integrated into railway systems. In addition, the findings of this research can be used to help practitioners and researchers to work towards not only recognizing but also resolving the specified integration challenges.

Publication history:

This chapter was published in the proceedings of the 10th International Conference on Through-Life Engineering Services 2021:

Ramtahalsing, Merishna and Haanstra, Willem and Braaksma, Jan and Rajabalinejad, Mohammad and van Dongen, Leo, Systems Control in Railway Transport, Challenges Towards Managing Integration (October 18, 2021).

Available at SSRN: http://dx.doi.org/10.2139/ssrn.3944752

This publication's predecessor was published in the proceedings of the IEEE 15th International Conference of System of Systems Engineering (SoSE) 2020:

M. Ramtahalsing, M. Jafari, J. Braaksma, M. Rajabalinejad and L. v. Dongen, The System (of Interest) Definitions phase: Key features and challenges in the Dutch Railway system (July 1st, 2020)

Available at: IEEE: 10.1109/SoSE50414.2020.9130473.

2.1 Introduction

Over the last decades, there has been increased attention for seamless railway mobility across borders, especially in Europe. To achieve this mobility within and between countries, modern railway systems are currently adopting technologies like ERTMS (European Rail Traffic Management System) and ATO (Automatic Train Operations) (Dumolo, 2007; Rajabalinejad et al., 2019). These recent developments require integration to improve the functionality and efficiency of the rail system as a whole but are also making such systems increasingly complex.

To deal with these challenges, railway system stakeholders are progressively required to closely collaborate at the inter-organizational-, as well as the international level. In this context, stakeholders are more likely to have diverging views, skills, responsibilities, goals, behavior, and interests. In addition, to achieve interoperability of technical systems, different technical subsystems also have to connect and communicate seamlessly. Hence, different countries, distinct organizations, technical systems, departments, and regulations need to converge on the shared goal of optimal mobility system performance.

All of this requires extraordinary amounts of systems integration (SI) on different levels and requires functioning within increasingly complex networks with dynamic interconnections and in a changing environment (Rajabalinejad & van Dongen, 2018).

SI is an omnipresent concept involved in nearly every aspect of the engineering of large systems and systems management (Sage & Lynch, 1998). It can be defined as the process of bringing together subsystems into one system and ensuring that the subsystems function together as a whole (International Standardization Organization, 2015; Madni & Sievers, 2010). It is the integration of subsystems and components that gives systems their superiority over a set of elements that do not work together without integration(Sage & Lynch, 1998). At its core, SI is a strategic activity that is integral to business management and cuts across technical, management, and strategic levels (Madni & Sievers, 2010). Moreover, SI ensures that appropriate communication occurs between technological, human, and organizational elements required to work together. Because of the aforementioned trends, and because systems continue to grow in scale and complexity, managing SI is a key concern within the railway sector.

2.1.1 Systems integration as an enabler of system performance

All novel and increasingly complex technologies previously mentioned are aimed at improving railway system performance. To achieve this, these changes need to be integrated into the existing railway context. This requires effective control and management, efficaciously shifting the focus on what needs to be integrated (or not).

The current literature mentions a diverse set of challenges related to SI. For example, Madni & Sievers (2010) mention that (1) integration with legacy systems, (2) lack of common language for communicating among disciplines, and (3) difficulties at interfaces are among these. Moreover, they state that the latter, interfaces, are where nearly all SI failures occur. In their follow-up research, Madni & Sievers (2014) indicate that SI is hampered by (4) the lack of common terminology and (5) the lack of clear definitions of technical and nontechnical interdependencies.

Furthermore, current literature pays some attention to SI challenges in railways specifically. I.e. Rajabalinejad (2018) mentions that (1) the degree of fragmentation of the rail systems and its interconnectivity, (2) the multi-stakeholder nature of decision-making, (3) the variety of views of stakeholders, (4) the numbers of (revised) rules and regulations, (5) and the arrival of modern technology may impose specific risks to the rail industry.

While SI has been narrowly defined in some industries by rigorous methodologies that achieve specific goals, the suitability of these methods to other industries such as the railway industry is not necessarily seen as practical (Madni & Sievers, 2010). In contrast to organizations such as NASA, system cost and integration capacity are limited in the railway sector.

The aforementioned literature mostly positions SI as ‘an end in itself’ whereas we posit that SI should be regarded more as ‘a means to an end’. In order to improve railway systems’ performance, changes need to be managed. This position draws attention to which aspects of the system require what level of integration, thus aiding capacity allocation. As such, we investigate SI from the perspectives of safety control and systems control in this article. In order to better understand the SI challenges in the railway context, their respective magnitudes, and to pinpoint the key factors that enable more effective SI, a series of interviews was carried out in the Dutch railway sector.

2.2 Methodology

To explore and identify SI challenges in the railway context, 43 semi-structured exploratory interviews were carried out in the Dutch railway sector and mapped on two consecutive frameworks.

This problem-oriented exploration will not only aid practitioners in recognizing these challenges but can also aid researchers and practitioners in finally resolving them.

2.2.1 The Dutch railway system

The Dutch railway system is divided into a core network and peripheral lines (Leijten & Koppenjan, 2010). The Dutch rail transport services were privatized in the 1990s and split into independent railway infrastructure manager (ProRail) and main railway operator Netherlands Railways (NS) (Leijten & Koppenjan, 2010). This separation of railways infrastructure manager and railway operator means that there is a limit to the improvements that can be achieved if they cannot work together effectively (Association of European Railway Industries, 2010).

2.2.2 Approach

The interviews at the infrastructure managing- and main railway operating organization were carried out within different organizational layers, in distinct departments to obtain a comprehensive understanding of SI challenges. Interviewees included: asset managers, change managers, network designers, innovation managers, operation managers, project managers, program managers, safety managers, safety specialists, (systems) engineers, system/infrastructure architects, train drivers, & quality managers. These interviews were transcribed and afterward analyzed using qualitative data analysis software ATLAS.ti, the process of which is shown in Figure 2.1.

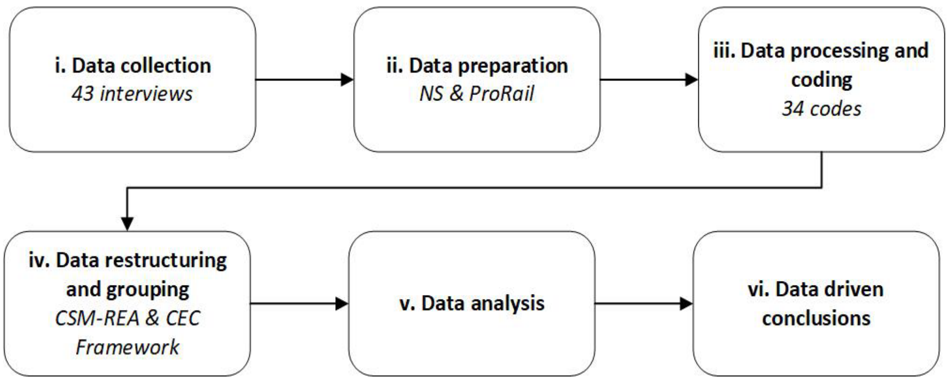


Figure 2.1: Data analysis process

This iterative process consists of (i) conducting the interviews and documenting these; (ii) grouping the interviews based on organization; (iii) manual data processing and coding based on SI issues mentioned during the interviews with help of the software's coding options open-, in-vivo- and list coding; and (iv) structuring and regrouping the analyzed data in order to discover patterns and relationships. This led to (v) a structured analysis of all the data from which (vi) data-driven conclusions could be derived.

Moreover, this process has been carried out with multiple researchers to improve the validity of the analysis. From this point on, 'codes' & 'challenges' will be used interchangeably throughout the paper.

To better understand the obtained data, the codes were mapped on two different frameworks (step iv). Initially, the Common Safety Methods on Risk Evaluation and Assessment (CSM-REA) (European Railway Agency, 2009b) was applied for data grouping. Subsequently, the 'Conditions for Effective Control' (CEC) framework (De Leeuw, 2002) was used to provide a second data grouping, as the CSM-REA did not fully map to the identified codes.

2.2.3 Common Safety Methods for Risk Evaluation & Assessment (CSM-REA)

The CSM-REA process, shown in Figure 2.2, is applied at the beginning of railway change projects to ensure that all applicable hazards are identified and managed. Risk management frameworks like this are required to fulfill obligations under the law, hence are quite well known in the Dutch railway context. The CSM-REA considers railway system safety from a systems perspective. It includes technical, operational, or organizational changes, which could impact the operating conditions of the railway system (Rail Safety & Standards Board, 2017).

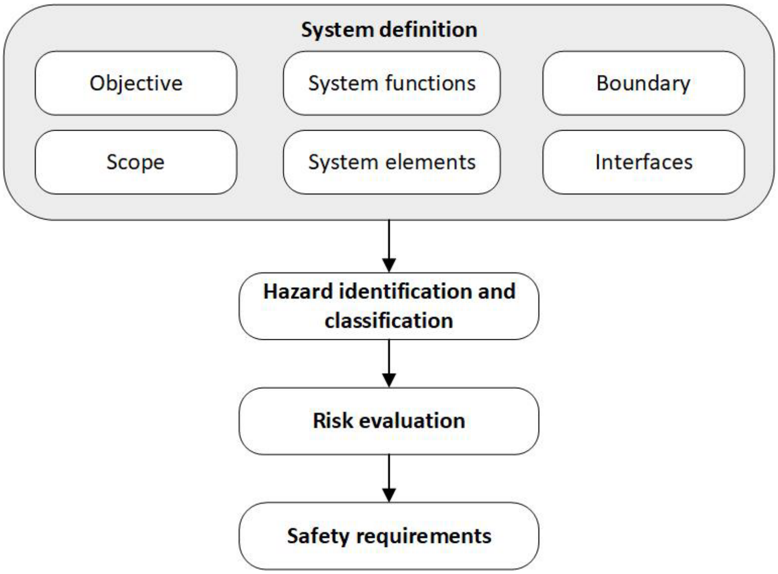


Figure 2.2: CSM-REA process adopted from Rail Safety & Standards Board (2017)

These regulations aim to implement changes safely within the railway system by using a structured standardized process for identification and evaluation which includes (Ramtahalsing et al., 2020):

- Identifying what the change entails with respect to objective, boundary, scope, elements & functions, and interfaces.
- Determining and classifying hazards.
- Identifying the magnitude of identified hazards.
- Requirements for managing hazards effectively.

Because SI is aimed at improving system performance by integrating changes in the existing railway system, the CSM-REA framework seemed fitting by broadening its scope from the safety perspective to an SI perspective i.e., using a structured process for code mapping.

Mapping codes on this framework, however, showed that a significant amount of the identified SI challenges did not necessarily fit one category, but could be fit onto multiple categories, as will be explained in Section 2.3. Additionally, the CSM-REA focuses mainly on evaluation not necessarily on planning and control (Maylor & Turner, 2017).

To upgrade railway system performance, different changes are required to be integrated, requiring purposeful influencing/controlling of part of an organization or system. This led to the second framework by de Leeuw (2002), which takes a systems perspective on conditions for effective control.

2.2.4 Conditions for Effective Control (CEC)

De Leeuw (2002) describes five conditions for effective control of systems from a systems viewpoint. This approach pays attention to problem orientation, thinking in contexts and processes, and thinking in systems and environments.

The conditions of this framework are based on the idea that a system is to be brought or kept in its desired state, which is precisely the case in railways. He states that effective control of a system is not possible until the conditions in Table 2.1 are met (De Leeuw, 2002).

The results of these comprehensive analyses will be further elaborated in Section 2.3.

Table 2.1:Five conditions for effective control from de Leeuw (2002)

CEC step	Description
Objective	Without an objective i.e., without a clear picture of the desired state of the system, it is impossible to determine whether the steering is effective.
Model of controlled system	To be able to influence a system, hence, to decide whether to take control measures, one must be able to predict the effect of measures. After all, a measure is chosen to bring about a certain effect. This requires a model that can approximately answer the question: How will the state of the system change if I take this measure?
Information about environment & state of the system	The future state of the controlled system is determined by the current state of the system, changes in the environment of the system, and the relationships between the elements of the system. Control, therefore, requires information about the state of the system and its environment.
Sufficient control measures	Influencing requires control measures; instruments with which the state of the system could be changed. In order to be able to control effectively, the number of available control measures must be in reasonable proportion to the variety of circumstances that can occur.
Information processing capacity	It is necessary to transform incoming information about the environment and state with the help of the model and take into account the objective into an effective measure. Hence information must be processed, requiring sufficient information processing capacity.

2.3 Results and discussion

Due to the amount of data available, different cross-sections were made of the analyzed data. These cross-sections are shown in Table 2.2.

Table 2.2: SI challenges faced in the Dutch railway context, through different cross-sections.

Cross-section	Description
Code frequency	Manual (iterative) data processing and coding based on SI issues mentioned during the interviews.
Mapping on CSM framework	Mapping the codes on the CSM framework in Figure 2.2.
Mapping on CEC framework	Mapping the codes on the CEC framework described in Table 2.1.

2.3.1 SI challenges based on code frequency

The analyzed data resulted in 34 codes, challenges, and improvement opportunities regarding SI in the Dutch railway context, depicted in Figure 2.3. Due to space limitations within this paper, only approximately 50% of the challenges identified based on code frequency (corresponding to 9 challenges) will be explained in detail in Table 2.3.

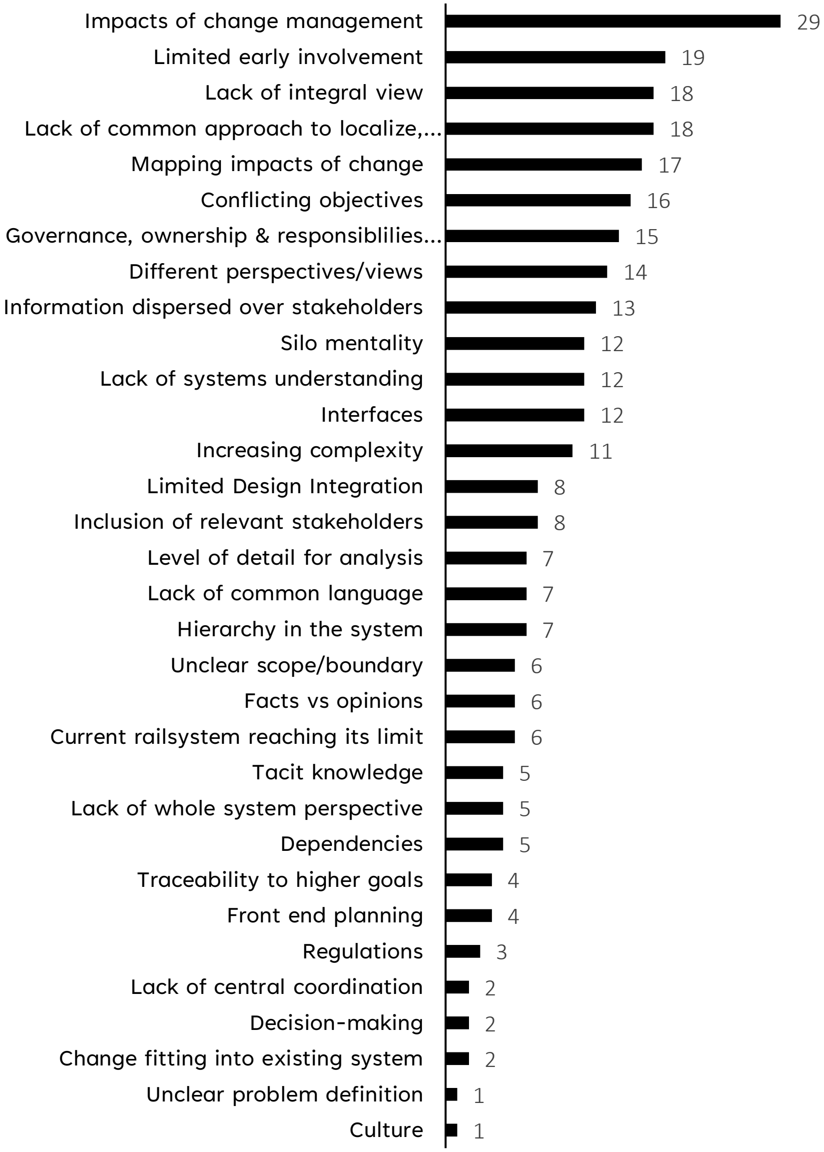


Figure 2.3: Code frequency of SI challenges

Table 2.3: 50% of SI challenges based on code frequency

Code	Description
Impacts of change management	Challenges in managing the impacts of a change. In the event of a change, what does that mean for the larger system? What other parts, (sub)systems, organizations, regulations, processes need to be taken into consideration to facilitate smooth SI (of the change).
Limited early involvement	The relevant stakeholders are not all involved early on in the SI process.
Lack of integral view	Impacts of changes are not viewed integrally: not viewed from a whole-systems perspective.
Lack of common approach to localize...	There is no common, generally accepted approach in this context to determine the impacts of change.
Mapping impacts of change	Creating insight in parts, (sub)systems, organizations, regulations, processes required to be taken into consideration to facilitate smooth SI.
Conflicting objectives	Conflicting objectives can occur between organizations. This certainly does not encourage SI.
Governance, ownership &	The ambiguity of mentioned aspects, due to increased complexity, numerous stakeholders, and overlapping system boundaries.
Different views	There are many different views within organizations, how people look at the system from their perspective. This could alter goals and scope.

2.3.2 Frameworks

As stated in Section 2.2, the codes were firstly mapped on the CSM-REA framework. The results of this mapping are shown in the Sankey diagram in Figure 2.4. Following this, the codes were mapped on the CEC framework, of which the results are shown in Figure 2.5. These diagrams indicate the relative frequencies: the distribution of coding across the framework categories concerning the infrastructure manager (ProRail) and main railway operator (NS).

2.3.2.1 Mapping on CSM-REA

The mapping in Figure 2.4 shows that **Scope, Interfaces**, and **Boundary** are among the largest identified code groups influencing SI. This indicates that SI is affected by difficulties identifying what exactly the change is (Figure 2.2). Interestingly, this mapping also shows that numerous challenges were identified that did not necessarily fit one-on-one onto the framework. During the mapping process, it became apparent that a significant portion (35%) of the codes i.e., ‘limited early involvement’, ‘silo mentality’, and ‘lack of common language’, covered all topics in the framework. Hence, were grouped as **Overarching**.

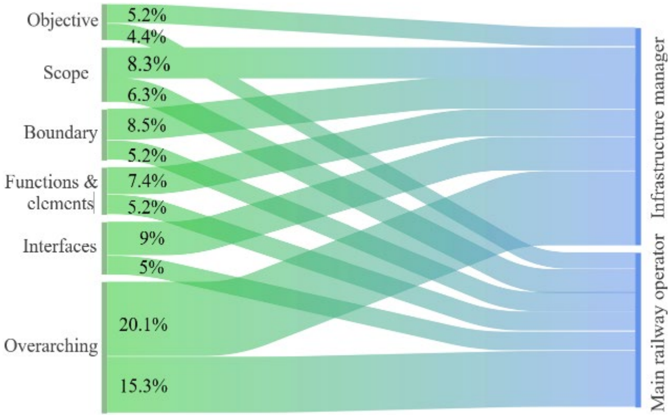


Figure 2.4: SI challenges mapped on the CSM-REA framework, indicating relative frequencies

Because **Overarching** appeared to be the largest code group after mapping on this framework, limited conclusions could be drawn from this framework. For this reason and, because this framework focuses mainly on evaluation not necessarily on planning and control, the codes were mapped on the CEC framework.

2.3.2.2 Mapping on CEC framework

Mapping the codes on the CEC framework resulted in the Sankey diagram in Figure 2.5. All challenges could be mapped on this framework, except for one: 'Culture' which accounts for 0.17% of the identified challenges.

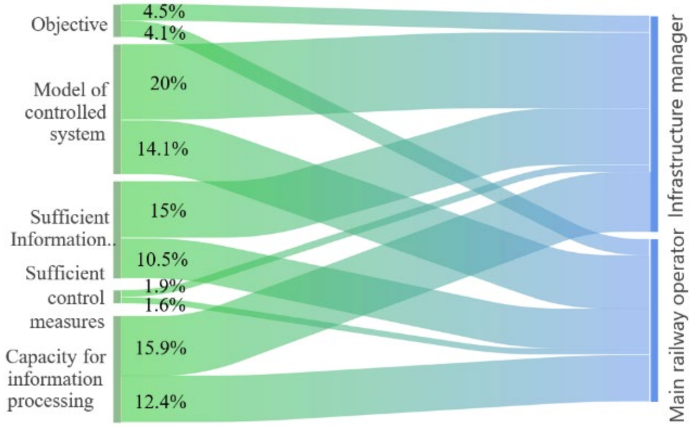


Figure 2.5: SI challenges mapped on the CEC framework, indicating relative frequencies

This figure allows us to interpret the challenges from another angle:

1. **Objective:** (1) Conflicting objectives between organizations, (2) silo mentality, and (3) different views/perspectives.
2. **Model of the controlled system**: In this case of the railway system as a whole, but also of changes required to be implemented. This is among others due to: (1) increasing system complexity, (2) silo mentality, (3) lack of common language, (4) lack of common, integral approach to mapping the impacts of changes in a complex context.
3. **Information concerning the environment and state of the system**: This is due to similar factors indicated in the previous point. In addition, limited early stakeholder involvement and interfaces/interdependencies are also mentioned as challenges in this group.
4. **Sufficient control measures**: A lack of control measures is indicated as the smallest SI challenge. This could mean, that according to interviewees, increasing control measures would not necessarily aid in managing SI in the Dutch railway sector. Another hypothesis is that the interviewees do not have the desire or ability to control the system as the pre-requirement of having a model of what to control, is limited.
5. **Information processing capacity**: This is impeded by (1) information dispersion across stakeholders, (2) lack of a common, integral approach to mapping impacts of changes in a complex context, (3) governance, ownership & responsibilities crossing blurred boundaries and, lack of systems understanding.

Based on this mapping, the following three factors from the CEC framework best matched SI challenges: **(1) a model of the controlled system, (2) information processing capacity, and (3) Information concerning the environment and state of the system**. Moreover, the Sankey diagram also shows that the mapped results from the main railway operator and the infrastructure manager differ percentages from each other, hence are more or less comparable.

2.4 Conclusion

As systems continue to grow in scale and complexity, managing SI has become a key concern. SI can be seen as ‘a means to an end’ that supports appropriate communication between technological, human and organizational elements, aimed at improving system performance. Consequently, the challenges related to SI can be similarly broad, varied, and of growing concern to railway organizations.

In order to investigate these challenges in the context of the Dutch railway sector, a series of interviews were carried out at the infrastructure managing- and main railway operating organization. Among the most frequent codes from the interviews were (1) 'Impacts of change management', (2) 'Limited early involvement', and (3) 'Lack of integral view'. This indicates the need for an SI overview and the need for actively managing SI challenges.

Mapping the challenges on both the CSM-REA and the CEC framework showed that the mappings to the infrastructure manager in comparison to the main railway operator are more or less comparable.

The mapping on the CSM-REA framework revealed that **Scope, Interfaces,** and **Boundary** are among the largest identified code groups influencing SI. This indicates that like CSM-REA, SI challenges also depend on clear objectives, boundaries, scopes, elements & functions, and interfaces. However, not all SI challenges fit neatly onto the CSM-REA framework leaving a significant part of the codes classified as **Overarching**. Hence, another perspective on the challenges was provided by looking at the CEC framework.

Except for one code ('Culture'), all determined challenges could be mapped on the CEC framework. This indicates that SI also depends on (1) **a model of the controlled system**, (2) **information concerning the environment & state of the system**, (3) **sufficient information processing capacity**, (4) **sufficient control measures**, and (5) **objective**, to get and/or keep systems in its desired state. For the Dutch railway system, the first three of these factors best matched the identified SI challenges. The results indicate that a model of the railway system and of changes required to be implemented are considered to be a prerequisite for effective systems control. If such a model is lacking or cannot indicate changed system states, the influence and control of these systems will be challenging at the least. This integration challenge is not only a challenge for the individual railway stakeholders, but it can also hinder the overall aim of achieving better overall railway system performance at the (inter)national level.

In conclusion, most of the discussed SI challenges are concerned with (i) effectively determining what exactly is being changed, (ii) the scope of this change, and (iii) how this change would fit within the existing railway system. The existence of these challenges may hinder the effective control of this system, especially considering that it is becoming increasingly complex. Further research is therefore required to help practitioners and researchers recognize and resolve the underlying SI challenges.

2.5 Future research

Based on the research conducted in this paper, several opportunities for future research are proposed: (1) For each of the identified challenges, e.g., impacts of change management in complex railway context, further research could aid in trying to resolve these. (2) Determining causal relationships (and loops) between the codes, can help identify reinforcing and balancing loops. This could help indicate dynamic behavior in the Dutch railway sector.

Acknowledgments

This research is co-financed from the Research and Innovation contribution (PPP) from the Dutch Ministry of Economic Affairs and Climate. The authors acknowledge the support of the NS and ProRail, making this research possible through the framework of the SIRA project.

Chapter 3 Application of System Definitions as a Foundation for Risk Assessments: A Multiple Case Study in the Dutch Railway System

Abstract:
In railway transportation, countless new (sub)systems and modifications to existing systems are continuously integrated to achieve desired levels of system performance. Existing literature emphasizes that system definitions appropriately describing such changes are critical prerequisites for successful risk assessment to ensure safety. Although literature sufficiently addresses the content of such system definitions, direct and thorough comparisons between theoretical best practices, and examples of industrial practice are scarce. To fill this gap, this paper summarizes the most prominent descriptions and assumptions present in the literature concerning system definitions into five postulates. These postulates are compared to industrial practice using a multiple case study conducted in the Dutch railway system. The results reveal divergent views on the usefulness and necessity of system definitions. A clear goal, domain expertise, and the involvement and collaboration of multiple experts seem to be crucial in the process of creating a system definition. Despite their importance, these elements are often considered on an ad hoc basis. Furthermore, although system definitions are iteratively developed, they are rarely updated afterward, causing them to lose their relevance as changes occur. Based on this analysis, several factors are identified in developing and maintaining system definitions that require attention, especially in case of more complex inter-organizational changes.

Publication history:
This chapter was submitted to the Safety Science Journal and is under review at the time of writing.

3.1 Introduction

In the field of railway transport, numerous modifications and new (sub)systems are constantly being integrated in order to achieve the desired system performance (Guerrieri, 2022). The rapid development of features such as railway heavy-haul, high-speed, electrification, automatic train operation, and electronic signaling systems, introduce new safety risks to the railway system (Liu et al., 2020). These trends result in railway transportation becoming increasingly automated and more dependent on safety-critical systems.

The European Union Agency for Railways (2020) states that whenever a new element is introduced into the railway system or an existing element is modified, regardless of the significance of that change, this should be safely integrated, ensuring that: (1) the new or modified element is compatible, and thus correctly interfaces with the other parts of the system into which it is introduced; (2) the impacts of human and organizational aspects on the operation and maintenance of that element and on the system are assessed and properly addressed; (3) the introduction of that new or modified element into its physical, functional, environmental, operational, and maintenance context does not have unintended, adverse and unacceptable effects on the safety of the resulting system into which it is being incorporated.

To ensure this, risks related to the integration of such changes are usually managed using methods and tools, including risk assessments, which can be regarded as the core elements of risk management (Liu et al., 2020). Kluppenberg et al. (2014) state that a risk assessment is a formalized approach to determining and assessing risk, with the objective to demonstrate that all identified hazards and risks associated with a proposed change are suitably understood and controlled to an acceptable level. Figure 3.1 shows that such risk assessments mainly include system definition, risk analysis, and risk evaluation.

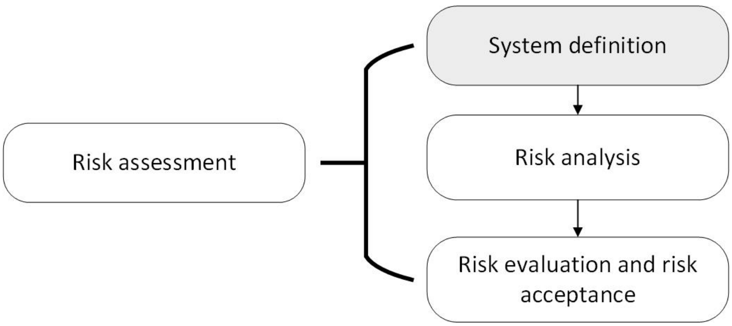


Figure 3.1: SD as a basis for risk assessment, adapted from CENELEC (2015)

The first step in the risk assessment is to develop a system definition (SD), which encompasses a clear definition of the investigated change and related scope, also referred to as the system of interest (SOI). The information within an SD influences the effectiveness of the risk assessment process (Høj & Kröger, 2002).

3.1.1 System definition as a basis for risk assessment

Hatfield & Hipel (2002) define SD as: *"the process of specifying the system that will be considered in the risk assessment and the definition of the risk measure that will be extracted from that system."* Largely, this constitutes deciding which information and interactions to include or to exclude, with the representation being a model of the relevant part of reality used for the evaluation (Hatfield & Hipel, 2002). Pasquini (2011) refers to this as defining the SOI by an SD, and considers this an important step in risk assessment: it should include everything required to effectively assess risk related to a change. This ensures a degree of certainty that an appropriate understanding of the system exists and that the risks and effectiveness of the strategies can be determined (Hatfield & Hipel, 2002).

The SD describing the SOI should include (CENELEC, 2015; Klüppelberg et al., 2014):

(1) The system objective, the intended purpose;

(2) The system boundaries, these can vary in nature, geographical (i.e. there is a need to assess the safety in a specific area), technical (i.e. the assessment concerns a certain component), or operational (i.e. the assessment concerns a specific procedure);

(3) The clarification of the interfaces to other systems, including the input that is required, and the output that can be expected (i.e. interfaces and interactions with other technological systems, people, and/or other stakeholders);

(4) The scope of operational requirements influencing the system;

(5) A description of the essential characteristics and functions of the system.

The combination of these factors limits the area of interest, and as such, the scope of the investigation. Moreover, it clarifies that elements outside of the considered SOI are not included in the analysis (Hackl et al., 2017).

Once the SOI is defined, safety experts can start identifying and listing the potential hazards which are caused by, and/or affect the system, thereby negatively impacting safety. The final SD and proposed risk measures reflect what the risk assessors deem to be important, and will greatly influence the final risk evaluation (Hatfield & Hipel, 2002).

The railway industry is a typical example of a sector in which ensuring the safety of operations is essential, as this sector operates within increasingly complex networks with dynamic interconnections and in a changing environment (Rajabalinejad & van Dongen, 2018). The Rail Safety and Standards Board (2014) states that the development of a suitable SD is a critical part of any successful risk assessment process, and therefore, a considerable amount of attention should be paid to SDs in this context.

3.1.2 System definitions in the railway industry

At European level, there is an increasing push for harmonization of many aspects of railway operation, and that includes all safety aspects (Mateu et al., 2021). In this regard, the European Railway Agency (2009) mentions the need to describe such changes: *“When incorporating a new element into the railways, or modifying an existing one, the change must be clearly and completely described, as well as limits of the railway system where the change is integrated (whether technical, operational, or organizational).”* According to the European Union's Agency for Railways (2020), an exhaustive SD is most pertinent to and critical for, comprehensive risk management and safe integration. This should provide insight into the change and describe all interfaces between the change, human operators, or subsystems, clearly and completely.

The European Railway Agency (2009b) states that whenever a change to a railway system is proposed, whether technical, operational, or organizational, it must be considered if this change has a significant impact on the system. In order to assess this significance, an SD should be developed. This is an analysis of what is being changed to the current working system (Rail Safety & Standards Board, 2014), irrespective of whether it concerns a piece of equipment, a procedure, or an organization.

For these reasons, several international standards and regulations (CELENEC, 2017; CENELEC, 2015) pertain to this issue. The NEN-EN 50126-1 norm, the Specification and Demonstration of Reliability, Availability, Maintainability, and Safety (RAMS) for railway applications states that before any analysis relating to RAMS is undertaken (e.g., hazard identification), an SD needs to be established. Additionally, according to the European Railway Agency, the Common Safety Methods for risk assessment and evaluation (CSM-REA) describe how the safety levels, the achievement of safety targets, and compliance with other safety requirements should be reached.

The adoption of the CSM method aims to achieve a standardized safety approach (Mateu et al., 2021). CSM-REA is applied at the beginning of railway-related projects in order to ensure that all applicable hazards are identified and managed. In the event of a change in organization, operation, or technology, a CSM-REA should be conducted by the initiator of this change: this process is initiated by creating a preliminary SD (Bearfield & McDonald, 2013; Rail Safety & Standards Board, 2017). Risk management frameworks such as this one are required to fulfill obligations in accordance with applicable laws and have to be submitted to the regulator for approval.

3.1.3 Gaps

Roe & Schulman (2018) indicate that the priority role given to SDs, especially when it concerns large-scale critical infrastructure when seeking to improve risk assessment and management, is not new. However, based on their observed long-term study it appeared that professionals, including risk managers both inside and outside the (infrastructure) systems studied, do not start with the SD describing the change that is to be operated and managed. They skip the SD step and instead start with the management of the (assumed) risks associated with the change. Skipping the SD step can lead to numerous challenges, as the experts involved may have a different implicit understanding of the SOI (Roe & Schulman, 2018). Additionally, Mauborgne et al (2016) mention that safety analysis processes and activities are usually performed with a silo mentality. Thus, safety engineers may misunderstand the SOI, which may result in errors. In line with this, Hatfield & Hipel (2002) demonstrate that the use of different SDs among stakeholders is at the root of many disagreements.

All of this can, for example, cause confusion and errors in the event multiple researchers or practitioners work on the same problem related to an assumed and implicit SOI (Cumming & Collier, 2005), which can cause challenges to effective communication and understanding of interfaces (B. Haskins & Striegel, 2006). Additionally, Barnatt & Jack (2018) mention current systems tend not to operate in isolation. As such, when changing and introducing these systems, sufficiently considering the interaction between the change and the existing environment can be challenging.

Consequently, these challenges can negatively affect performance and planning and can lead to expensive changes, delays, rework, and cost overruns (Fageha & Aibinu, 2014; Mirza et al., 2013). This means that an integral SOI view may prove vital, as general agreement on the SD among stakeholders, appears to result in agreement regarding final decisions (Hatfield & Hipel, 2002).

In summary, although the development and understanding of an SD appear to be a logical first step for risk assessment, the existing literature concludes that this step is not always conducted. Furthermore, although the current literature, laws, and regulations stress the importance and contents of SDs, and what needs to be included in order to adequately describe the SOI, this is not satisfactorily reflected in the literature concerning the development and use in industrial practices.

3.1.4 Aim and research focus

Currently, the dependency of railway transport on the number and type of safety-critical systems is ever-increasing, and safely integrating them is vital. Therefore, it is essential to identify whether the existing literature still supports the risk assessment of these systems, or whether there is a mismatch between the current literature and practice. As such, this paper aims to examine whether a number of assumptions found in the literature concerning SDs as a basis for risk assessment and their use are supported by empirical evidence, as well as explore possible reasons for organizations to deviate from what is generally assumed in the literature. Moreover, this study aims to gain an improved understanding of the factors that contribute to the successful development of SDs in practice, by conducting a multiple case study in the Dutch railway system.

This paper is organized as follows: Section 3.2 discusses the methodology, Section 3.3 describes the case study context, after which, in Section 3.4, the postulates are derived from existing literature. This is followed by Section 3.5, which presents results based on empirical findings and Section 3.6 presents the discussion as well as suggestions for future research. Finally, Section 3.7 concludes the paper.

3.2 Methodology: Case study and postulates

The methodology used in this article consists of applying postulates within case study research. Case study methods allow investigators to retain the holistic and meaningful characteristics of real-life events (Yin, 2003). Essentially this method attempts to highlight why certain decisions were taken, why these were implemented, and with what results (Yin, 2003).

Moreover, case studies are the preferred strategy when ‘how’ or ‘why’ questions are posed (Yin, 2003). In this sense, they can aid in understanding possible reasons for organizations to deviate from what is generally assumed in the literature.

Furthermore, Yin (2003) also states that case studies benefit from the prior development of theoretical propositions in order to guide data collection and analysis, and as such, this paper makes use of postulates. The term 'postulate' refers to a commonly accepted truth, which serves as a starting point for deducing and inferring other (theory-dependent) truths (Braaksma, 2012). The confirmation, or lack thereof, of conceptual insights found in the literature, is organized around these postulates.

This paper formulates postulates based on several common assumptions regarding SDs found in the literature. Each postulate is derived from a focused review of the relevant literature related to its respective topic. Subsequently, these postulates are either refuted, qualified, or elaborated on, based on the empirical findings from the case studies.

3.2.1 Procedure

In case study research, data collection procedures are not routinized, which increases the reliance on a well-defined procedure as well as the skills of the researcher (Yin, 2003). Yin (2003) also emphasizes that the researcher requires an inquiring mind during data collection, and needs to pose appropriate questions in order to reach the desired result. The procedure conducted in this research is represented in Figure 3.2.

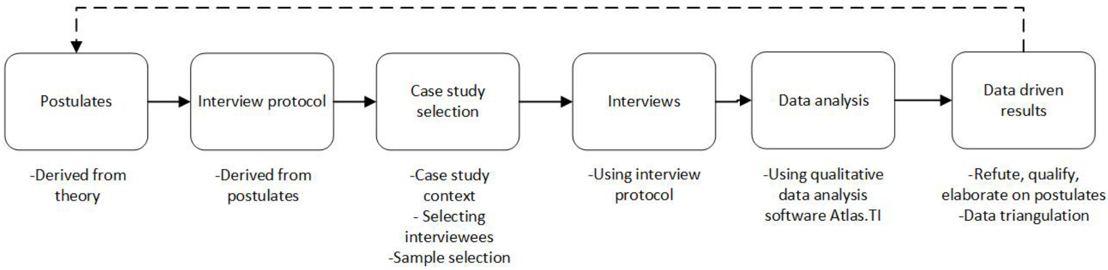


Figure 3.2: Research procedure

3.2.1.1 Postulates

The postulates employed in this article are structured according to the well-established CSM-REA framework presented in Section 3.1.2, which indicates the main steps applied in risk assessment and in which SD forms the foundation.

3.2.1.2 Interview protocol

To maintain consistency across the data obtained from each conducted interview, a structured interview protocol was developed in order to gather data for the study. The interview questions in this protocol were developed using the established postulates.

The protocol, which can be found in Appendix A-1, was pre-tested with researchers to ensure that the questions were unambiguous.

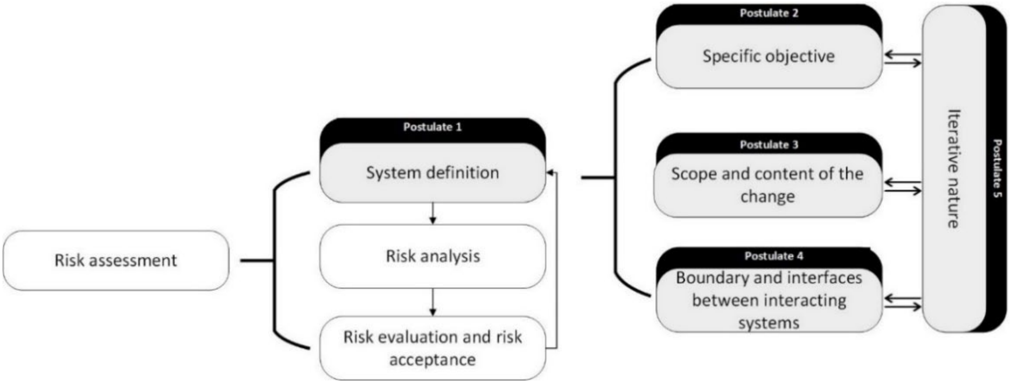


Figure 3.3: Main steps of the CSM-REA framework and positioning of the postulates

3.2.1.3 Case study selection

To examine whether certain assumptions in literature concerning the application of SDs in risk assessment can be supported by sufficient empirical evidence, it was essential to explore and better understand the reasons why organizations deviate from what is generally suggested by literature.

Firstly, a case study context was determined. Secondly, in order to ensure a representative overview of empirical practices, a wide range of cases and related SDs were necessary in this context. To realize this, the following case selection criteria were employed: (1) the scope of the change, (2) the approximate costs associated with the change, (3) the novelty of the change, (4) the complexity of the change, (5) the inter-, and/or intra-organizational nature of the change, (6) the project duration, (7) the reversibility of the change, and lastly (8) the possible impacts of the change. This resulted in 13 case studies, summarized in Table 3.2.

Within the case study context, interviewees were selected based on their in-depth knowledge of, and senior experience with the application of the CSM-REA process in diverse projects, and personal experience with the development and use of SDs in the risk assessment process of various changes to be implemented. Furthermore, multiple units of analysis were taken into account per interview.

3.2.1.4 Interviews and transcription

For each selected interviewee, the structured interview protocol was used, and these interviews were transcribed. Moreover, during the interviews, additional data sources, such as written documentation and presentation materials were provided by the interviewees, which complemented and/or clarified their accounts.

3.2.1.5 Triangulation

In addition to the structured interview protocol, triangulation was used. Multiple sources were used throughout the research to supplement the findings, adding rigor, breadth, and depth to the study (Yin, 2003). This included documentation, a longitudinal case study, research of archival documents, exploratory- and semi-structured interviews, joining and observing multiple expert sessions held within the respective organizations, and surveys on the use and usefulness of SDs.

3.2.1.6 Data analysis and results

Once obtained, the interview data was structured and labeled to allow for cross-case analysis. To facilitate this process, the qualitative data analysis software ATLAS.ti was used. This iterative process consists of (1) interview documentation, (2) data processing and coding aided by coding options provided by the software, and (3) structuring and regrouping the analyzed information in order to discover patterns and relationships, which resulted in (4) data-driven conclusions. Based on the results from the analysis, the derived postulates could be refuted, qualified, or elaborated on.

Furthermore, throughout this process, multiple measures were taken to ensure the validity and reliability of the research, as summarized in Table 3.1.

Table 3.1: Ensuring validity and reliability

Criterion	Implementation
Construct validity	Involvement of multiple cross-organizational interviewees, and validation of the obtained results by interviewees
Internal validity	Research framework, pattern matching using postulates, and structured data analysis using qualitative data analysis software
External validity	Selections of interviewees from throughout the railway system with a high degree of experience based on numerous projects with diverging goals, scopes, and types of changes
Reliability	Structured case study protocol, fixed case study questions, structured documentation of interview data

3.3 Case study context: The Dutch railway context

The Dutch railway system was used for this research as the case study context. Due to legislation by the European Union, previously nationalized railway companies have been split up into different, smaller companies. In the Netherlands, for example, the state-owned organization ProRail is solely responsible for the infrastructure, while there are several passenger and freight operators (Huisman et al., 2005; Leijten & Koppenjan, 2010; Nakamura & Sakai, 2022). The Netherlands Railways (Nederlandse Spoorwegen NS) is by far the largest passenger railway operator (Merkus et al., 2017).

During the previous decades, there has been an increased focus on seamless railway mobility across borders, especially in Europe (Guerriero et al., 2022). As a result, existing railway systems, such as the Dutch one, are adopting novel technologies to achieve mobility within and between countries, particularly concerning control and communications (Dumolo, 2007). These developments need to be integrated in order to improve the functionality and efficiency of the railway system as a whole (Dumolo, 2007) and require the corresponding risks to be managed accordingly.

3.3.1 Case study selection

Interviewees were selected from within the Dutch railway system based on their in-depth knowledge of, and senior experience with the CSM-REA process, as applied to numerous diverse changes and associated projects, as well as their personal experience with the development and use of SDs as a basis for this risk assessment process, for which guaranteeing the safety levels is/was essential. Interviewees in this context included senior engineers, safety managers, QHSE specialists, infrastructure managers, and program managers employed by either NS or ProRail. The expertise of the interviewees covered a variety of changes, ranging from completed projects to projects currently in progress, and projects expected to start in the near future. Moreover, as stated in the previous section, multiple criteria were employed for the selection of case studies, as summarized in Table 3.2, where the case studies are classified by criteria. Detailed information on the scoring per category can be found in Appendix A-2.

Table 3.2: Overview of changes, distinguished based on their scope, costs, novelty, complexity, inter- and intra organizational nature, duration, reversibility, and impacts. Colors distinguishing the smallest-largest scales

System Definitions as used in:	Short description	Scope	Costs (€)	Novelty	Complexity	Intra- or Inter-organizational	Duration	Reversibility	Technical, Organizational, and Operational Impacts
Automatic train operations (ATO)	ATO is a technology used to automate the operation of trains to various degrees	multiple changes, affecting the whole railway system	> 100 mil	Very High Novelty	Very Complex	Inter	>5 Years	Somewhat reversible	Multiple
European Railway Traffic Management System (ERTMS)	Standards for management and interoperation of signaling for railways by the European Union	multiple changes, affecting several organizations	> 100 mil	High Novelty	Very Complex	Inter	>5 Years	Not reversible	Multiple
Train introduction	The introduction of new trains to the railway system	multiple changes, affecting the whole railway system	between 10 and 100 mil	Medium Novelty	Complex	Inter	>5 Years	Somewhat reversible	Multiple
High-frequency scheduling	Multiple simultaneous extensive modifications to the railway infrastructure, allowing for higher frequency scheduling and increased line capacity	multiple changes, affecting several organizations	> 100 mil	High Novelty	Very Complex	Inter	>5 Years	Not reversible	Multiple

Table 3.2 - continued

Train modernization	Adapting trains to meet modern or updated needs and/or habits	multiple changes, affecting several organizations	> 100 mil	Medium Novelty	Complex	Intra	Between 1 and 5 Years	Not reversible	Multiple
Train-towing vehicle	The vehicle tows trains stranded on the high-frequency railway network.	multiple changes, affecting several organizations	Between 1 and 10 mil	High Novelty	Very Complex	Inter	Between 1 and 5 Years	Reversible	Multiple
Signaling systems within railway infrastructure	Multiple modifications in the signaling system accommodating high-frequency train schedules	multiple changes, affecting several organizations	Between 1 and 10 mil	High Novelty	Very Complex	Inter	Between 1 and 5 Years	Not reversible	Multiple
Stickering trains and stations	Stickering trains and stations during the Covid-19 Pandemic	medium change, affecting multiple departments	<1 Million	Low Novelty	Not Complex	Inter	<1 Year	Reversible	Multiple
Modifications of train seats	Modifications of e.g., the color of the train seating	medium change, affecting multiple departments	<1 Million	Low Novelty	Somewhat complex	Intra	Between 1 and 5 Years	Somewhat reversible	Multiple
LED lights	Replacing lights with LED lighting in trains	medium change, affecting multiple departments	<1 Million	Medium Novelty	Somewhat complex	Intra	Between 1 and 5 Years	Somewhat reversible	Multiple
Modifying storage tank	Replacing the 5L storage tanks for coolant within heat exchangers in trains with 40L ones	small change, affecting 1 department	<1 Million	Low Novelty	Not complex	Intra	<1 Year	Reversible	Technical
Speaker sound levels	Reducing the sound level of speakers	small change, affecting 1 department	<1 Million	Low Novelty	Not complex	Intra	<1 Year	Reversible	Technical
Cockpit power outlets	Changing the power outlets for the train drivers in the cockpits	small change, affecting 1 department	<1 Million	No Novelty	Not complex	Intra	<1 Year	Reversible	Technical

3.4 Postulate formulation

In this section, the five postulates that are based on a review of the current literature regarding SDs as a basis for risk assessment will be presented. These postulates cover three parts: (I) SD as a starting point for risk assessment (postulate 1), then zooming into SDs and focusing on (II) the content of SDs (postulates 2, 3, and 4), and finally (III) the iterative nature of SDs, as depicted in Figure 3.4.

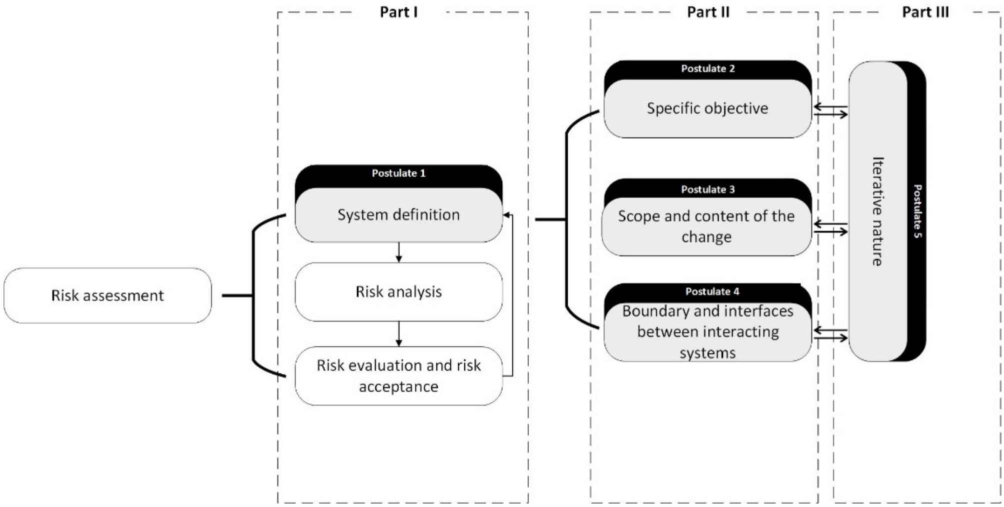


Figure 3.4: Positioning and distinction of postulates

3.4.1 Postulate 1: A system definition is a critical success factor for risk assessment

A crucial initial step is clearly defining the SOI, which includes the need for the investigated system to be clearly defined, as is commonly done in an appropriate engineering) analysis (Klüppelberg et al., 2014). According to Pasquini (2011), the SD is an important step in risk assessment. Additionally, Braband & Siems (2002) mention that, based on lessons learned from several case studies in the railway field, a clear, systematic SD, which should be clearly communicated to all stakeholders, is a crucial factor for success. Once the SOI is defined, the safety experts can start identifying and listing the potential hazards caused by the system: all negative effects on safety.

3.4.2 Postulate 2: A system definition is focused on a clearly defined goal

An SD typically addresses a specific objective e.g., an intended purpose. This is typically a short statement of the purpose and function of the changed system, whether it is a technical, operational, or organizational change (Rail Safety & Standards Board, 2017).

Depending on the type of change, it is useful to explain the reason for the change, such as whether it concerns a specific improvement in capacity, safety, or a reduction in cost.

3.4.3 Postulate 3: A developed system definition always has a clear scope

An SD provides the key details of the system that is being changed and how it is being changed (Rail Safety & Standards Board, 2017). It is important to understand not just the technical elements of the system and their functions, but also the organizational and operational procedures, and human actions required. This is equally important for technical, operational, and organizational changes. An understanding of the scope of the change is important for defining and stating the limits of the change, and therefore, the scope of the hazard identification and risk evaluation activities.

3.4.4 Postulate 4: Interfaces between parties/stakeholders/subsystems are an essential part of the system definition

When defining and analyzing a system change, interfaces should be considered. The University of Cambridge dictionary (2022) states: *"An interface is a situation, way, or place where two things come together and affect each other."* Moreover, according to Healey (1997), *"an interface is a boundary where an interdependency exists across that boundary and where responsibility for that interdependency changes across that boundary."*

An early understanding of the boundaries and interfaces in the SD can enable the key actors to be identified, thus creating the possibility for joint planning. If it is found that safety requirements extend beyond the current boundaries, then these may need to be reviewed and expanded. As the project evolves, and assumptions are clarified, the understanding of the boundaries will improve and should be revised. Therefore, the identification of interfaces should help to indicate where a collaborative approach is needed from actors, parties, or organizations from either side of the interface for the implementation of safety requirements (NASA, 2007; Rail Safety & Standards Board, 2017; Stretton, 2016). When a failure occurs in a system, it may propagate through its interfaces and have implications that can only be addressed by another organization, which emphasizes the necessity of including interfaces in SDs. Neglecting interfaces or underestimating their importance in critical infrastructure systems can cause designers, experts, managers, and decision-makers to underestimate the overall inter-infrastructural risks (Liu et al., 2020; Nogal et al., 2016).

3.4.5 Postulate 5: A system definition is continuously updated based on information that becomes available during the development process

The SD forms the basis of hazard identification and risk analysis at various project stages and should be treated as an evolving document. Moreover, at each stage of a project, the SD should be maintained using the most up-to-date information in the form of spreadsheets, specifications, flow diagrams, system architecture diagrams, photographs, charts, other visual representations, etc. This iterative cycle will continue until the identified safety requirements and SD are finalized. Usually, the process of reviewing and revising the SD, hazard identification, risk evaluation, and safety requirements is iterative until final versions are agreed upon.

The information included in the SD may have been gained from a wide array of project documents and deliverables. These sources must be well documented so that the rationale and basis for safety requirements and assumptions are clear and traceable. They may need to be reviewed and revised at later stages of the system's life. Additionally, in complex changes, several companies, bodies, people, or actors may be involved in the development of the project details. Some may be involved at the definition stage; others may become involved at later stages. As the implementation of the change progresses, however, each of the actors will clarify the detailed aspects of their own work within the larger project; this should be reflected in the SD. The details of a change project develop throughout its duration, so it is necessary to review the SD at various stages of the process.

3.5 Postulate results

This section presents the research findings. For every presented postulate, the following subsections will describe whether these are supported, not supported, or supported to a limited extent, based on the empirical findings from the case studies.

3.5.1 Postulate 1 results: A system definition is a critical success factor for risk assessment

This postulate is supported by roughly 66% of the interviewees, who agree that SD is a critical success factor for risk analysis. Safety manager C mentioned:

"An SD is 100% important. We usually know what we want to do, and what is affected by a change. A clear understanding of what is being affected by a change is very important. For example, this box has to be integrated into a specific location, and to achieve that, this cable also needs to be considered. When you take a narrow view, you miss the bigger picture."

Furthermore, safety manager B stated:

"If you do not know what you are assessing, you do not know whether it is safe or not. If you have the scope, someone can also assess what has happened, at a later time, what attention has been paid to."

The interviewees mentioning SD as a critical success factor explained that SDs provide different insights, all of which provide a basis for subsequent steps of the CSM-REA process. The interviews revealed that an SD has many uses, among which, it aids (1) in defining the scope of the change (and thus of the CSM-REA), (2) in defining interfaces with external entities, (3) with hazard identification (which hazards can already be dismissed, and to which attention should be paid), (4) in providing context knowledge, (5) in arranging admission of relevant change(s), (6) in ensuring that experts participating in risk sessions have a mutual understanding of the change and its context, before proceeding to the risk identification phase, (7) in ensuring that clients and service providers have a shared understanding of what is to be delivered, and (8) in establishing integral safety considerations later on.

Moreover, by providing all of the insights mentioned above, SD creates much-sought clarity concerning changes that require integration. This helps to identify the current system setup, as well as the expected set-up after the integration of the change. That difference aids in identifying everything which needs to be safe before the newly integrated system can be realized. Regarding this, safety specialist B said:

"SD is really important because it describes how the system is currently set up. What is the delta: It must be clear what the system is like now, what it should look like, and the difference."

A more specific example was mentioned by senior engineer B:

"If you want to change a switch in a train, you should not look at the whole train, you need to define the context of that switch."

Moreover, the remainder of the group mentioned that an SD is a critical success factor in the process, but not necessarily for risk analysis. The SD is important to help define the scope of the change/project, which in turn helps to scope the risk analysis, but according to these interviewees, there is no or a limited, direct link between the SD and the risk analysis. Regarding this, senior engineer A stated:

"What makes an SD useful, is that it helps to outline the scope. However, it is not a success factor. It does need to be made explicit to make sure everyone is on the same page and has the same understanding, but it is not decisive for obtaining increased safety levels."

Additionally, this study also encountered developed SDs that were never used for risk assessment:

"*In practice, we find that during hazard sessions, we do not bring in that system definition itself to go through the system, but rather several underlying documents, for example, sketches. So far, the SD is mainly a background document.*"- Safety Specialist C

Furthermore, the differences in opinion regarding the usefulness and necessity of SDs that existed within the organizations were not unfamiliar to some interviewees. Concerning this, safety manager C mentioned:

"An SD is more than just writing down what the change encompasses. It is essential to know what we are going to do and making this explicit certainly helps. However, not everyone is convinced about its usefulness and necessity. Awareness must be created that it is really important."

In line with this, it was stated:

"The added value of an SD is certainly not recognized by everyone. For me the SD is THE basis for CSM, for others, it is not; they consider it hollow paperwork. Often, they assume to know what a change means and, as such, what needs to be included in an SD, but in 10 years the person will not remember. They must understand that they are not doing it for themselves, they are doing it for someone else who will read or use the SD at a later stage, without the knowledge the current developers have." - Safety Manager B

Finally, some interviewees mentioned that SDs are becoming more important as changes, and the projects that strive to realize them, are becoming increasingly complex, larger, and include more (inter-organizational) stakeholders who have to understand the change, as well as contribute to its integration, for example in the ATO and ERTMS projects (Abbas et al., 2022).

This also means that as the scope increases, the number of interfaces increases, the number of hazards can increase, and more experts are to be included who require a mutual understanding of the SOI at hand. Thus, with these developments, SDs are becoming more important to have, but at the same time are also becoming more difficult to develop:

"*Projects/changes are getting bigger and bigger, and because of this there are more people who come in and have to understand the whole thing.*" - Safety Manager B

3.5.2 Postulate 2 results: A system definition is focused on a clearly defined goal

For this postulate, there were opposing opinions regarding the clarity of the goal. Approximately 60% of interviewees confirmed that an SD is focused on a clearly defined goal.

Some interviewees emphasized that a significant amount of time is spent clarifying the goal among the team, or project members. If ambiguities concerning this exist, questions come up, they are discussed and clarified, and the team proceeds to the next phase. Regarding this, safety manager A stated:

"Those are the first conversations you aim to have with each other. These are key conversations to ascertain what the specific goal is we will be together working toward."

Conversely, approximately 40% of the group mentioned that the goal is often not clear. For example, safety expert C stated:

"No, the goals are not clear enough. Unfortunately, you usually notice this afterward: When you go through the SD at a later stage, or when it is read by someone else. While working on it, in the moment it is perfectly clear, but afterward, you notice that it could have been written more clearly."

Moreover, the goal can be made clearer when it is made explicit, for example, when it is written down, and/or discussed among the parties involved. Furthermore, goals become more concrete over time, as more details emerge. This is confirmed by safety manager B who stated:

"The goal is often unclear, for example, in the case of adjusting the brakes of a train, the goal concerns the acceleration of the train, but there is always a discussion. People have the goal in their heads and do not write it down. As a result, you notice during hazard identification sessions that people have different interpretations of the goals."

When discussing projects in an inter-organizational context, safety expert C said:

"NS and ProRail always have diverging goals, which causes differences. Sometimes it is unclear to them whether they have to split the project and see it as their own change or not. On the other hand, I saw that in a project where NS and ProRail really wanted/needed to work together, by continuing to engage in question/answer sessions, it was noticeable that they moved closer toward each other. Achieving that required a lot of conversations, though."

In addition to disagreement concerning the clarity of goals, research shows that the goals can slightly change over time, but never radically. This was mentioned in an interview:

"It does happen along the way that the goal changes, precisely because people from different disciplines are included and view the change from their perspective. In this sense, talking about the goal certainly helps to make the goal more concrete." - Safety Manager C

Furthermore, safety manager A mentioned these conversations being important to reaching a common understanding of the goal:

"That is why the 'question game' is very important: It always ends with a common, mutual goal when we talk about it."

There are also external factors that can influence goal changes, such as an unplanned reduction in the time allotted for the introduction, a lack of personnel, and/or changing regulations (in the case of long-term projects), but this varies per project. For relatively small and simple changes such as the case of the cockpit power outlets described in Table 3.2, the goals are easily determined and often not misinterpreted. However, when dealing with larger, more complex changes such as ATO and ERTMS, that becomes much more complicated. It is possible for the goals to change in such cases, which means they need to be managed accordingly. Additionally, several interviewees stated that while at the highest level, the goals hardly change, at a lower, more detailed level, numerous changes are often noticeable. Concerning this, safety manager A said:

"At the highest level, the purpose of the change of for example ERTMS does remain the same. But at lower levels, the goal may change. In the SD it is then also clear which (smaller) aspect of the change is involved. For example, for ERTMS at equipment type z at wagon X, we are going to do it slightly differently than expected."

In conclusion, it is beneficial to make the goals explicit and have discussions regarding these, thus ensuring a shared understanding of the goal among diverse parties. This can make the rationale for decisions clear for both the current stakeholders and for stakeholders who may become involved, for example, 10 years from now.

3.5.3 Postulate 3 results: A developed system definition always has a clear scope

A large part of the group, namely 70%, did not agree that SDs have a clear scope and details important for risk analysis, thus, this postulate was not supported by the majority of the group. Regarding this, safety manager C stated:

"No, the scope and details are never clear at first, when you start talking about this it is really disappointing."

It was also mentioned that the clarity of the SD scope depends on the individuals developing the SD. If more experienced people contribute, the result is often a higher quality SD with a clearer scope. Additionally, as is the case for the goal, the scope can also become clearer after multiple iterations, and it is essential to include stakeholders in this process. The more perspectives are included when defining the scope, the more comprehensive the scope is defined. On the other hand, interviewees mentioned they have to provably stay within the defined scope, especially in inter-organizational projects. Additionally, the research showed that scope discussions occur more often in large-scale, complex projects. Safety manager A mentioned:

"*Regarding the scope, it seems you can forget something very quickly, especially with big projects like ERTMS. Do the two of us working out the SD know everything? Of course not! You might run into surprises because you did not know something at the time of making the SD. For example, if someone else looks at the SD and thinks it needs to be changed, we do that. This is definitely more common in bigger projects."*

Additionally, several members indicated that it is not always clear into how much detail they need to go during the development of an SD: There is an opportunity for improvement there. Furthermore, assumptions in SDs are very important for their usefulness and reusability. If these are not adequately documented, the SD is only useful and understandable to the person/group developing it.

3.5.4 Postulate 4 results: Interfaces between parties/stakeholders/subsystems are an essential part of the system definition

This postulate was unanimously supported by 100% of the group. All participants mentioned the importance of interfaces in SDs and emphasized that identifying interfaces is essential, as changes can often affect numerous subsystems or adjacent elements across those interfaces. Therefore, identifying interfaces is essential, in order to make sure which adjacent system elements are impacted and to what extent. Especially in long-term, large-scope projects such as ATO and ERTMS, where aspects on either side of an interface can be subject to change.

Moreover, interviewees mentioned that interfaces never, or barely change, and that is why it is important to properly identify them from the start.

"If there is clear agreement among colleagues on what happens on those interfaces, you avoid a lot of problems. Small changes on a train can have a large effect, for example, which means you have to monitor that." – Senior engineer A.

However, it was also stated by all interviewees that although interfaces are essential, they are not an easy aspect to take into consideration in SDs. Because interfaces are mostly determined based on experience and prior knowledge, this is especially noticeable when junior employees, with limited experience and knowledge, have to determine the interfaces. Concerning this, safety expert C mentioned:

"Interfaces are a fixed part of an SD; you easily identify the interface you know. If you do this together with other stakeholders, it is a lot more useful, because everyone approaches it from their own perspective/experience. Therefore, it is more profitable and useful to do it collectively."

Furthermore, a part of the group mentioned that there are no practical, readily available tools to aid in managing interfaces. Although some tools for technical interfaces are available, there is a trend towards more sociotechnical changes. These types of changes impact multiple domains and result in different types of interfaces. Currently, limited attention is paid to those interfaces, and interface management is still a challenge. An example illustrating this:

"The Automatic Train Safety system has a notification light, which activates when the driver has braked in a certain way. Of course, the driver should know what this means; what happens when the light is on." - Safety Manager C

Furthermore, safety manager B stated:

"Currently, we mostly pay attention to technical interfaces, such as wheel and track, pantograph and catenary, and traverse systems. There used to be only technical interfaces, however, you increasingly see operational and organizational interfaces. So, we are looking at how we can address these as well because ultimately this is essential."

In addition to changes expanding into the sociotechnical domain, changes are also becoming more extensive, expanding into the inter-organizational domain. Safety manager B noted:

"*Things usually go wrong at the interfaces, managing the grey areas in between, especially where they cross over into other organizations, it's completely problematic. The advantage of physical technology is that people can see it in front of them, it is tangible. We know the need for, and importance of, those interfaces, but it is very difficult to include the organizational side."*

As such, although interfaces are an essential aspect which need to be included in SDs, actually including them, and subsequently managing the interfaces, is still challenging. Furthermore, some tools that aid in identifying technical interfaces are currently available, however, due to sociotechnical and inter-organizational innovations, the number and types of interfaces that need to be managed are constantly increasing. Practical, readily available tools to assist with this remain scarce.

3.5.5 Postulate 5 results: A system definition is continuously updated based on information that becomes available during the development process

This postulate was supported by approximately 75% of the interviewees, who mentioned the importance of keeping SDs up to date, this is typically done by sending the SD to managers/experts for review, or by incorporating feedback. However, it was also stated that for smaller changes, such as modifying a storage tank, they deemed it notable that the SD is a one-off occurrence, rather than an iterative one. Conversely, in large-scale complex projects such as ATO, PHS, and ERTMS, the SD is often reiterated based on adjustments to the project, or due to more detailed information becoming available. Safety specialist B explained this in the following manner:

"Imagine an SD is made based on concept A. It may turn out later in the process that it is outdated if things have changed on the back end, while the SD may not have changed along. If we arrive at new insights, one should be aware that this has an impact on the SD and consequently, on some analyses. Because of that, it may well be that some aspects of the SD are no longer correct. If we change the goal solution, the SD can also be affected, which should definitely be taken into account, so that we know what we still need to consider. With bigger changes, this is harder to predict. For both the project and overall safety, it is essential to keep the SD up to date."

Furthermore, some interviewees mentioned that the required number of iterations depends on the initial quality of the SD, which in turn depends on the knowledge and experience of the developers. When inexperienced people work on an SD, additional guidance is required during the development process. Additionally, at a certain point in the development process, the SD is to be used as input for the rest of the CSM-REA process, therefore, it needs to be in a fixed state in order to continue.

Senior Engineer C stated:

"It would be impractical if the SD was still updated while admission is already being worked on, that really would not work."

Moreover, although most agreed that SDs must be updated, they also mentioned that in practice this is rarely the case. One explanation offered for this was the difficulty of keeping an SD updated in large-scope projects, where information is highly dispersed across different stakeholders, and sometimes across different organizations. To still keep the SD updated, it needs to be managed, which means someone needs to be responsible for this. Regarding this, safety manager B stated:

"Sometimes changes are introduced, after which the scope is expanded, but this is then not adjusted for in the SD: it is not updated. I have never experienced or witnessed an SD being adjusted."

Differences in opinion regarding the usability and usefulness of SDs also play a role, as can be understood from the following statement by senior engineer A:

"Ideally, the SD is adjusted based on the information that becomes available in the process. Sometimes you do notice that the SD is somewhat adjusted, however, it does not happen systematically. A reason for this is that the added value of an SD is certainly not recognized by everyone."

Thus, whenever a change is revised, it should be determined whether the SD should also be altered to maintain its useability. Moreover, it should be determined, based on the SD, whether revisions to that change could have additional impacts.

3.5.6 System definition development process (part III)

Although CSM-REA provides insights into different aspects that should be included in SDs, such as interfaces, the research showed that there are no guidelines for how to actually apply it. Thus, in addition to the results directly related to the postulates, the research revealed multiple other aspects related to SD development, making SDs more useful. These aspects include (1) front-end definitions, (2) the quality of SDs, (3) the experience and expertise of the developer(s), and (4) the inclusion of multiple experts in the SD development process.

3.5.6.1 Front-end system definitions

The interviews indicated that having an SD early on in the project creates shared insight among those involved, aids in the transferring of knowledge, and reduces the need for repeating work at a later stage in the project.

As such, this underscores the importance of establishing the SD in the front-end. Concerning this aspect, safety expert C said:

"Anytime you discuss safety, framing is important all through the process. With ERTMS, for example, you see that at every step, the scope is essential."

3.5.6.2 The quality of a system definition and the expertise of its developers

The interpretation of the guidelines and how these are executed is highly dependent on the experts working on the SDs. Moreover, the quality of an SD is highly dependent on the expertise and experience of its developers. Safety Manager C explained:

"We have a file with titles such as scope, and interfaces, as such, guidelines exist for what must be included in such a system definition, but that is all. How developers achieve this depends on the people working on it. We use expert judgment; the experts ultimately know what they are going to change. Furthermore, the regulation is very open, so you have to rely on the knowledge of the experts."

Safety manager A confirmed this and stated:

"There is a checklist for this per change. Depending on the change, the expert decides whether to exclude something or to focus on a particular aspect."

Moreover, the research shows that some practitioners develop SDs in a fairly structured manner, while others do not. For the practitioners that do follow a relatively structured approach, the procedure is supported by generic guidelines in common use in their department, and/or by merit of the coordination of an individual who manages the steps in the procedure:

"How we need to develop an SD is now documented in our online safety system; there is a standard procedure for it. As such, we know how it should be done, however, how it is actually developed depends on resource availability, experience, time constraints, and stress levels." - Safety Manager A

3.5.6.3 Inclusion of multiple experts

Much of the work at the SD stage will be dictated by the facts and data surrounding the situation, but it is an inherently value-based exercise, the outcome of which will be greatly affected by who is participating (Hatfield & Hipel, 2002). As such, the most important part of the analysis is the qualitative part, in which all relevant application domain experts should be involved (Braband & Siems AG Transportation Systems, 2002).

The results of this research indicate differences in when and how various experts are involved in the SD development process. This varies per project and may include: (1) engineers or experts developing the SD on their own, (2) sending out the developed SD for review, and/or (3) developing SDs with the inclusion of multiple experts. Several interviewees mentioned that in cases where experts or engineers work on the SD by themselves, they usually send it out for review afterward, because less experienced colleagues often have difficulties developing an SD, and that sending it out for review often happens due to lack of time as well. If more experts were to be included in the development process, it would take longer. Safety expert C stated:

"I often work on the SDs myself and then offer it for review. We do not often work on the development together, because others who do not conduct it as often find it very difficult."

Depending on the existing knowledge and experience which certain changes, and the significance of the quality of an initial SD, more experts should be included in the development process, as SDs are developed based on expert knowledge. With regards to the inclusion of more experts, safety expert C commented:

"Collaboration with the manager or whoever is running the project is essential for developing an SD, as they have the in-depth knowledge of the change. My team and I help those managers navigate the process by asking targeted questions."

Furthermore, some interviewees mentioned that in cases of inter-organizational projects, this can range from actively cooperating in the development process, to simply sending the SD out for review across organizational boundaries:

"For PHS and ATO, for example, we are continuously engaging in sessions with people from ProRail: We look at everything together. We then try to provide the steering committee with a single comprehensive recommendation, but of course, that is not always possible." - Safety Manager A

Moreover, the results indicate that whenever an SD is used in hazard sessions, this is an essential check of the SD, showing whether some aspects are missing in the SD and whether all experts or stakeholders have the same understanding of the SD and the change it represents. Regarding this, senior engineer A said:

"All variants are used, some are not sent for review, and some are jointly substantiated or endorsed by experts. When we are in a hazard session the SD is reviewed, then it is supplemented; it is organic. It all depends on the person, their background, and their knowledge of the subject matter. For example, for safety-critical changes, there is a safety guy there who is always involved, and his participation in the process is very important because he has a lot of knowledge and experience."

As illustrated by the examples mentioned above, the SD development process does not always proceed systematically and effectively:

"Drafting SDs is not a standardized, generally accepted procedure within our organization. We try to encourage it of course, but it is not yet standard practice. If within our organizations, all departments working on [managing] changes, would work according to a similar, consistent process, it would help a lot." – Senior Engineer C

According to interviewees, this also leads to diverging opinions regarding the usability and usefulness of SDs. Moreover, as a result of multiple aspects affecting the SD development process, the research showed diverse configurations of SDs across organizations, but even within organizations. These varied from Excel sheets and templates to detailed block diagrams, and text documents which ranged from single sentences to whole booklets.

3.6 Discussion, implications, and future research

3.6.1 Discussion and implications

SDs as a basis for risk assessment and their use are supported by empirical evidence, as well as explore possible reasons for organizations to deviate from what is generally assumed in the literature.

Firstly, the findings show that in general, the SD is a critical success factor for risk assessment. Although SD is deemed to be important for the scope definition, some interviewees indicated that they believe it is not very important for the actual risk analysis. Furthermore, the results indicate that there are different opinions regarding the usefulness and necessity of SDs, and as a result, the amount of effort spent on developing them also varies. Some interviewees mentioned that they consider SDs to be hollow paperwork; they develop SDs because it is mandatory, not because they consider them to add value to the risk assessment process. This is an interesting finding, as it contrasts the existing theory which states that SDs are a vital starting point, moreover reaffirms literature that states that some experts often skip the supposedly crucial step. Possibly the perceived usefulness is seen differently as the studied SDs are dissimilar in structure and approach.

Secondly, the second postulate 'A system definition is focused on a clearly defined goal' was supported by the empirical findings to a limited extent.

On the one hand, some interviewees emphasized that a significant amount of time is spent on establishing clarity on the goal among the team- or project members and that making the goals explicit certainly aids in gaining more clarity over time. On the contrary, however, other interviewees indicated that the goals are often unclear, as different stakeholders have an implicit understanding of the goal(s) and assume that all stakeholders share this understanding. This is especially common in projects in an inter-organizational context, where multiple organizations and stakeholders need to cooperate for the successful integration of changes. Furthermore, for relatively small and simple technical changes, the goals are easily determined and often not misinterpreted. However, in the case of larger, more complex changes, establishing a clearly aligned goal among stakeholders becomes much more complicated, especially when insufficient attention is paid to this.

Thirdly, a large part of the group did not agree with postulate 3, which states that SDs always have a clear scope. The research shows that the quality and clarity of the scope seem to depend on the developers of the SD, their knowledge of, and experience with, relevant changes and SDs in general. Moreover, when more experts are involved in the development process of the SD, more diverse knowledge, experience, and perspectives are synthesized. Additionally, when the scope is iterated based on information that becomes available later on in the project, the scope of the SD becomes clearer. These aspects create more mutual agreement among experts and/or stakeholders.

Fourthly, the level of detail in SDs was often mentioned as a challenging aspect: The results show that more detail in SDs is not necessarily better. For example, in a certain case study, over a year was spent on the development and improvement of the SD as related to the modification. In the end, however, the SD was not used in the actual risk assessment, as it was deemed too big, too complex, and too information-dense, and thus hard to understand without a thorough explanation from the developer. This indicates that there should be a balance between the level of resources spent on the development and the level of detail in SDs. In addition, if an SD is to be used in a wider group, it should be developed with the needs of the end-users in mind and thus user-friendliness becomes more important. Often, SDs that attempt to contain everything are difficult to build, understand, maintain, and use.

Fifthly, all experts mentioned the importance of interfaces in SDs, thus validating postulate 4. They emphasized that interfaces are essential, as changes can often affect numerous subsystems or adjacent elements on the other side of the interfaces. Moreover, interfaces can indicate where different stakeholders need to coordinate.

Thus, if those interfaces are clear and agreed upon, unnecessary revision can be prevented later on. Although interfaces were deemed essential by all interviewees, it was indicated that they are deemed difficult to include in SDs.

While some tools exist to identify and manage more technical interfaces, the trends toward more sociotechnical and inter-organizational changes result in more and different types of interfaces, the identification and management of which remain challenging.

Sixthly, interviewees agreed on the importance of updating SDs, confirming postulate 5; they need to be kept up to date in order to remain usable. The number of iterations depends on (1) the initial quality of the SD, (2) the duration of the projects, and (3) the amount of information becoming available over time. Furthermore, although the necessity of updating SDs was agreed upon by most interviewees, it also became evident that in practice this is not always achieved, due to the difficulty of keeping an SD updated in large-scope projects, where information is highly dispersed across different stakeholders, responsibilities may be unclear, and, as previously stated, different opinions concerning the usefulness and necessity of SDs exist. Moreover, for smaller changes, it is noticeable that the SD is usually not iterative, while in large-scale, complex projects, the SD is often iterated based on adjustments in the project, or more detailed information becoming available. Additionally, interviewees mentioned that at a certain point, SDs need to be finalized in order for the experts to continue with the risk assessment process, as the SD can not be updated indefinitely. The results suggest that this 'freezing point' should be decided on by multiple experts included in the process, because they have a solid understanding whether certain aspects that might still be subject to change may affect the SD, and thus the risk assessment.

In addition to the postulate results, several essential factors inherent to the SD development process were revealed by the research, contributing to the successful development of SDs in practice. After the evaluation, practitioners agreed that paying attention to these factors can ensure higher quality SDs that are more usable and useful. These factors are synthesized and illustrated in Figure 3.5 and include:

(1) SD development is not simply a task, but a process.
(2) Making the goal (2a) and assumptions (2b) related to the change(s) at hand explicit is a vital starting point of this process.
(3) The quality of an SD is highly dependent on the expertise and experience of its developers. It is essential for developers to have the required capabilities, and for the organization to provide them with adequate guidance and support in the process.
(4) Involving multiple experts and synthesizing their expertise in the process is essential and results in integral and mutual insights.

(5) Discussions among experts and stakeholders are essential for creating mutual understanding concerning the change and related SOI.
(6) Interfaces are essential to be included in an SD, not only those relating to technology, but also those relating to processes, and organizational components.
(7) Clarity regarding responsibilities (roles, tasks) is vital.
(8) Relatively simple SDs are more easily understood and agreed upon than complex SDs. However, simple SDs lack the detail required for a comprehensive risk assessment of the entire system.
(9) Updating SDs should be considered in order to remain usable after their initial development.

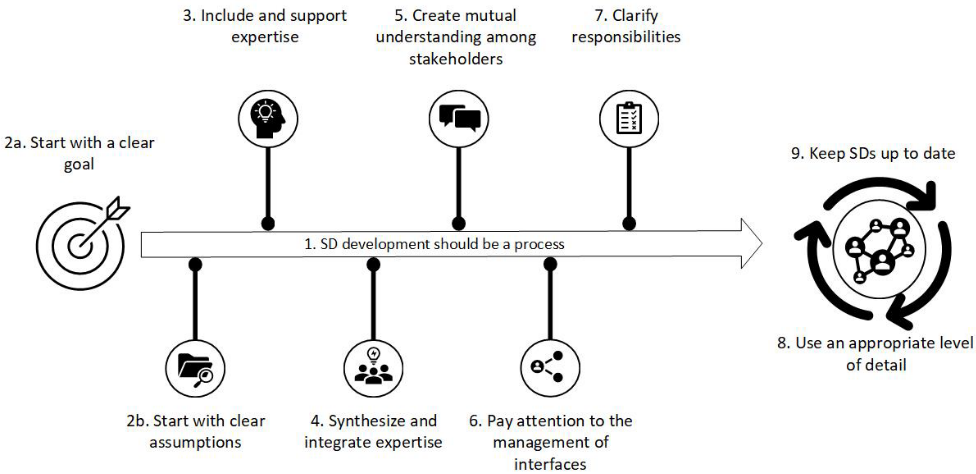


Figure 3.5: Proposed SD development process

3.6.2 Future research

Given the current trends in the Industry 4.0 era, which include increased automation and data exchange in manufacturing technologies, cyber-physical systems, the internet of things, cloud computing, and artificial intelligence (Xu et al., 2021), and their sociotechnical and inter-organizational nature, this will keep SD processes to remain important. However, these are also becoming more difficult to develop and have a shorter life span due to continuous, rapid modifications.

This emphasizes the need for SDs to be updated in order to remain a useful means for risk assessment. However, this can be challenging due to increasingly scarce resources, and this raises the question of whether the preference should be for simple and easy-to-understand SDs or highly detailed models. There might be considered to develop smaller, better scoped SDs that are developed more easily and with a shorter lifespan in mind.

Furthermore, the current findings show that considerable attention is currently being paid to SD from the safety perspective within the railway industry. However, the scope of integration in complex inter-organizational systems reaches beyond safety, as reliability, capacity, and cost are becoming more important. These systemic changes can vary widely in their nature, and the impacts of these changes tend to affect multiple domains, spanning different organizations. This extends to the scope of systems integration, which is a key challenge to be mastered in the design and delivery of inter-organizational projects, particularly in the infrastructure environment (Muruganandan et al., 2022).

As such, several directions for future research have presented themselves. Research on: (1) the development process of SDs, (2) developing dynamic SDs that can be updated quickly, (3) effective interface management in inter-organizational projects, and (4) the use of SDs in large-scope systems integration developments.

3.7 Conclusion

By formulating postulates and through the use of multiple case studies in the context of the Dutch railway system, several interesting insights were gained regarding SDs, summarized in Table 3.3. The results show that there are divergent opinions regarding the usefulness and necessity of SDs. SDs goals are often ambiguous, especially in the early development stages. As such, ambiguity needs to be addressed through the inclusion and alignment of multiple experts, and create mutual understanding regarding remaining ambiguity. Especially interfaces are seen as critical to the SD but are often perceived as a ‘gray’ area, making them difficult to manage and maintain. Furthermore, The majority of the interviewees agreed on the necessity of updating SDs and indicated that SDs are iterative in nature in their initial development. Although system definitions are iteratively developed, they are rarely updated afterward. Consequently, system definitions start losing their relevance as changes occur.

Overall, several factors contribute to the usefulness and useability of SD as a basis for risk assessment, which are not always followed up in practice. The results indicate that there are several success factors in developing and maintaining SDs. These success factors have been summarized and linked to crucial steps of the SD development process, as shown in Figure 3.5.

The process of creating an SD plays an important role in ensuring the SDs usefulness. Despite their importance, these elements are often considered on an ad hoc basis. SDs provide a means for understanding among stakeholders involved in the risk assessment process. They can facilitate effective communication and collaboration between engineers, safety experts, regulators, and other stakeholders.

Table 3.3: Summarized postulate results

		Postulate	Results based on case studies	Description
SD as a basis for risk assessment	1	A system definition is a critical success factor for risk assessment	Partially supported	Although mandatory, in practice the SD does not always seem to aid the risk analysis. There are varying opinions among experts regarding the usefulness and necessity of SDs in relation to risk analysis.
SD content	2	A system definition is focused on a clearly defined goal	Partially supported	There were opposing opinions regarding the achieved clarity of the SD goal. The goal however seems to have become clearer over time in some case studies, especially when made explicit.
	3	A developed system definition always has a clear scope	Not supported	The majority of the interviewees mentioned that the scope was ambiguous more often than not. The usability for risk analysis seemed to depend largely on the level of involvement of experienced and knowledgeable individuals in refining the scope.
	4	Interfaces between parties/stakeholders/subsystems are an essential part of the system definition	Fully Supported	Risks can originate from interfaces, making them essential to incorporate in the SD. Interviewees indicate that interfaces are often perceived as a 'gray' area, making them feel out of their depth, and making them difficult to manage and maintain.
SD's iterative nature	5	A system definition is continuously updated based on information that becomes available during the development process	Supported	The majority of the interviewees agreed on the necessity of updating SDs and indicated that SDs are iterative in nature in their initial development. However, they also indicated that they have never witnessed an SD being revised based on new information after approval.

As such, clear SDs can enable a shared understanding of the risks and mitigation strategies, promoting better decision-making and coordination. Thus, more attention to the identified factors is needed, especially in case of more complex and inter-organizational projects.

Declaration of competing interest

None.

Declaration of generative AI in scientific writing

None.

Author contributions

Merishna Ramtahalsing: Conceptualization, Validation, Investigation, Software, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Project administration; **Willem Haanstra**: Methodology, Validation, Writing - Review & Editing, Supervision; **Jan Braaksma**: Methodology, Validation, Writing - Review & Editing, Supervision; **Leo van Dongen:** Funding acquisition, Validation, Writing - Review & Editing, Supervision.

Acknowledgment

The project was funded by TKI High Tech Systems Materials (HTSM) via the Dutch Ministry of Economic Affairs and Climate Policy allowance scheme for Research and innovation.

The authors acknowledge the support of NS and ProRail, who have made this research possible through the framework of the SIRA (Systems Integration for Railways Advancement) project. Furthermore, the authors acknowledge the peer-review feedback which led to the improvement of this paper.

Chapter 4 MOSAIC: Design of a Structured Multidisciplinary Approach for Managing Integration of Inter-Organizational Change

Abstract:

Sociotechnical systems like railways are becoming increasingly complex as numerous changes are constantly being integrated to improve or maintain desired performances. A crucial aspect enabling this integration is to define the scope of the changes, referred to as the system of interest. This can be challenging for engineering managers due to mounting system complexity caused by: an inter-organizational environment, a multitude of diverse stakeholders, the multidomain environment, and an increasing number of interdependencies. By employing Design Science Research, this study proposes an analysis that supports engineering managers in managing sociotechnical and inter-organizational change integration (MOSAIC) by facilitating a structured, multidisciplinary assessment of system impacts and interdependencies. The design was evaluated by applying it to an inter-organizational project in the Dutch railway system. The findings show that with MOSAIC, a system of interest can be collectively defined using the proposed process and a multidisciplinary and inter-organizational group of experts, creating mutual understanding. MOSAIC can further aid engineering managers in front-end project planning.

Publication history:

This chapter was published in the Engineering Management Journal:
Merishna Ramtahalsing, Willem Haanstra, Jan Braaksma, Mohammad Rajabalinejad & Leo van Dongen: MOSAIC: A Structured Multidisciplinary Analysis for Managing the Integration of Inter-Organizational Change (02 December 2022).
Available at: https://doi.org/10.1080/10429247.2022.2143709

4.1 Introduction

Rapid change, globalization, fierce competition, rising customer expectations, and rapid advancement of technology characterize current society (Rasmussen, 1997).

Because of the advancement of technology, the connectivity of different systems increases, which supports engineering managers (EM)s in achieving a more optimized performance. In addition to the abovementioned trends, numerous operations now require cooperation between employees from different organizations, as their operations are increasingly inter-organizational (Milch & Laumann, 2016). These developments give rise to complex sociotechnical systems and add to system complexity (Perrow, 1999), as Geels (2002) illustrated in Figure 4.1.

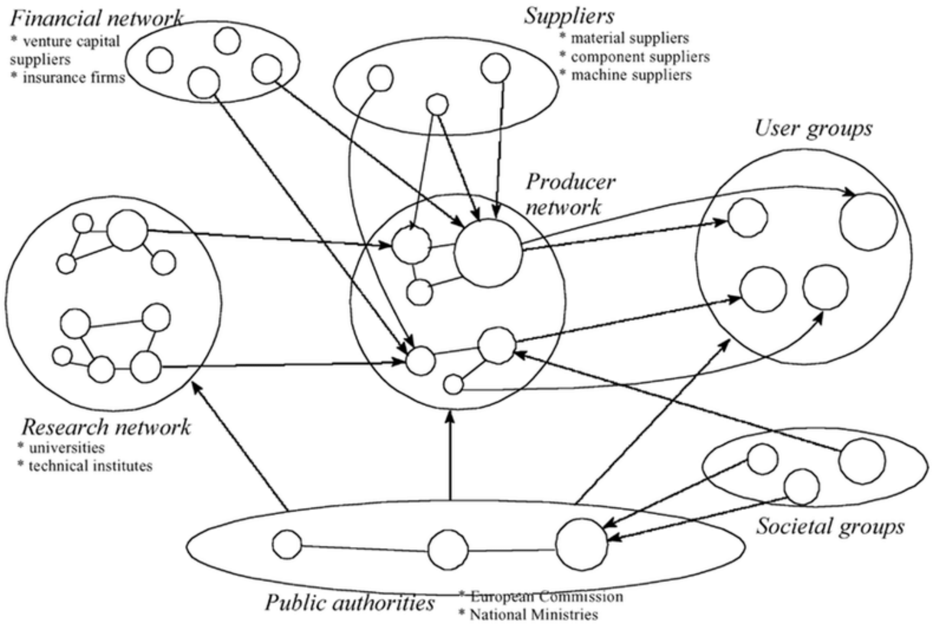


Figure 4.1: Actors involved in sociotechnical systems (Geels, 2002)

In complex sociotechnical systems, various domains, such as processes, personnel, capacity, technical systems, and rules and regulations, align with existing technology (Clemson & Lowe, 1993; Geels, 2002). However, because of this, new modifications often do not match existing sociotechnical frameworks and are often difficult to integrate and establish (Geels, 2002). Therefore, there is an increasing need for EMs to understand the complexity to identify how changes and the projects that strive to realize them can be integrated into this context (Potts et al., 2022). As such, EMs must pay significant attention to inter-organizational and multidomain environments, interconnections, and interdependent elements, thus increasing the scope of integration.

The broadening scope of systems integration (SI) poses many challenges for EMs:

(1) While the SI phase, where all unexpected and unforeseen problems surface, is systematically underestimated in conventional projects (Muller, 2007), the number of unexpected and unforeseen problems increases in large-scope projects.
(2) More organizations, suppliers, users, and processes are included when SI increases scope. More inter-organizational collaborations are required, making the SI phase significantly more complicated (Muller, 2007).
(3) In practice, crosscutting functionality and quality suffer from decomposition. As the scope broadens, these challenges increase (Muller, 2007).
(4) In large projects, there can be a lack of ownership and communication across organizational boundaries (Muller, 2007; Ramtahalsing et al., 2020).
(5) The stakeholders can view complex systems differently (Hagan et al., 2011). As the project increases in scope, more stakeholders are to be included.
(6) The number and type of interfaces also increase as the SI scope is broadened.

EMs need to pay continuous selective attention to integration in order to meet these challenges (Muller, 2007), especially regarding what specifically needs to be integrated. Therefore, determining the scope of the change is vital for setting bounds on different aspects considered to be of interest, which is defined as the system of interest (SOI). Railway systems are examples of such sociotechnical systems where changes are constantly implemented to upgrade system performance, and insight into SOIs is important for EMs to achieve this.

During the past few decades, there has been an increased focus on seamless railway mobility across borders, especially in Europe. Existing railway systems are adopting novel technologies to achieve mobility within and between countries, particularly in control and communications (Dumolo, 2007). These developments require integration to improve the functionality and efficiency of the railway system as a whole (Dumolo, 2007) and require collaboration between various multidisciplinary and (non)engineering stakeholders. Depending on the change to be integrated, these can include engineering, logistics, procurement, finance, operations, configuration management, safety, and risk management.

The European Railway Agency (2009) mentions the need to describe changes: *"When incorporating a new element into the railways, or modifying an existing one, the change must be clearly and completely described, as well as limits of the railway system where the change is integrated (whether technical, operational, or organizational)."*

According to the European Union Agency for Railways (2020), an exhaustive overview of the SOI is most pertinent to and critical for comprehensive risk management and safe integration. This provides insight into the change and should describe all interfaces/interdependencies between the change, human operators, or subsystems clearly and completely. As a result, considerable attention is paid to SOIs from the safety perspective within the railway industry.

However, the scope of integration in complex inter-organizational systems is not limited to safety. As systems are continuously changing, adequately sharing information between involved organizations is a prerequisite for adequate management of the railway system because a change in one part may affect other parts of the system (Guillerm et al., 2012). These systemic changes can vary widely in nature, and the impacts of these changes tend to affect multiple domains spanning different organizations. This not only broadens the scope, as mentioned but also makes the SOI more ambiguous for EMs (Potts et al., 2022), which can result in several challenges:

(1) Create confusion and errors, for example, when different researchers or practitioners work on the same problem related to an assumed SOI (Cumming & Collier, 2005).
(2) Cause challenges to effective communication and understanding of interfaces for example (B. Haskins & Striegel, 2006).
(3) The people element of each system/subsystem can cross boundaries and blur distinctions (Wilson, 2014).
(4) Discussions concerning scope (Dasher, 2003).

This makes managing changes increasingly difficult for EMs but also shows the necessity of the scope definition, the SOI, and describing what exactly is required to be integrated.

4.1.1 Research Aim

This study aims to support EMs in managing inter-organizational change integration in the sociotechnical railway system by designing an expert-based analysis that aids in jointly creating insight into high-level inter-organizational SOIs.

The remainder of this paper is organized as follows: The next section presents a comprehensive literature review. The methodology section describes the methodology that resulted in the design of the management of sociotechnical and inter-organizational change integration (MOSAIC) analysis. The 'Design of MOSAIC' section presents the MOSAIC analysis, and the 'Demonstration of MOSAIC' section demonstrates this through application to a case study. This is followed by the 'Evaluation & discussion' section, which discusses the implications of this paper for EMs, and finally, it concludes with the contributions.

4.2 Literature review

This section provides an overview of the current state of research and describes where the research fits in the overall body of work in Engineering Management. After this, it focuses on several characteristics related to the present inter-organizational and sociotechnical context that require attention to support EMs in managing change integration. Based on these characteristics, several *subgoals* and related design principles are derived, which will be included in the design and development of MOSAIC at a later stage.

Change projects in complex systems can significantly impact other processes or departments across organizations; thus, it is vital to set bounds on different aspects to be of interest. Current literature describes this as project scope definition (Fageha & Aibinu, 2013) providing information for identifying the work which needs to be performed. Defining project scope using input from all stakeholders is a vital task that needs to be adequately carried out at an early stage (Dasher, 2003). While adequate front-end project planning with a clear project scope definition can avoid negative effects on project performance, inadequate project planning and poor scope definition can lead to expensive changes, delays, rework, cost overruns, schedule overruns, and project failure (Fageha & Aibinu, 2013). Therefore, a well-defined scope during the front-end planning stage is crucial for successful project execution and achieving a satisfactory project outcome (Fageha & Aibinu, 2013).

While a change may appear simple at first glance, this can become more complex when attention is paid to the context in which it must be integrated. There have been concerns about the appropriateness of traditional tools and techniques developed for simple projects for use in complex inter-organizational projects (San Cristóbal et al., 2018).

The described context has several characteristics that make it challenging: a multitude of multidisciplinary stakeholders and their coordination, the existence of various independent models, a multidomain environment, the existence of interdependencies, diverse objectives, and a dynamic environment. These are elaborated upon in the following sections.

4.2.1 Characteristic: A multitude of multidisciplinary stakeholders and their coordination

Milch & Laumann (2016) refer to inter-organizational complexity as a complex sociotechnical system that involves multiple companies and work processes, requiring the collaboration of employees from different organizations and coordination across organizational boundaries. In this context, integration is as important as difficult because knowledge and information are dispersed across different departments and organizations. Moreover, the diverse engineering and non-engineering stakeholders need to collaborate for effective change integration.

In such cases, each project stakeholder has a different mental model of the project, assumptions about it, interpretations of realities, and expectations (Danilovic & Browning, 2007). Thus, such intensive interactions often cause conflicts due to differences in experience, knowledge, organizational or professional loyalties, understanding of the purpose and goals, and contradictory purposes and goals (Proehl, 1996).

This leads to *subgoal 1: Facilitate multidisciplinary stakeholder/expert involvement.*

Multidisciplinary or cross-functional teams should be advocated to address this by providing collective expertise, information, and resources for effective model-building and problem-solving (Madni, 2007). Hence, experts from different technical and non-technical backgrounds should be brought together (Sousa-Poza & Kovacic, 2008).

This can be addressed through integral expert-based sessions. In these sessions, experts from different backgrounds contribute their knowledge and expertise, exchange information, and discuss the impact of change (Smith & Hinchcliffe, 2003). Thus, tacit knowledge is deployed (Abbas et al., 2020), and multiple multidisciplinary stakeholder perspectives can be synchronized. These experts can include actors, parties, or organizations with whom an agreement is needed to implement the change.

Ruitenburg (2017) showed that expert sessions deliver insights and aid in identifying opportunities that might otherwise be overlooked. Furthermore, expert sessions improve stakeholder engagement, close the gap between experts and professionals, and combine scattered resources. Instead of having a single person provide information for the SOI, a multidisciplinary group of experts is employed to define it collectively. This process enables a broad, holistic perspective and means that trust and acceptance are built during the process itself (Haanstra et al., 2021).

Thus, *subgoal 1: Facilitate multidisciplinary stakeholder/expert involvement* can be achieved through integral expert-based sessions.

4.2.2 Characteristic: The existence of various independent models

Stakeholders from various disciplines and organizations have their own insights, models, and approaches to describing and understanding an SOI (Haveman, 2014; Potts et al., 2022). Thus, diverse stakeholders cannot easily discuss an SOI when they do not share a common language (Haveman, 2014; Madni & Sievers, 2010). In these instances, a shared model can test and align participants' mental models through discussion, leading to a joint understanding of the reality of projects (Danilovic & Browning, 2007).

During the last decade, systems engineering has improved significantly with the advent of model-based systems engineering and systems engineering markup language. These advances have enabled collaborative engineering teams to communicate using a common language and share information in digital models (Madni et al., 2014). However, a disadvantage of these methods is that they are not suitable for addressing the needs of all stakeholders, especially non-engineering stakeholders (Madni et al., 2014).

Rouse (2007) explained that large-scale complex systems require a broad perspective. Systems thinking is often described as balancing multiple perspectives to understand and guide problem resolution (Sauser & Boardman, 2015). Additionally, Browning (2002) suggested that systems thinking would enhance the management of SI by synchronizing multiple perspectives into an overview of the SOI. Systems thinking as a practice is intended to aid in creating an overarching perspective, understanding how independent elements come together into a unified SOI, understanding the environment in which it should perform, identifying the synergy of combined systems, and describing the SOI from all relative perspectives (Boardman & Sauser, 2008; Potts et al., 2022). Moreover, Browning (2002) mentioned that a classic approach to addressing and understanding complex reality is through modeling. A model is an abstract representation of reality built, analyzed, and manipulated to increase the understanding of reality (Browning, 2002). (Browning, 2009) states that tools are needed to provide improved visibility, appropriately simplify complexity, and highlight important areas. In the context of multi-disciplinary teams, three main approaches have been identified (Haveman, 2014): (1) approaches based on functional modeling, describing the SOI at an abstract level, (2) visualization applications (Madni & Sievers, 2014), and (3) condense architectural information into a single and accessible overview. This is performed, for example, in the A3 architecture overview method (Borches, 2010).

This leads to *subgoal 2: Create a shared SOI among various stakeholders.*

Moreover, attempting to provide all information about the SOI can cause information overload. This is often more detrimental than not providing information, owing to the false assumption that effective communication has occurred (Browning, 2009). As such, models that attempt to contain everything about a project are cumbersome to build, maintain, understand, and use (Little, 1970). It has been noted that managers prefer simple models, which they understand and trust, over more realistic ones (Little, 1970).

Because the details of a project develop throughout its duration, it is necessary to update the SOI at various stages of the process (Rail Safety & Standards Board, 2014). Thus, it should be flexible. In addition, the models must be based on the latest and most accurate input information if they provide helpful output (Danilovic & Browning, 2007). Therefore, high modeling flexibility is appropriate for realizing different railway projects in a changing environment. As such, it can be stated that any approach to creating a common understanding of the SOI should be compatible with existing SOIs, simplify complexity, be on the abstract level, be visual, combine multiple perspectives, and be condensed. This means that *subgoal 2: Create a shared* SOI *among various stakeholders* can be achieved through integral expert-based sessions, high-level insights, and high modeling flexibility.

4.2.3 Characteristic: A multidomain environment

Infrastructures are complex sociotechnical systems. They are highly interconnected networks of interacting social and technical components that cannot be addressed separately (Kroes et al., 2006). A change's impacts can include processes, personnel, capacity, technical systems, and rules and regulations in sociotechnical systems such as railways. As such, it is important to understand the technical elements of a change and the organizational and operational procedures and human actions required.

This leads to *subgoal 3: Take a broad perspective that should include more than the technical perspective.*

Describing multiple domains provides a sound basis for structured analysis during the later stages of a project (Rail Safety and Standards Board, 2014). Bartolomei et al. (2012) formalized the identification and definition of domains common to all sociotechnical systems and projects as follows: (1) environmental domain, including exogenous components that affect or are affected by the sociotechnical systems, such as laws, policies, and regulations; (2) social domain, including individual stakeholders, teams, and organizations; (3) functional domain, including goals and purposes of the sociotechnical systems, as well as its functional architecture; (4) technical domain, physical, and nonhuman components of the system, including hardware, infrastructure, software, and information; (5) process domain, processes, subprocesses, and tasks performed within or by the system.

Furthermore, (Qureshi et al. (2007) explain that sociotechnical systems should be viewed as encompassing at minimum human, technical, and organizational domains, with intrinsic complexity arising from interactions and interdependencies between components. This is illustrated by Bartolomei et al. (2012) in Figure 4.2.

Thus, *subgoal 3: Take a broad perspective that should include more than the technical perspective*, can be achieved by considering sociotechnical viewpoints.

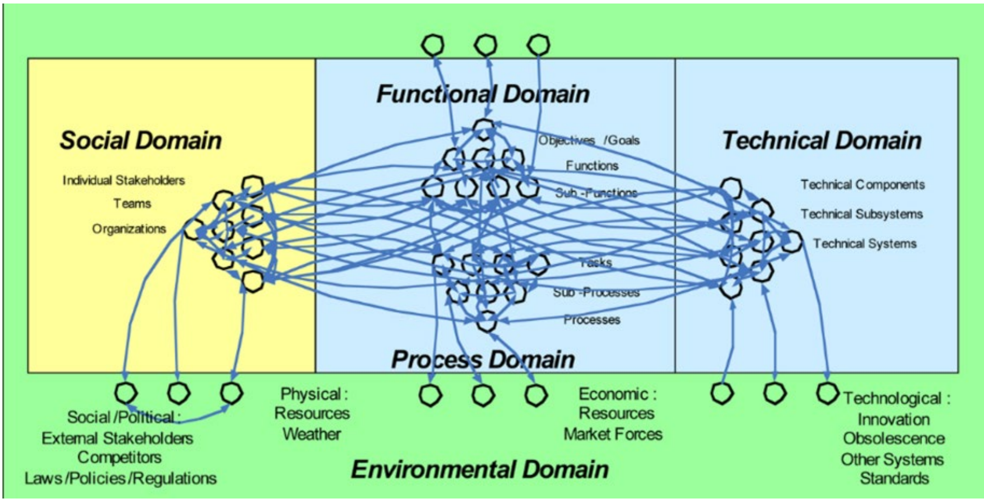


Figure 4.2 Distinct domains and their interactions in sociotechnical systems (Bartolomei et al., 2012)

4.2.4 Characteristic: The existence of interdependencies

Davies & Mackenzie (2014) suggested that organizations cope with complexity by decomposing a project into different levels of SI with interfaces between individual subsystems. The definition of the parts may depend on technology or geography for example. In addition, the EM can impose interfaces to help manage the project. These include interdependencies, organizational or contractual interfaces, relationships, and shared or separate responsibilities.

However, in complex inter-organizational contexts, coordination among diverse groups becomes more challenging as their number and interdependencies increase. Regardless of how tasks are divided, linking various parts is always complicated, and as such, there is a constant need for their management to facilitate the exchange of information across these interfaces (Long & Spurlock, 2008; Stretton, 2016).

Identifying interdependencies indicates where a collaborative approach is needed from actors from either side of the interface. These can exist between departments in the same organization or across different organizations (Rail Safety & Standards Board, 2014; Stretton, 2016), and knowing where relevant interdependencies exist (Dasher, 2003) reveals which topics require knowledge and information to be shared across organizations.

This leads to *subgoal 4: Facilitate the structured exchange of inter-organizational knowledge and information.*

The interdependencies can be classified as pooled (each part provides a discrete contribution to the project, irrespective of other parts), sequential (one organization's output becomes an input for another part), or reciprocal (outputs of each unit become inputs for others and vice versa) (Geyer & Davies, 2000). Additionally, a dependency structure matrix (DSM), which displays the relationships between the components of a system in a compact, visual, and analytically advantageous format, can provide an excellent approach for mapping interfaces in SOIs (Browning, 2001). However, in complex inter-organizational contexts where different perspectives make up the SOI, additional preliminary steps are required first to identify the SOI.

Furthermore, in an inter-organizational project, distinct parties perform multiple tasks to achieve the main objective. However, not all tasks must be performed simultaneously. A method for distinguishing these is the circle technique, which focuses on progress-oriented instead of problem-oriented work (Visser, 2013). This method consists of three steps: (1) writing down everything that has already been achieved and operates well in the inner circle; (2) noting what still needs to be achieved in the outer circle; and finally, (3) discussing which of the items in the outer circle need to be worked on to be moved to the inner circle (Visser, 2013). This technique mainly revolves around inventorying, brainstorming, and the creative process behind these to gather as much useful information as possible.

Thus, *subgoal 4: Facilitate the structured exchange of inter-organizational knowledge and information* can be achieved by creating insight into inter-organizational interdependencies/interfaces and creating insight into task sequencing.

4.2.5 Characteristic: Diverse objectives

In temporary organizational systems such as projects, independent and interdependent entities cooperate for a limited period to achieve specific objectives (Pezzillo Iacono et al., 2012). The objective is typically a short statement outlining the purpose and function of the change and whether it is technical, operational, or organizational (Rail Safety & Standards Board, 2014). Depending on the type of change, it is helpful to explain the reason for the change, for example, whether it is for an improvement in capacity, safety, or reduction in cost.

According to Foster-Fishman et al. (2001), reducing organizational barriers and creating mutual goals and objectives is important to enhance inter-organizational collaboration and facilitate the exchange of information and resources across organizational boundaries. In such cases, all project participants must be clear about their goals and objectives, including owners, managers, contractors, and consultants (San Cristóbal et al., 2018). Thus, the objective provides a useful context and clarifies the main reasons for the change and the requirements of a successful assessment. Furthermore, discussing the objective aids in jointly producing a mutually valued outcome.

Thus, *subgoal 4: Facilitate the structured exchange of inter-organizational knowledge and information*, can be achieved by determining a clear objective.

4.2.6 Characteristic: A dynamic environment

As previously stated, the current society is characterized by rapid changes and advancements in technology. Moreover, system changes occur at various time scales (Sterman, 2002). This means that while jointly creating insight into high-level inter-organizational SOIs to support EMs, additional information might become available, be subject to changes, or even the intended change itself might be susceptible to adjustments (Keating et al., 2008). Establishing processes to maintain stability while dynamically responding to uncertain and changing conditions is one of the most challenging aspects of SI (Davies & Mackenzie, 2014).

A more flexible and incremental approach is required to solve this problem.

This leads to *subgoal 5: Cope with significant modeling changes*, which can be achieved by providing a high degree of modeling flexibility.

While it can be concluded that the current literature focuses on the individual characteristics describing the present context and related solution directions, no pragmatic solution is provided that synthesizes the aforementioned subgoals and design principles into a single method or tool to support EMs with the project scope definition. Therefore, this study aims to support the management of inter-organizational change integration in the sociotechnical railway system by designing an expert-based analysis that aids in jointly creating insight into inter-organizational SOIs, aiding the scope definition. This is done by (1) facilitating multidisciplinary stakeholder/expert involvement, (2) creating a shared high-level SOI among various stakeholders, (3) taking a broad perspective including more than merely the technical perspective, (4) facilitating the structured exchange of inter-organizational knowledge and information, and (5) coping with significant modeling changes.

4.3 Methodology

This study utilizes the design science research methodology (DSRM), which aims to design an artifact to address an unsolved and important problem (Hevner & Chatterjee, 2010). The DSRM involves a rigorous process for designing artifacts to solve observed problems, make research contributions, evaluate designs, and communicate results to appropriate audience members (Peffers et al., 2007). It constitutes a systematic but flexible methodology that aims to improve practices through iterative analysis, design, development, and implementation based on collaboration among researchers and practitioners in real-world settings, leading to context-sensitive design principles and theories (Wang & Hannafin, 2005). Peffers et al. (2007) designed a commonly accepted framework for carrying out the DSRM, as displayed in Figure 4.3. As this research resulted from observing the problem, this problem-centered approach is particularly appropriate.

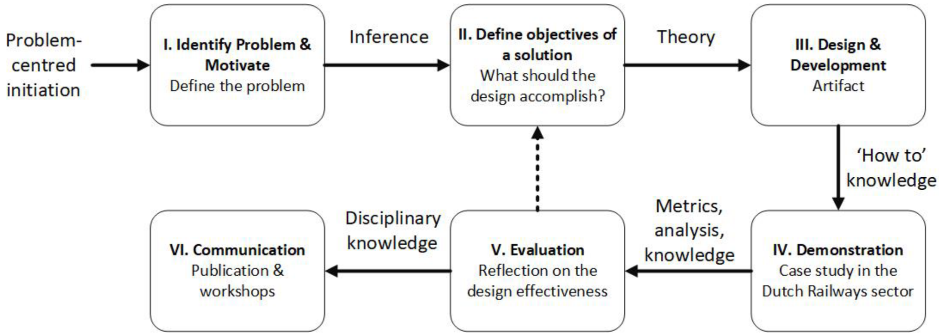


Figure 4.3: DSRM approach adapted from Peffers et al. (2007)

Furthermore, this study used triangulation by employing multiple methods to collect data on the same phenomenon of interest (Campbell et al., 2020). This type of triangulation, frequently used in qualitative studies, includes interviews, observations of expert sessions within the industry, and documents on existing models and modeling approaches in the industry, which aim at achieving nearly identical objectives but on a small scale and in a decentralized manner.

4.3.1 Design objective and principles

The main objective of this study (II in Figure 4.3) was to design an expert-based analysis that aids EMs in jointly creating SOIs. This design is broken down into multiple subgoals, which have been addressed using design principles: (1) provides high-level insights, (2) includes sociotechnical viewpoints, (3) utilizes integral expert-based sessions, (4) provides insight into inter-organizational interdependencies, (5) has a high degree of modeling flexibility, (6) focuses on a clear objective, and (7) provides insights into task sequencing. Moreover, the developed analysis should provide the 'how' and give insight into the process which results in the SOI.

The combination of the subgoals and principles is summarized in Table 4.1.

Table 4.1: Design subgoals and related design principles

Subgoals	Design principles
Subgoal 1: Facilitate multidisciplinary stakeholder/expert involvement	Integral expert-based sessions
Subgoal 2: Create a shared SOI among various stakeholders	High-level insights
	Sociotechnical viewpoints
	Integral expert-based sessions
	Insight into task sequencing
	Insight into inter-organizational interdependencies/interfaces
Subgoal 3: Take a broad perspective that should include more than the technical perspective	Sociotechnical viewpoints
Subgoal 4: Facilitate the structured exchange of inter-organizational knowledge and information	Insight into inter-organizational interdependencies/interfaces
	Integral expert-based sessions
	Insight into task sequencing
	Clear objective
Subgoal 5: Cope with significant modeling changes	High modeling flexibility

Moreover, emergent design principles arise from the iterative nature of the design cycle. The combination of the design principles mentioned above and their iterations led to the design and development (III in Figure 4.3) of the MOSAIC analysis.

4.4 Design of MOSAIC

The developed MOSAIC analysis consisted of four steps, visually represented in Figure 4.4. This is described in the following paragraphs.

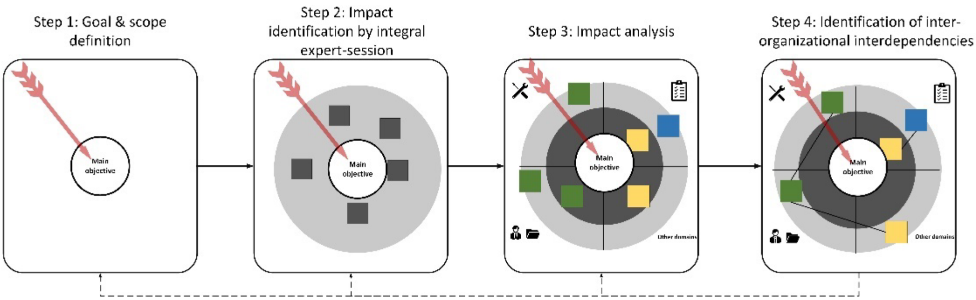


Figure 4.4 Proposed MOSAIC steps

4.4.1 Step 1: Goal & scope definition of the change

The first step of MOSAIC is to develop an understanding of the main goal and preliminary assumptions regarding the change, the type of change, and an initial overview of the stakeholders impacted by it. This determines the initial scope of the change project, and which multidisciplinary experts from distinct organizations are required to be involved in MOSAIC Step 2. Additionally, the starting assumptions are important: they provide a record of circumstances for which the analysis is valid. If these assumptions change later, the MOSAIC steps should be reviewed and revisited, if necessary.

In Step 1, the following guiding questions from Bartolomei et al. (2012) and Maier & Rechtin (2000) can be useful: (1) Who affects/is affected by the change (2) Who decides on the project (3) Who carries out work in the project? (4) Who benefits from it? (5) Who provides what? (6) Who loses?

4.4.2 Step 2: Impact identification by means of integral expert session

To meet the objective established in Step 1, an understanding of how the change affects the previously determined stakeholders needs to be reached. Therefore, this step strives to determine what impacts the change will have. These can include impacts on various sociotechnical domains: social (individual stakeholders, teams, organizations), functional (functions), process (tasks, processes), technical (technical components, subsystems), and environmental domains (laws, policies, regulation).

These impacts can be identified by bringing together selected experts in an expert session, during which collective expertise and information are employed and synchronized, and diverse tasks required to be conducted by distinct entities to integrate the change effectively are determined. Figure 4.4 depicts these using rectangles, representing the sticky notes used in the expert sessions. Thus, this second step leads to an initial, synchronized, high-level overview of the SOI.

During this session, the following questions can be raised: (1) What is the effect of the change on the aforementioned domains? (2) What adjustments are required for change to be properly integrated? (3) Are these adjustments a part of the project? (4) Which tasks must be conducted by distinct departments and stakeholders to achieve the identified objective?

4.4.3 Step 3: Impact analysis

After the information collection steps, the initial SOI can be analyzed to highlight important features. The information presented on sticky notes, such as grouping related tasks and impacts, should be checked for possible duplication and clustering. Furthermore, it is important to distinguish which individual, department, and organization is responsible for each task for effective follow-up.

Depending on the entity responsible, this can be done by recoloring the sticky notes. In addition, there is a difference in the sequence of the identified tasks. Although some tasks have already been completed, some tasks remain to be conducted to achieve the main objective. This differentiation can be made by moving existing sticky notes to the inner or outer circle, as shown in Figure 4.4. Furthermore, this information can be reorganized into distinct domains. Because preliminary research showed that the technical, process/organizational, and compliance/regulatory domains are the most significant in the railway context, the SOI is divided into quadrants reflecting this. This demonstrates which sociotechnical domains the current focus is on, whether there is a tendency toward a specific domain, or whether more attention should be paid to other domains.

Therefore, Step 3 leads to a more detailed, synchronized, high-level overview of the SOI, providing insights into the responsible stakeholders per identified task (colors), task sequencing (inner and outer circles), and any tendencies toward different sociotechnical domains (quadrants), highlighting directions for further analysis.

4.4.4 Step 4: Identification of inter-organizational interdependencies

Because integration mostly fails at interfaces, it is essential to identify the interfaces between the elements mentioned above and manage them accordingly. Especially in inter-organizational contexts, it could be the case that some responsibilities are shared between organizations and, as such, require close collaboration on that interface for effective integration of the change. These interdependencies can be inter- and intra-domain as well as inter- or intra-organizational.

Relevant questions to ask during this step include (Browning, 2002): (1) What inputs are needed to do the work? (2) What is the source or supplier of each input or task? (3) What is the destination or customer for each output? (4) Which tasks depend on inputs from other departments/organizations?

Step 4 leads to an overview of interfaces in the SOI. These can include (1) tasks that are interdependent (i.e., sequential or reciprocal) or (2) tasks in which responsibilities are shared between stakeholders (i.e., there is an interface between responsible parties, and collaboration is necessary).

After carrying out steps 1–4, the SOI is defined.

4.5 Demonstration of MOSAIC: A case study on a multipurpose train towing vehicle

The MOSAIC analysis was applied to a case study in the Dutch railway sector to demonstrate its practical applicability. This concerned a project on a multipurpose train towing vehicle. The purpose of the vehicle's deployment by the Incident Response Department of the infrastructure managing organization is to tow trains belonging to the main railway operator when stranded on the high-frequency railway network. This towing process should be conducted as quickly as possible in situations where a train is stranded owing to problems with the traction systems or in case of problems with the overhead contact line. Furthermore, this vehicle is powerful enough to pull or push a full passenger train and is unique in its ability to operate on both roads and rail, allowing easier access to stranded trains. Because of its inter-organizational nature, this project included multidisciplinary representatives from the infrastructure managing organization and the main railway operating organization.

Based on structured interviews to explore challenges in this case study, conducted with all project team members, it became apparent that a standardized process for integrating this type of joint initiative in existing railway operations has not yet existed.

The newly introduced vehicle affected the operations of the main railway operator and the infrastructure manager and their responsibilities in towing stranded trains. Mutual responsibilities and ownership needed to be well established during this phase and after commissioning. The problem investigation indicated that the multipurpose train towing vehicle was (1) a large project with a broad scope involving different departments and organizations, which made its scope unclear. Moreover, because of its large scope, (2) numerous multidisciplinary stakeholders with different perspectives and a lack of shared understanding were involved. Additionally, (3) predicting the impact of this change in the inter-organizational context was challenging.

The following subsections demonstrate the step-by-step application of MOSAIC to the case study, which is briefly summarized in Figure 4.5.

4.5.1 Step 1: Defining the goal and scope of the project concerning the implementation of a multipurpose train towing vehicle

The type of change, goal and scope, and starting assumptions of the case study were determined ahead of the expert session, together with project leaders from the infrastructure managing organization and the main railway operating organization. The knowledge of their own organizations aided them in understanding which departments and processes would be affected by the project. This highlights the scope and indicates that collaboration is necessary to clarify the scope in the inter-organizational context. In this regard, Project Member A from the Safety Department mentioned:

"In case of an internal project, it is easier to get the right parties together. It is important to look across departments and have a project interest, and not only a departmental interest."

The inter-organizational scope aided in identifying the most important experts required to be involved in Step 2. Because the project was quite large, the emphasis of this case study was ultimately on a subgoal of the project: to have a complete file finalized for the independent assessment body containing demonstrable evidence concerning safety requirements, as shown at the center of Figure 4.5.

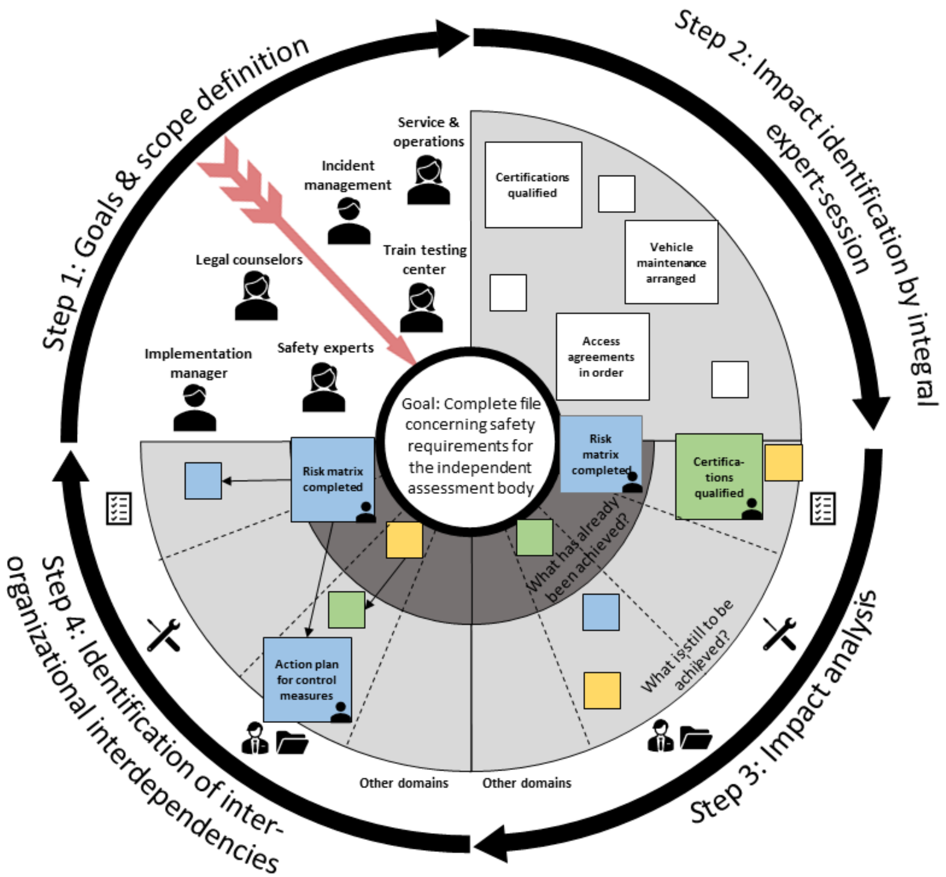


Figure 4.5 Demonstration of MOSAIC steps applied to the project concerning the implementation of a Multipurpose Train Towing Vehicle

4.5.2 Step 2: Impact identification by integral expert session of the project concerning the implementation of a multipurpose train towing vehicle

The experts identified in Step 1 were requested to join an integral expert session. These included inter-organizational representatives from the service and operations department, train testing center, incident management, legal counselors, project leaders, implementation managers, and safety experts, as depicted in Figure 4.5.

Due to the Covid-19 pandemic, the integral expert session could not be held in person and was required to take place online. Because of this, several online collaborative tools were tested to maintain optimal effectiveness and efficiency. The visual collaborative software MIRO was chosen to carry out the session because of its ability to support the collaboration of multiple users simultaneously, allowing the step-by-step building of the design, and providing opportunities for easy adjustments and analysis.

To reach the goal set in Step 1, the impacts of the change needed to be clear, and tasks required to be conducted by the stakeholders involved in the expert session were identified. Examples include access agreements in their proper order, arranging vehicle maintenance, certifications, and safety systems to be up to date. A project member working in service and operations stated the following:

"He must pick up on signals for train drivers in this session and represent the interests of the drivers: determine what training is needed, whether safety agreements are covered, and arrange capacity for drivers for testing."

During impact identification, participants could use sticky notes to write down aspects of which they had knowledge and place them on the digital board. This resulted in an overview of the various impacts of the changes and tasks that needed to be arranged to integrate the change effectively. The facilitator then addressed the sticky notes to encourage open discussion within the group. This discussion aided in clarifying various tasks and provided insightful discussions within the group. An example of such a discussion dealt with the inter-organizational cooperation between the organizations during vehicle operation and shared responsibilities in the case of accidents.

4.5.3 Step 3: Impact analysis of the project concerning the implementation of a multipurpose train towing vehicle

After information collection, the SOI was checked for duplicates and clusters, such as tasks related to risk management. At this stage, participants could recolor the digital sticky notes produced in Step 2, depending on who was responsible for the task listed on them. Project member X, who focused on legal aspects, mentioned the following:

"The different roles and responsibilities must be clear when the multipurpose towing vehicle is operational."

In addition to using different colors, the participants were required to tag each sticky note with a name. The layout distinguishing task sequencing (inner and outer circles) and sociotechnical domains (quadrants) were already prepared in MIRO to facilitate brainstorming; hence, sticky notes could be easily repositioned accordingly. This step revealed a strong tendency toward regulations/compliance and less toward the technical domain of the project.

Project member Y from the Safety Department stated the following:

"The project includes a lot of inter-organizational regulations, and because of that, there is a lot more to be considered."

4.5.4 Step 4: Identification of inter-organizational interdependencies of the project concerning the implementation of a multipurpose train towing vehicle

To identify interdependencies, the facilitator opted to use multiple questions regarding tasks represented by sticky notes: Which tasks depend on others? What is required by other stakeholders to carry out these tasks? Are these inputs for other tasks? Do these factors lead to additional impacts (not previously identified)?

"There are quite a few challenges in this project, the train drivers and vehicle operator have to work together, which is very different compared to other projects. How are the responsibilities shared when a stranded train is towed by the vehicle? We should manage these dependencies correctly." – Safety expert Y.

Because there was already substantial discussion in steps 2 and 3, interdependencies between different tasks had already been referred to, albeit indirectly. However, these were not explicitly stated in the SOI or assumptions.

"We should ensure that we know these interdependencies at the front end, so we can get our own processes up and running properly in time." - Project member Z.

This demonstrates that each MOSAIC step leads to intermediate results. Moreover, further details of the SOI are obtained during the process. A representative focusing on project implementation stated the following:

"In the beginning, it did not seem that complicated, but during the project, it turned out that there were many more aspects that had to be considered."

4.6 Evaluation & discussion

The next step in the DSRM process (V) presented in Figure 4.3 concerns design evaluation. This involves comparing the objectives of the proposed solution with the observed results from the use of the artifact in the case study. The MOSAIC analysis was evaluated using information from preparatory meetings, observations during the case study, and evaluations after the expert session.

This section will evaluate each MOSAIC step in detail and describe to what extent the design principles worked to achieve the different *subgoals*.

4.6.1 Evaluation of MOSAIC Step 1: Goal & scope definition of the change

Step 1 describes the main objective of the change and type of change. By mentioning this, the main reason for the change and the requirements for a successful assessment were made explicit. Moreover, the objective provided a useful context and helped determine which *multidisciplinary stakeholders/experts (subgoal 1)* were required to be included from the affected processes, departments, and stakeholders at a high level for each specific objective. To do this, project leaders relied on their knowledge of the organization and departments and their understanding of whether a change would affect different organizational units. A project member working in service and operations stated:

"The key to reaching the objective is collaboration and connecting the right people."

Furthermore, the iterations in the case study application show that MOSAIC analysis is highly flexible in its application and can easily be adjusted to changing goals and, as such, determining which experts are required to be involved. Project member B:

"One must very clearly define the scope within one's own work, and a clear overall objective helps with this."

Multiple participants stated that it would be easy to include this approach in different projects due to its flexibility, and it would certainly help to carry out this session as early as possible in projects. Moreover, this indicates that the MOSAIC analysis aids significantly in clarifying the initial scope of the project by determining which departments, processes, and organizations are impacted by this change. This analysis can also respond to changes over time, which means that MOSAIC can *cope with significant changes (subgoal 5)*.

4.6.2 Evaluation of MOSAIC Step 2: Impact identification by means of an integral expert session

Step 2 determines the impact of the change by using an integral expert-based session. This session helped *involve the identified multidisciplinary stakeholders and experts (subgoal 1)*. Project member B stated:

"The people involved have different backgrounds, e.g., more 'outside people' who are more hands-on versus more 'inside people' who know less about the actual calamities and work more from a procedural perspective. The collaboration between them is essential."

The impacts included high-level impacts on sociotechnical domains. Moreover, because visual aids support these insights; *subgoal* 2: *Create a shared SOI among various stakeholders* was met. By asking guiding questions related to sociotechnical viewpoints, *subgoal 3: Take a broad perspective that should include more than the technical perspective* was also met. This combination led to an initial, synchronized, high-level overview of the SOI, which *facilitated the structured exchange of inter-organizational knowledge and information (subgoal 4)*. Project member Y from the Safety Department stated the following:

"Conducting such an exercise shows how complex the project is, and that every expert has their own understanding of impacts related to their field of work."

Moreover, according to several participants:

"Doing such an exercise in a group provides more consensus."

In this step, it was essential to give participants time to reflect and write down the aspects they considered relevant. Additionally, the role of the facilitator is important; while it did help that the facilitator present had content-related knowledge of the project in this case, it would have been beneficial to have a process facilitator present who focused only on the MOSAIC process and analysis without engaging in content-related discussions.

4.6.3 Evaluation of MOSAIC Step 3: Impact analysis

Although stakeholders from various disciplines each had their own models and approaches for describing and understanding an SOI, the integral expert session *facilitated the involvement of multidisciplinary stakeholders/experts (subgoal 1)* to a great extent. By focusing on high-level insights and multiple generalizable cross-sections such as sociotechnical perspectives (showing a tendency toward specific domains) and insights into task sequencing (to achieve the objective), the attendees could easily share knowledge from their own experiences, ensuring that the analysis aids in *creating a shared SOI among various stakeholders (subgoal 2)* and *facilitates the structured exchange of inter-organizational knowledge and information (subgoal 4)*. One interviewee stated:

"You always have an idea of the impacts of a change by and large, but not exactly what that would mean. Only after the impact analysis and discussion does it become clearer."

The evaluation revealed that MOSAIC created an understanding within the group that different domains play a role in reaching the defined objective.

Despite this, the reorganization of sticky notes in one of the sociotechnical quadrants did not proceed smoothly.

This suggests that, although acknowledging different sociotechnical perspectives is important, this way of thinking does not come naturally to the participants. Furthermore, the evaluations showed some inconsistencies regarding the tagging of sticky notes. It was unclear whether the tag referred to the individual responsible for the task mentioned on the sticky note or whether the tag referred to the participant who added the sticky note. Project member B mentioned:

"Sometimes we are not explicit enough about the responsibilities, which results in a lack of ownership."

Overall, participants mentioned that MOSAIC helps to identify concrete tasks and identify the responsible stakeholders required to take action. In addition, this process and the resulting overview create insight into conducted tasks and what the focus should be on next. Moreover, it helps prioritize important aspects and improve relationships among project members.

4.6.4 Evaluation of MOSAIC Step 4: Identification of inter-organizational interdependencies

Close collaboration across interfaces is required to integrate changes effectively in an inter-organizational context. Evaluation with participants indicates that the insight into interdependencies to a large extent, aids in clarifying (1) how different tasks fit into the project as a whole, (2) how different tasks are linked to each other, and (3) how a change in adjacent tasks could impact dependent tasks, and as such, should be planned accordingly. This shows that making these insights explicit *facilitates the structured exchange of inter-organizational knowledge and information (subgoal 4)* on specific tasks/impacts. One attendee mentioned:

"Applying regulations between 2 companies takes a lot of time. This shows that we need to start earlier with such exercises and have the right people join at the right times."

In some instances, the guiding questions asked by the facilitator led to impacts that had not been considered previously. However, because there were inconsistencies with the tagging of the sticky notes in steps 2 and 3, it was not explicitly stated who and which organization was responsible for which task. This made it more difficult to identify tasks in which responsibilities were shared.

An additional session is necessary for future applications to identify the interdependencies. Moreover, because a significant number of tasks with possible interdependencies were identified, a simple, compact, and visual representation is preferable for further analysis. Further research on this is required, which should include paying attention to the differences in pooled, sequential, and reciprocal interdependencies (Davies & Mackenzie, 2014), as well as how interdependent tasks should be followed up on.

During steps 2, 3, and 4, a significant number of assumptions and clarifications were discussed throughout the expert session; making these explicit and including them in the SOI could improve the follow-up in later sessions. In addition, the SOI which resulted from the application of MOSAIC is based on information contemporary to the execution of the different steps. This means that for the SOI to remain relevant and usable, it must be updated continuously based on the latest information available. Project member Q from the safety department stated:

"If you want to plan everything in advance and not be flexible to changes, it is not going to work."

All interviewees mentioned that the resulting SOI and a structured analysis to get to such an integral, mutually agreed upon are important to facilitate the structured exchange of inter-organizational knowledge and information. According to project member A:

"This method could be introduced in all other projects that want to move forward. If you do this well with the right delegation of people involved in the project or those who are going to be affected by it, there are always insights and/ or confirmations in the vein of 'we are on the right track,' or 'there is still work to do here.' It gives direction and ensures connections regarding content and relationships."

4.7 Implication for Engineering Managers

EMs are frequently required to oversee the integration of changes in complex sociotechnical systems. Similar to the case study in this study, EMs in this context outside of the railway sector are often faced with large projects with a broad, ambiguous scope involving different departments and organizations. As a result, numerous multidisciplinary stakeholders with different perspectives and a lack of shared understanding are involved. Additionally, predicting the impacts of changes in an inter-organizational context can be challenging for EMs. Fortunately, the MOSAIC can provide useful guidance.

The application and evaluation of MOSAIC in a practical case study have multiple implications for EMs:

(1) By bringing together experts from different backgrounds and different organizations in the expert session with a clear, explicit goal and supported by visual aids, the impacts of the change on their respective disciplines and domains can be mapped and discussed. This ensures that diverse insights and domain-specific SOIs can be combined into an integral overview, facilitating multidisciplinary group communication and sharing of information across organizational boundaries.
(2) Additionally, confusion between different practitioners working on the same change is reduced by not basing an SOI on assumptions related to the change, but building it on explicit information. Instead of having a single person providing information for the SOI, a multidisciplinary and inter-organizational group of experts can be employed to define the SOI collectively. Thus, conducting MOSAIC in a group setting helps create a consensus on the SOI.
(3) By including an appropriate delegation of experts in the process, both from the project and those affected by it, MOSAIC provides a broad range of insights for EMs. These include the tendency toward specific domains and insights into task sequencing, which are relevant for EMs in steering and controlling the project.
(4) Based on the discussions observed during the case study, the MOSAIC analysis, inherent discussions, and resulting SOI seem to have stimulated the working relationship among project members by providing opportunities to understand each other's perspectives and expertise while still systematically synchronizing these in a high-level, visual, and condensed manner.
(5) Carrying out MOSAIC can aid EMs in front-end planning, which is critical for uncovering project unknowns by focusing on explicit objectives, developing an adequate scope definition, and recognizing key stakeholders.
(6) The MOSAIC results can be used to identify concrete tasks, and responsible stakeholders required to take action for the progress of the project. The case study shows that interdependencies between tasks are implicitly known to individual experts; however, making these explicit and placing appropriate levels of focus on these also clarifies topics/impacts requiring more detailed coordination between multiple stakeholders to support the EM with the integration of different parts.
(7) MOSAIC can be easily generalized and applied by EMs to other projects within the railway industry and beyond. These projects (a) involve multidisciplinary experts; (b) concern a variety of (non)engineering stakeholders who are required to collaborate for effective change

integration; (c) require information that is dispersed over (multiple) departments and organizations; and (d) concern a sociotechnical system change, where multiple domains play a role. While MOSAIC focuses mainly on the technical, process, and regulatory domains which are deemed important in the railway industry, other domains may play a significant role in other industries. In this sense, the MOSAIC is flexible and can be adjusted accordingly.

4.8 Conclusion

Sociotechnical systems are becoming more complex and inter-organizational, causing the number of inter-organizational components and interdependencies to increase drastically. As such, a change in one part may affect other system parts, impacting multiple domains across different organizations. This broadens the SOI and makes it more difficult to describe, understand, and manage EMs. This study designed the MOSAIC analysis to support EMs in managing inter-organizational change integration in a sociotechnical railway system to aid in achieving performance upgrades resulting from change integration.

This paper shows that MOSAIC contributes to this by (1) focusing on a clear objective and incorporating relevant stakeholders; (2) providing a structured process and analysis to determine the SOI; (3) synchronizing the perspectives of inter-organizational and multidisciplinary experts through an integral expert session; (4) enabling an open-yet focused discussion, supported by guiding questions and visual aids; (5) identifying diverse impacts of the change across sociotechnical domains, and tasks required to be carried out by diverse stakeholders to achieve the determined objective; (6) highlighting ownership and responsibilities; and (7) identifying interdependencies across which collaboration is essential. Furthermore, the evaluation shows that the designed analysis is pragmatic and flexible in dealing with the changes. Owing to the high-level insights it provides, MOSAIC is adaptable for use in other engineering management contexts. Moreover, because MOSAIC is an analysis in which experts exchange information, interact with, and discuss the impacts of the change based on their expertise and experience with similar changes, the analysis is less appropriate for changes related to radical innovations with which experts have no experience.

The world is becoming increasingly connected, inevitably causing challenges that are too difficult to solve by applying methods from a single discipline. This is reflected in the growing trend toward multidisciplinary collaboration. By applying the MOSAIC analysis, collective expertise and information are synchronized in high-level SOIs, highlighting what the change entails, its scope, inherent sociotechnical domains, and inter-organizational responsibilities, all of which require attention to reach the foreseen improvements. Moreover, by establishing a stepwise SOI in a group setting, mutual understanding and acceptance are built during the process, facilitating the exchange of information and resources across organizational boundaries, thus enhancing collaboration and supporting EMs in managing inter-organizational change integration.

Acknowledgment

This study was co-financed by the research and innovation contribution (PPP) of the Dutch Ministry of Economic Affairs and Climate. The authors acknowledge the support of NS and ProRail in making this study possible through the framework of the Systems Integration for Railway Advancement (SIRA) project. Furthermore, the authors acknowledge peer review feedback, which has improved this paper.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The work was supported by the Research and Innovation contribution (PPP) of the Dutch Ministry of Economic Affairs and Climate.

Orchid

Merishna Ramtahalsing http://orcid.org/0000-0003-4011-7193

Chapter 5 Climate Change in Dutch Railway Infrastructure: Towards a Framework for Adaptation Strategies

Abstract:
Extreme meteorological events such as floods, droughts, heatwaves, and storms cause significant damage to infrastructures across the world. These events can damage expensive infrastructural assets, but can also incur a high societal cost when disrupting the transportation of people, goods, and energy. Due to climate change, these extreme meteorological events will increase in severity and frequency in the coming decades. Infrastructural management organizations are, therefore, looking to adapt their infrastructural assets to cope with this. Existing literature stresses the need for translating climate risks and opportunities into concrete, mitigating actions. In practice, however, this translation poses a significant challenge for infrastructural management organizations. The challenges are further exacerbated by the high number of dependencies and the need for alignment with both operational and strategic objectives and the interests of multiple internal and external stakeholders. To address this gap, a framework for identifying climate adaptation strategies and prioritizing the risks and actions is proposed. The framework can be used to identify, organize, and prioritize the 'missing links' between climate risk and adaptation strategies by taking into account synergies, prioritization, and an integral view. The novel features of the presented framework are explained by comparing them to practice at a Dutch railway infrastructural management organization. The evaluation of the preliminary framework suggests that it can assist railway infrastructural management organizations with developing concrete climate adaptation strategies in a smart way.

Publication history:
This chapter was published in the proceedings of the 10th International Conference on Through-Life Engineering Services 2021:
Ramtahalsing, Merishna and Kuiper-Hutten, Laura and Haanstra, Willem and Braaksma, Jan and Rajabalinejad, Mohammad and van Dongen, Leo, Climate Change in Dutch Railway Infrastructure: Towards a Framework for Adaptation Strategies (October 18, 2021).
Available at SSRN: http://dx.doi.org/10.2139/ssrn.3944747

5.1 Introduction

The global climate is changing and the frequency of extreme weather events is increasing (Quinn et al., 2018). These extreme meteorological events such as floods, droughts, heatwaves, and storms cause significant damage to infrastructures across the world. In the coming years, thousands of billions of euros will have to be invested in transport, energy, water, and telecommunication networks to preserve the connectivity, efficiency, and resilience of infrastructure (Dépoues, 2017). Those infrastructures will have life expectancies of several decades and will therefore be exposed to the impacts of climate change (Dépoues, 2017). Additionally, due to climate change an increase in the number and magnitude of the so-called NaTech events is expected (natural hazard triggered technological accidents involving the release of hazardous materials) (Girgin & Krausmann, 2013).

Because of this, the need for Climate Change Adaptation (CCA), adapting assets to a changing climate, has attracted increasing attention both from practice and theory during the past decade. Quinn et al. (2018) mention that it is highly desirable to consider adapting to extreme weather and future climatic change as part of effective asset management which contributes to business as usual, rather than regarding it as an optional or a separate stream of activity for which extra funding is required.

5.1.1 Climate change adaptation in the transportation sector

Because of the aforementioned challenges, the current transportation literature stresses the need for translating climate risks and opportunities into concrete, mitigating actions for CCA. Firstly Quinn et al. (2018) proposed an iterative framework that has the overarching ambition to embed CCA within organizational procedures. Secondly, Bollinger et al. (2014) proposed a framework for supporting governance for CCA of interconnected infrastructures. Thirdly, Moser & Julia (2010) demonstrate a framework for diagnosing barriers to CCA. Fourthly, Preston et al. (2011) pay attention to CCA in practice, evaluating plans from three developed nations.

Among these infrastructures are railways all across the globe, where climate-related events are already among the factors frequently causing disturbances for railways (Lindgren et al., 2009). In this context, Dépoues (2017) discusses the organizational uptake of scientific climate change information by infrastructure managers in the French railway company. Additionally, Lindgren et al. (2009) pay attention to CCA in practice: providing lessons learned on CCA of railways in Sweden.

Comparing the mentioned CCA literature revealed several important aspects and limitations for managing CCA in infrastructures. Among these is the CCA process which includes prioritization, synergies, and consideration of CCA at multiple levels of analysis, which will be discussed in more detail further on.

5.1.1.1 CCA Process

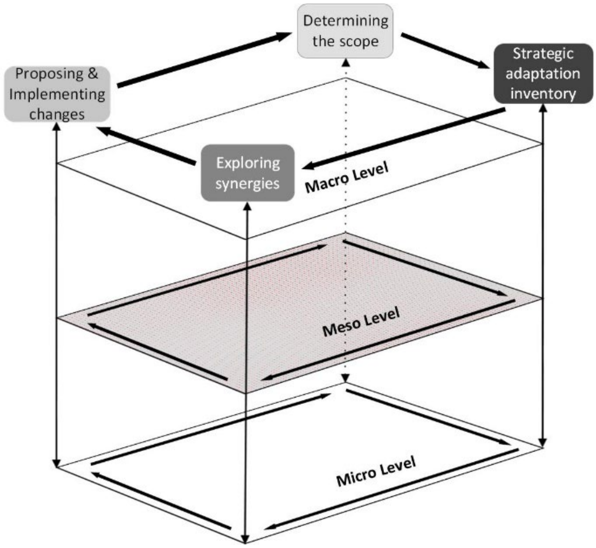
The CCA process refers to the different steps leading to adaptation strategies. Quinn et al. (2018) mention that the process should be responsive and iterative, and not linear. Furthermore, they also mention that people from different areas of a business or organization will have knowledge or experience which will be relevant for adapting to climate change. This personnel can lend support and expertise in the CCA process. In addition to this, Lindgren et al. (2009) state that systematic mapping of types of climate threats, vulnerabilities, and consequences is necessary to guide the implementation of adaptation measures and prioritization of efforts. This systematic mapping is also highlighted in NaTech methodologies where attention is paid to among other identification of natural hazards, critical equipment, damage severity and probability (Girgin & Krausmann, 2013).

Also related to the process, is the planning of CCA activities. Lindgren et al. (2009) mention that a weakness in the planning process of CCA is the lack of consideration of climate change impacts in the early stages of planning. Risk and vulnerability aspects are often dealt with in the later stages of planning, then the focus lies on the management of the risks rather than prevention.

5.1.1.2 CCA Context: Macro, Micro & Meso levels

The CCA context is concerned with variations in organizational levels, depicted in Figure 5.1. Quinn et al. (2018) say that through experience, organizations have found that there can be too great a step between overall organizational objectives that have potential national or international aspects (macro), and the individual adaptation actions that can be implemented in the short-term (micro), which ultimately can lead to stagnation of the adaptation process.

Furthermore, Lindgren et al. (2009) say that based on lessons learned in the Swedish railway sector, no tailor-made climate change indicators were delivered (on a micro level). Additionally, according to several interviewees from Dépoues (2017), climate change will not just affect a few procedures or standards that could be easily listed, but will also have impacts across the whole railway system (macro level). All of this suggests the necessity of the intermediate meso level, linking the macro and micro levels.



-

Figure 5.1: CCA context: Macro, Micro, and Meso levels

5.1.1.3 Strategic adaptation inventory

There are never enough resources to carry out all CCA activities simultaneously, hence prioritization is required. Lindgren et al. (2009) mention: to make well-founded prioritizations among different CCA measures, potential consequences of climate events should be thoroughly evaluated. Furthermore, appropriate methodologies should be used when performing risk and vulnerability assessments so that the results balance the frequency of events against their consequences in a systematic way. On strategic adaptation inventory, Quinn et al. (2018) mention that considering hazards, vulnerabilities, and losses enables a holistic approach that must determine the most significant risks to the organization and determines what risks should be addressed to achieve the objectives set out from the start. In extension, resilience assessment methods could help give insight in (less) vulnerable aspects/assets (Argyroudis et al., 2020; Ouyang & Wang, 2015; Rehak et al., 2018). Their aim to assess asset resilience under individual or multiple hazards, at asset level, infrastructure network level, and community or national scale (Rehak et al., 2018), could be complementary to strategic adaptation inventory, aiding the prioritization of critical assets.

5.1.1.4 Exploring synergies

Synergy refers to the interaction or cooperation of two or more organizations, or other agents to produce a combined effect greater than the sum of their separate effects. Lindgren et al. (2009) refer to synergies from a goal perspective: the possibility of creating synergies with climate mitigation goals and other environmental goals should be investigated and exploited.

When planning and designing adaptation actions, the effects of potential goal conflicts should be carefully assessed, to avoid the implementation of counter-productive measures.

While existing frameworks and methodologies like e.g. NaTech methodologies pay attention to i.e. the risk identification and management, other important aspects like the inclusion of synergetic opportunities are not taken into account.

The studied literature shows several important aspects and limitations for managing CCA in infrastructures, summarized in Table 5.1.

Table 5.1: Key aspects for managing CCA in infrastructures based on current transportation literature

Aspect	Description
Process	The CCA process should be (1) responsive and iterative, and (2) should include expert knowledge. (3) Systematic mapping of climate threats, vulnerabilities, and consequences is essential to guide implementation and prioritization. (4) Considering climate change impacts in the early stages of planning results in a risk management focus, rather than a risk prevention focus.
Context	Concerns levels of CCA. The existing literature tends to focus on the micro-level (the impacts on individual infrastructure components) and the macro level. A void is left at the meso- or intermediate level.
Strategic adaptation inventory	A holistic approach is necessary to determine the most significant risks for organizations. Here potential consequences of climate events should be thoroughly evaluated using appropriate methodologies.
Synergies	Although mentioned from a goal perspective in CCA theory, a recognized gap is 'project' synergy, acknowledging that within a certain scope, multiple other projects/programs can be simultaneously present. Combining these efforts with CCA plans can result in multiple advantages (e.g. adequate usage of available resources like time, budget, manpower).
Integrality	CCA should be considered as part of effective asset management which contributes to business as usual rather than regarding it as an optional, or a separate stream of activity for which extra funding is required.

Furthermore, the existing literature indicates processes of 'what' needs to be done going toward CCA strategies, but not necessarily 'how' this should be done. In this regard, this research aims to develop a framework that consequently and effectively takes into account identified theoretical aspects and limitations for managing CCA from Table 5.1, focusing on the complex process of risk translation into concrete adaptive strategies.

5.2 Methodology

This research aims to address the aforementioned by proposing a framework for identifying climate adaptation strategies and prioritizing the risks and actions.

In order to do so, six in-depth semi-structured interviews were carried out within the Asset Management- and Corporate Control departments of the Dutch railway infrastructure managing organization. Based on the interviews, the current CCA process in the organization could be mapped, illustrated in Figure 5.2. Furthermore, these interviews confirmed the identified theoretical gaps in the CCA process mentioned in Section 5.1.1.

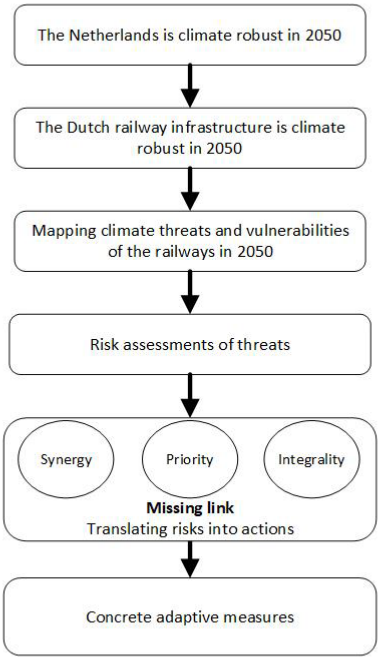


Figure 5.2: The CCA process at the Dutch railway infrastructure manager, including the identified 'missing link'.

These gaps are further referred to as the 'missing link' depicted in Figure 5.2. In this missing link, a few elements are identified as essential for the translation of risks into CCA strategies and actions. These elements correspond to some of the key aspects mentioned in Table 5.1: 'synergy' (synergies), 'priority' (prioritization) & 'integrality' (an integral view). The interviewees in the railway company have indicated difficulties with the usage of the first two in the development of CCA strategies, and the relationship between them. The latter element, 'integrality' does not touch CCA solely, but describes the need for more integrality throughout the whole organization.

It means that within an organization, where multiple projects run simultaneously, limited resources are better spent when various departments work together on shared objectives. When CCA becomes a part of that collaboration, it will fit seamlessly into existing policies and can become part of the business as usual, instead of a separate project that requires special funding.

With the use of these explorative preliminary interviews, the existing scientific literature, and archival research of organizational reports, essential design principles for the framework were determined. This led to important phases and key features included in the primary version of the developed framework. This version was afterward updated based on expert input from involved key stakeholders within the organization.

In the next sections, the preliminary developed framework is presented, followed by practical applications of the different framework features at the Dutch railway infrastructure manager.

5.3 The framework

The developed framework is depicted in Figure 5.1, and its detailed steps are shown in Figure 5.3. It consists of multiple facets:

- CCA Context: Macro, Meso & Micro levels

CCA plans need to fit both long-term strategic objectives as well as more immediate, operational requirements. Additionally, CCA involves collective action from multiple stakeholders at each level. A useful design principle was, therefore, to consider CCA at multiple distinct levels of analysis by adopting a macro-meso-micro structure (Bocong, 2015).

- Step 1: Determining the scope

Depending on the level of abstraction, CCA strategies can range from a complete systems redesign to only a handful of simple improvement actions. An important first step is, therefore, to consider the goal and scope of CCA strategies, especially concerning the relevant climate effects, affected asset(s), geographical location, and the expected lifespan of the asset(s). The resulting system of interest (SOI) is input for the next phase, step 2.

- Step 2: Strategic adaptation inventory

The SOI can be investigated for scope-specific climate risks and subsequently prioritized according to the expected severity and/or frequency of extreme weather effects. Specific CCA strategies can then be generated which are tailored to a specific SOI.

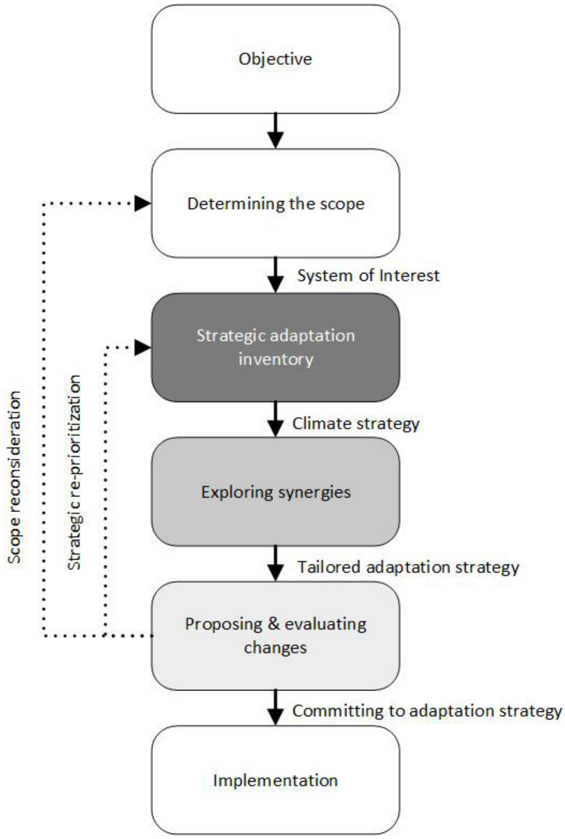


Figure 5.3: CCA framework: step-by-step

- Step 3: Exploring synergies

In the next phase, these SOI-specific risk-based CCA strategies are compared and adapted to existing and proposed programs from both internal (company) and external stakeholders (e.g. municipality, utilities, and other railway organizations). By mapping and adapting CCA strategies to these existing plans, synergetic and/or collective efforts can be identified that may lower the burden of implementing CCA strategies and even solve multiple problems simultaneously. From these synergies and opportunities, a tailored strategy is formed, where it is possible that a risk that was supposed to be accepted, can be restricted due to a synergetic opportunity.

- Step 4: Proposing, evaluating & implementing changes

The tailored CCA strategy can then be considered for implementation by means of a cost-benefit analysis. Earlier phases may have revealed opportunities or limitations that require a reconsideration of the scope or the most appropriate adaptation strategy.

The iterative nature of the CCA framework allows for multiple subsequent cycles of the four phases. It also allows for starting in either of the four phases, depending on whichever phase is most appropriate.

This can lead to finding quick wins, even when managerial matters are not yet solved. These quick wins may not reach the desired quality, but waiting for the strategies to be implemented might lead to missed opportunities.

5.4 CCA at Dutch railway infrastructure manager ProRail

5.4.1 ProRail

An example of a railway infrastructure manager is the Dutch organization ProRail. With one of the densest railway infrastructures in Europe, efficient and effective asset management is key. In addition to this, ProRail has identified climate change as a large (future) threat to its goals and ambitions. One of the main threats to the Dutch railway system is the increase in extreme rainfall, where tunnels and rails can be flooded and become inaccessible. Another threat is the expected increase in temperatures during summer, where electrical installations can overheat and fail. These expected effects of climate change can already be seen nowadays, where they disrupt service.

5.4.2 Framework application

In this section, the developed framework is explained by comparing its features to practice at ProRail. Moreover, this section explains how the different steps of the framework can be approached from a practical point of view. Currently, ProRail is exploring how CCA fits into its policies and programs and is developing multiple decision-making tools.

5.4.2.1 CCA context: Macro, Meso & Micro levels

The three different levels of context can be distinguished at ProRail, where the macro level indicates goals and ambitions at the organizational level, and, the micro level contains the different projects that are carried out to manage and build the railway infrastructure. The meso level is essential for translation between these two levels and alignment between the different layers has to be achieved for consensus and cohesion. Examples from the meso level will be used for further demonstration of the framework, to emphasize the added value of this framework for organizations like ProRail.

An example of an input objective for the meso level is the ambition of the asset management department to make an asset climate robust in 2050. This objective can follow from strategies formulated at the macro level, or for instance from a reaction to an extreme weather event (at the micro level).

5.4.2.2 Step 1: Determining the scope

First, the scope needs to be determined. Here, ProRail has identified five climate effects, based on climate change scenarios from the Dutch weather institute, KNMI[1]. They recognize threats concerning heat, excess water, drought, flooding, and storms.

For scoping on assets, ProRail looks at asset types or groups, or specific single assets that are significantly important and require their own CCA strategy. The same holds for locations, where critical sections of the railway network require specific attention. The lifespan of assets plays an important role as well, for example, the track bodies have an almost infinite lifespan, while rails and switches have shorter lifetimes and will endure less climate change in their lives. The SOI as output defines these four aspects in order to create specific strategies.

5.4.2.3 Step 2: Strategic adaptation inventory

ProRail has created maps where the vulnerabilities of the SOI regarding the different climate effects can be assessed. This shows for example the amount of flooding that is expected for a particular rainfall in a certain region. These threats can be translated into risks, by determining the impact and probability of occurrence, for which ProRail has developed its corporate risk matrix.

ProRail does not have the resources to eliminate all identified risks. Hence, risk prioritization, converging to risks requiring immediate attention, is necessary.

In order to do so, a lot of data has to be processed, including the knowledge and experiences of experts in the field. For this, ProRail is developing decision-making guidelines, together with the Ministry of Infrastructure and Water Management. They have defined four possible action perspectives: accept, repair, restrict, and prevent, which need to be assigned to the risks, resulting in a risk-based CCA strategy. Following the guidelines using only the abstract data available, however, does not necessarily solve the decision-making problem. For this reason, it is proposed that expert sessions are organized in this phase, where experts from different backgrounds and management levels come together and discuss the inventoried data. Bringing these experts together gathers tacit knowledge present within the organization.

Additionally, gathering experts from different levels of the organization creates alignment between these levels. That way, decisions can be made based on available knowledge and expertise, while aligning mentioned organizational levels.

[1] https://knmiprojects.archiefweb.eu/?subsite=klimaatscenarios#archive. Accessed June 2021

5.4.2.4 Step 3: Exploring Synergies

An example of synergy in ProRail is the scheduled replacements of assets, such as electrical installations, which can be used to replace the asset with an updated and more climate-robust version. Acknowledging synergies can lead to (initially) unplanned CCA actions. A recent example of this is the railway station Driebergen-Zeist which has undergone a huge metamorphosis, where climate change was not included in the initial design[2]. During the adaptation process of this station, many stakeholders aligned on the desire to make the station climate-robust for the expected future increase in rainfall. This agreement resulted in specific CCA measures for the station and its surrounding environment.

5.4.2.5 Step 4: Proposing & evaluating changes

As shown in Figure 5.3, in some situations rescoping can be required after a cost-benefit analysis. An example of such rescoping in ProRail can be found in solving heat stress on railway stations. Here, it was primarily thought that the risk could be managed independently by the infrastructure-managing organization. It became apparent, however, that cooperation with transport operators was required to solve mentioned issues, broadening the scope of analysis.

When no further re-scoping or prioritization is required, implementation of the CCA strategy can be done. An example of CCA implementation at the meso level is updating the design specifications of an asset, to ensure that all future built assets are climate-robust. This could mean: using different materials for electrical installations or placing them on higher ground to prevent flooding. But the strategy could also lead to the design of a different maintenance- or replacement schedule. These strategies can then ensure that on the micro level, assets are built and maintained in a climate-robust way.

5.5 Framework evaluation

The practical examples of the proposed framework features provided by ProRail not only revealed 'what' can be done with CCA, but also shows 'how' an integral approach to CCA can be supported by four defined steps in the preliminary framework.

The preliminary evaluation of the framework suggests that it could assist railway infrastructural management organizations with developing concrete

---

[2] https://klimaatadaptatienederland.nl/actueel/actueel/interviews/toekomst-complex-spoornetwerk/. Accessed June 2021

CCA strategies in a smart way by taking into account ‘synergies’, ‘prioritization’, and an ‘integral view’.

The development of an ‘integral view’ can be supported by not thinking of CCA as a project on its own, but as something which needs to be included in the existing way of working where new assets are built and existing assets are maintained.

The consideration of ‘synergies’ appears to be a particularly welcome addition for ProRail, as it has the potential to integrate the resources required for implementing CCA strategies into already existing programs or to share these burdens with other stakeholders that have similar climate concerns. Combined with the prioritization step, this can considerably lower the barriers to take climate adaptation action, especially compared to actions that are initiated with only climate adaptation itself in mind. This process may lead to the identification of low-hanging fruit and no-regret actions. Therefore, an important question for future research will be how the framework can be most effectively applied, using the least amount of resources required.

5.6 Conclusion

Due to climate change, extreme meteorological events will increase in severity and frequency in the coming decades. This research proposes a framework that takes into account: prioritization, synergies, and integrality at different levels of abstraction. The framework aims to connect the strategic and operational levels by considering CCA at multiple levels of analysis (micro, meso & micro).

Furthermore, the examples of practical applications of the framework features show how the different steps can be approached.

Finally, the evaluation of the preliminary framework suggests that it can assist railway infrastructural management organizations through the complex process of developing concrete climate adaptation strategies by determining a clear scope and focusing on systems of interest, exploring synergies, and based on this, having tailored adaptation strategies. After a thorough analysis, these strategies can be either committed to and implemented, or require rescoping and reprioritization.

Given the conceptual nature of this early design, further evaluation is required by testing the framework on a novel railway CCA issue from start to finish, going through all four steps. In a later stage, the generalizability of the framework can be further tested by applying it in non-railway contexts.

Acknowledgment

This research is co-financed from the Research and Innovation contribution (PPP) from the Dutch Ministry of Economic Affairs and Climate. The authors acknowledge the support of the NS and ProRail in the SIRA project.

Chapter 6 Interface Management in Inter-Organizational Projects: A Process Approach Towards Mutual Integral Insight and Coordination

Abstract:
In railway projects, distinct tasks are carried out by various business units, across diverse organizations. While identifying and managing interfaces is seen as essential in inter-organizational projects, existing tools predominantly focus on technical aspects and less on effective collaboration. As a result, actors from various organizations and disciplines tend to stick to their own insights and interpretations of a project's decomposition. We propose an interface management process for gathering, organizing, integrating, and analyzing dispersed information. This process supports interface identification, increases understanding, raises awareness, and enables maintenance of critical interfaces as demonstrated in the Dutch railway context.

Publication history:
This chapter has been submitted to the Project Leadership & Society Journal.

6.1 Introduction

In railway systems, there is a continuous request for improvement, enabling faster, safer, and more reliable transport, preferably at low costs. In order to achieve these system-level performance qualities, changes of different kinds, scales, and complexities are continuously implemented. Furthermore, to develop or implement such changes, collaborative work is organized in projects (Alin et al., 2013; Botchkarev & Finnigan, 2015), which are often complex and inter-organizational, because multiple organizations interact to create value together and achieve pre-specified project goals (Braun, 2018; Cropper et al., 2008; Jones & Lichtenstein, 2008; Scott-Young & Samson, 2008).

The complexity of such projects can be defined as a system in terms of the number and variety of components and interdependencies among them (Baccarini, 1996; Hobday et al., 2005). Ahn et al., (2017) complement this and mention that project complexity is related to the multiplicity of a project's interrelated parts, processes, parties, systems, and technologies. Thus, such projects are characterized by a large number of participants and stakeholders, different levels of expertise, a multiplicity of interdependent disciplines/processes, dispersed project execution, high costs, unclear goals and scope, overlapping roles and responsibilities, and difficulties in effectively managing a multitude of interfaces and interdependencies between different parties (Baccarini, 1996; Jones & Lichtenstein, 2008; Kiridena & Sense, 2017; Pritesh & Konnur, 2019). The array of stakeholders involved, and the levels of accountability and scrutiny on such projects present a raft of challenges for project management practitioners (Kiridena & Sense, 2017).

To cope with such inter-organizational projects and enable effective project management (Healey, 1997), organizations often attempt to decompose a project (Davies & Mackenzie, 2014). This decomposition results in the granulation of work into numerous diverse tasks, which are executed by various actors in different departments across organizations (Healey, 1997). As such, the execution of a successful inter-organizational project requires coordination among employees from different organizations (Browning, 2010; Milch & Laumann, 2016). To better cope with this, interface management (IM) has been introduced and gained increasing popularity among practitioners during the last decade (Ahn et al., 2017).

IM is defined as the management of information, coordination, and responsibility across physical, contractual, and organizational boundaries, which are referred to as interfaces (Shokri, 2014). According to the International Council on Systems Engineering (2015), one of the objectives of IM is to facilitate agreements between stakeholders.

This includes agreements on roles and responsibilities, timetables for providing interface information, and the identification of critical interfaces early in the project using a structured process (Haji-Kazemi et al., 2013). Identification of interfaces should indicate where a collaborative approach is needed from actors from either side of the interface (Braun, 2018; NASA, 2007; Rail Safety & Standards Board, 2017; Stretton, 2016). Thus, the success of a project largely depends on how well these interfaces are identified and managed (Shokri, 2014).

Current literature highlights the importance of IM in different fields of research, for example in product development, where tasks are often complex regarding the number of activities, individuals, teams, and organizations involved, and their relationships (Danilovic & Browning, 2007). Additionally, IM is considered vital in the construction management industry, where integration among diverse teams within a project is considered to be integral to project success (Dao et al., 2017; Davies & Mackenzie, 2014; Pritesh & Konnur, 2019; Shokri, 2014; Yang et al., 2020). Applying IM however, can be challenging in practice in case of a large number of interdependent organizational elements in the project, such as people, departments, organizations, and complicated rules/regulations (Ahn et al., 2017; Krane et al., 2012; Maylor et al., 2018). Moreover, as the project scale increases, the number of interfaces to manage increases exponentially, and managing them becomes more difficult.

6.1.1 Gap

To enable IM, multiple hard systems thinking tools exist including (International Council on Systems Engineering, 2015): (1) N^2 diagrams applied to system interfaces equipment (e.g., hardware), (2) functional flow diagram, (3) data flow diagrams, and (4) other analysis methods that may be useful for interface definition e.g. the Design Structure Matrix (DSM). These tools typically require engineers to generate complete definitions of the system or project interfaces in a rigid fixed framework (International Council on Systems Engineering, 2015).

These IM tools can be quite straightforwardly applied in the case of technical products, or projects with unambiguous decomposition and limited diverging interpretations among actors. However, this can become more challenging in case of inter-organizational projects within the complex railway context.

In this context, stakeholders from different organizations can view the complex railway system differently (Hagan et al., 2011), knowledge and information about railway system are dispersed, and individuals from various organizations and disciplines have their own insights, (mental) models, experiences, assumptions, expectations, and approaches to describing and understanding such projects. As a consequence, this results in varied interpretations of an inter-organizational project's decomposition (Danilovic & Browning, 2007), and associated interfaces. As such, the mentioned hard systems thinking tools are not directly applicable in inter-organizational projects within the complex railway context because:

- Knowledge and information about the railway system are dispersed and obtaining comprehensive data from multiple organizations concerning the project can be challenging.
- The availability of data may be limited, inconsistent, or subject to varying interpretations, making it difficult to construct accurate models using hard systems thinking tools.
- Many tasks to be conducted within an inter-organizational project do not have neat and easily identified interfaces to project participants (business units), as a result, the interfaces can be 'hidden', or easily overlooked.

When these interfaces are not identified early on and properly managed this can be exemplified as mismatched parts, and system performance failures, which can lead to poor quality, waste, delays, and cost overruns, significantly influencing overall project performance (Chen et al., 2008).

Furthermore, in the described railway context, coordination is both challenging and essential because organizations share high task interdependence (Coyote & Thompson, 1967; Oliveira & Lumineau, 2017). In inter-organizational projects, each organization must perform tasks in a timely manner to avoid disrupting the work of other parties so that the project's objectives are met (Atkinson, 1999; Pinto & Prescott, 1988). As such, in addition to the tools focusing on the identification of interfaces, there is a significant amount of literature focusing on interdependencies and coordination in inter-organizational projects, directed more toward the 'soft' human side.

According to Whyte & Davies (2021), as complexity and uncertainty emerge across organizational boundaries, a process is required that guides and enables conversations that enable expertise to be mobilized to address interfaces. Thus, when actors on either side of the interface have a common understanding of their responsibilities, required resources, and requirements for their interface tasks, they can communicate and coordinate effectively (L. Wu et al., 2021).

6.1.2 Aim

Given the described context of inter-organizational projects in the railway system, we posit that identifying interfaces is essential to indicate whether and where coordination is needed from actors from either side of the interface(s), to facilitate project integration. Thus this research aims to answer the following research question:

How to facilitate interface management within inter-organizational projects with the aim of achieving focused coordination in the railway context?

By answering this research question, this paper aims to bridge the 'hard' and 'soft' sides and to develop a structured pragmatic IM process, supporting practitioners in gathering, organizing, and analyzing dispersed information, with the aim of achieving focused coordination across organizational boundaries.

This paper is organized as follows: the second section discusses characteristics of the railway context that require attention with regard to IM. This leads to design requirements which are considered in the third, and the use of an iterative design science research (DSR) methodology is described and motivated. Subsequently, the fourth section presents the designed artifact, and inherent used design principles, followed by the artifact's demonstration by application to a case study in the Dutch railway system. This is followed by the fifth section, which presents an evaluation and discussion. The sixth section then provides implications for practice, and finally, the seventh section concludes this article.

6.2 Interface management in inter-organizational projects

As already briefly touched upon in the introduction, several characteristics related to the railway context make IM in inter-organizational projects challenging. These include (1) the complex sociotechnical context, (2) a multitude of interfaces in these contexts, and (3) the amount and variety of business units (BUs) involved. These challenges and their corresponding requirements will be taken into consideration in the design, and are described in the following subsections.

6.2.1 Complex sociotechnical system

Railways are complex sociotechnical systems. They are highly interconnected networks of interacting social and technical components that cannot be addressed separately (Kroes et al., 2006). In such systems, an inter-organizational project's scope can include processes, personnel, capacity, technical systems, and rules and regulations across different organizations.

As such, it is important to understand the technical impacts of a project and the organizational and operational procedures and human actions required. However, this can be challenging because stakeholders from different organizations can view complex systems differently (Hagan et al., 2011). Hence, defining project scope using input from all stakeholders is a vital task that needs to be adequately carried out at an early stage (Dasher, 2003; Ramtahalsing et al., 2022) to facilitate IM. This leads to requirement 1.

Requirement 1: Adequately defining the inter-organizational project scope.

Furthermore, in such inter-organizational projects, project stakeholders often have differences in experience, knowledge, organizational or professional loyalties, understanding of project purposes and goals, and/or contradictory purposes and goals (Danilovic & Browning, 2007). As a consequence, they have different mental models, assumptions, interpretations of realities, and expectations of the project (Danilovic & Browning, 2007) resulting in varied interpretations of a project's decomposition. A shared model can test and align participants' mental models through discussions and lead to a joint understanding of the reality of projects (Danilovic & Browning, 2007). This leads to requirements 2 and 3.

Requirement 2: Effectively collecting dispersed expert knowledge on the inter-organizational project impacts.

Requirement 3: Enabling the unification of mental models.

6.2.2 The multitude of interfaces in inter-organizational projects

IM becomes considerably more challenging in large projects, where complexity increases due to the rapid growth of the number of interactions between and among the many individuals and activities that comprise the process (Browning, 2010; Parraguez et al., 2016). Regardless of how tasks are divided, linking various parts is always complicated, and as such, there is a constant need for their management to facilitate the exchange of information across these interfaces (Long & Spurlock, 2008; Stretton, 2016).

In many large projects, IM is used to enhance coherence among stakeholders and reduce potential conflicts, such as when a large number of stakeholders with different responsibilities is involved in the project (Yang et al., 2020). Also, according to Pritesh & Konnur (2019), IM can be particularly useful in large, complex, and urgent projects, where lines of responsibility, relationships of authority, and interfaces must be clearly defined and coordinated intensively, and the work must be delegated and explained strictly in accordance with these. Nevertheless, defining interfaces has consistently proven challenging due to their complexity, the varied natures of projects, the multi-organizational composition of project teams, and a lack of appropriate documentation procedures (Chen et al., 2010).

Whenever interface information is gathered, this needs to be organized to pinpoint areas where conflicts may arise, or where coordination is necessary so integration can proceed efficiently (International Council on Systems Engineering, 2015), leading us to requirements 4 and 5.

Requirement 4: Structuring of gathered expert-based information to facilitate the understanding of a large number of interfaces.

Requirement 5: Condensing interface information aiding prioritization.

6.2.3 Inter-organizational projects involve inter-organizational business units

In inter-organizational projects, it is crucial to understand and explore interfaces, as well as the need for information exchange between different domains of organizations and processes (Danilovic & Browning, 2007). The challenge for managers lies in finding the appropriate method to organize individuals, appropriately pace the assignment of work, facilitate communication, and synchronize activities (Danilovic & Browning, 2007).

Stretton (2016) mentions that project interfaces can be broadly categorized into internal interfaces (i.e. interfaces within the project itself), and external interfaces (interfaces between the project and external entities). Additionally, differences exist depending on whether an organization is project-based or production-based. In case of the former, there is a clear differentiation between internal, and external project interfaces. However, in the case of production-based organizations like railways, this is more complicated, because projects interface with two external environments. One is that of the production-based organization itself, and its wider external environment. Stretton (2016) represents both situations in adapted Figure 6.1.

Figure 6.1: Primary categories of project interfaces for project-based (L) and production-based organization (R) adapted from Stretton (2016)

In production-based organizations, interfaces with the project's external environment can include (Stretton, 2016): regulatory agencies, competitors, suppliers, subcontractors, and governments. Moreover, interfaces with the rest of the organization can include top management, line management, line personnel, social contacts, personnel, and training. Challenges associated with integration for these internal and external project interfaces include how well the project activities are coordinated among the different stakeholders (Oliveira & Lumineau, 2017).

Thus, in an inter-organizational project where the tasks are carried out by various actors from BUs across distinct organizations, interfaces can cross organizational lines, which require management to support the integration of the dispersed project parts. As such, involved parties should be aware of the existence of such interfaces, enabling the exchange of information across them. This leads us to requirements 6 and 7.

Requirement 6: Creating awareness on the existence of inter-organizational interfaces.

Requirement 7: Enabling the exchange of information across different inter-organizational parties.

Based on these distilled requirements, this paper aims to develop a structured, continuous IM process intended to gather, organize, integrate, and analyze dispersed information with the aim of achieving coordination across organizational boundaries in inter-organizational boundaries. It does this by (1) adequately defining the scope of the inter-organizational project, (2) effectively collecting dispersed expert knowledge on the inter-organizational project impacts, (3) enabling the unification of mental models, (4) structuring of gathered expert-based information, (5) condensing interface information aiding prioritization, (6) creating awareness of the existence of inter-organizational interfaces, and (7) enabling the exchange of information across different inter-organizational parties.

6.3 Methodology

6.3.1 Design science research

As stated in the introduction of this paper, this research aims to provide insights and tools to practitioners to aid IM in inter-organizational projects within the complex socio-technical railway system. As such, this research uses DSR. In DSR, academic research objectives are of a more pragmatic nature (J. E. Van Aken, 2005).

It is solution-oriented, but the ultimate objective of academic research is to produce knowledge that can be used in designing solutions to field problems (J. E. Van Aken, 2005).

Moreover, DSR comprises a process of designing artifacts to solve observed problems, making research contributions, evaluating designs, and communicating results to appropriate audiences (Peffers et al., 2007). Moreover, DSR constitutes a systematic but flexible methodology that aims to improve practices through iterative analysis, design, development, and implementation, based on collaboration among researchers and practitioners in real-world settings. A widely accepted framework for carrying out DSR was designed by Peffers et al. (2007), an adapted version of which is shown in Figure 6.2. While the problem identification and requirements of a solution have been addressed in the first and second sections, the following paragraph will describe how subsequent DSR steps are established in this research.

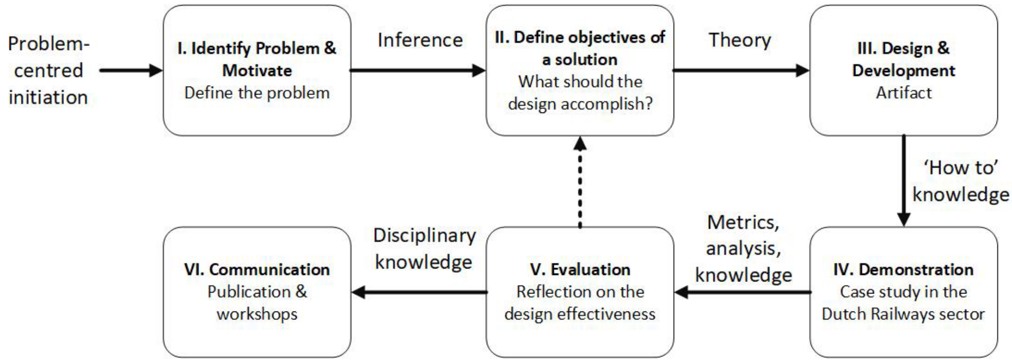


Figure 6.2 DSR process adapted from Peffers et al. (2007)

6.3.2 Applying DSR

By using the requirements described in the second section of this article, design principles inferred from theory, and multiple design cycles included in an iterative design process, a proposed IM process (artifact) is designed which will be elaborately discussed in the fourth section. Afterward, the designed artifact is then demonstrated by step-by-step application in a case study: The construction and implementation of a new train stabling yard in the Dutch railway system.

In the Dutch railway system, the managing responsibilities are divided between an independent railway infrastructure manager ProRail and several railway operators, of which the largest is the NS. Within this system, a multitude of inter-organizational projects are carried out throughout the system's life cycle.

By using triangulation (semi-structured interviews with the project- and implementation managers, observation of multiple project meetings, and archival research), it became apparent that some tools existed in the Dutch railway system which focused on IM, however, these were limited to the technical interfaces. Moreover, some tools enabling inter-departmental cooperation were already available. However, a standardized process aimed at gathering, organizing, integrating, and analyzing information to support IM in this context did not yet exist.

By applying and demonstrating the developed artifact in a case study, the artifact has been evaluated and is discussed in the fifth section, by comparing the design principles to actual observed results gained from the use of the artifact in the case study.

6.4 Design and application

To achieve the goals of IM, a systematic approach to gathering, organizing, integrating, and analyzing the information regarding a project is necessary (Danilovic & Browning, 2007). According to the International Council on Systems Engineering (2015), Lindgren et al. (2009), Pavitt & Gibb (2003), Shokri (2014), and Wren (1967), the IM process should at a minimum include a scope definition, an interface identification, an interface analysis and communication.

As such, the DSR process conducted throughout this research resulted in the design of an **expert-based process approach (DP 1)** consisting of 5 subsequent steps, depicted in Figure 6.3, aimed at gathering, organizing, and analyzing the collected information.

These will be described in the following subsections.

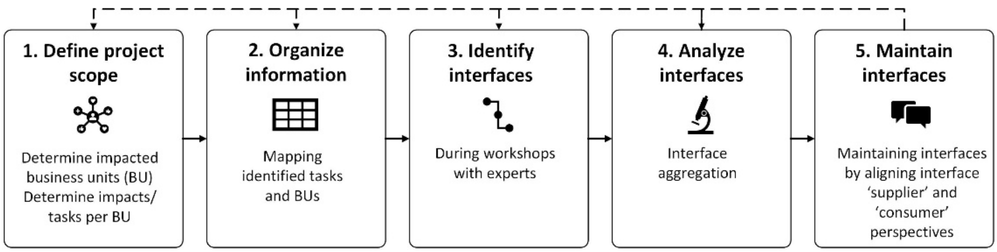


Figure 6.3: Proposed Interface management process for inter-organizational projects

Furthermore, to demonstrate its practical applicability, the developed IM process has been applied to a case study in the Dutch railway sector concerning an inter-organizational project focused on the construction and implementation of a new train stabling yard. For every proposed IM step in Figure 6.3, the practical application in the case study will be elaborated on.

6.4.1 Case study

Because of a projected upcoming shortage of train- handling and stabling capacity, the Dutch infrastructure manager and the main railway operator have invested in service locations in recent years. Existing stabling yards have been expanded and new ones are being built; the current case study deals with an instance of the latter category. In this case, the main railway operator will build the operating assets on the site, such as staff accommodations, and entry and exit facilities, and the infrastructure manager will provide the track infrastructure, train security, and substations. This inter-organizational project is intended to provide handling and stabling capacity for 110 units of passenger rolling stock.

According to Sosa et al. (2007), the first thing a project team typically does is break the project down into manageable pieces, which are then assigned to dedicated BUs. Therefore, it is vital to know where between which tasks interfaces exist, and at which interfaces information needs to be exchanged between inter-organizational BUs on either side of the interface.

The initial investigation indicated that the project concerning the construction and implementation of the new train stabling yard: (1) concerns a large project with a broad scope, (2) affects multiple BUs which are a part of either the main railway operator or the infrastructure manager, (3) affected actors with differences in experience, knowledge, mental models, assumptions, and expectations of the project, resulting in varied interpretations of the project's decomposition, (4) consists of numerous tasks, dispersed across the inter-organizational BUs in the project. Additionally, (5) consists of various interfaces between those tasks, which need to be identified and managed to enhance coordination. All of which made the case study an excellent fit for the research.

6.4.2 IM process step 1: Define project scope

Before interfaces in the project can actually be identified, let alone be coordinated and managed, it is essential to define the project scope (Wearne, 2014). Previous research (Ramtahalsing et al., 2022) covers the defining of inter-organizational project scope elaborately. In this step, it is necessary to: (1) establish the project context, (2) identify which BUs and actors are affected or affect this project (across all involved organizations) (Scott-Young & Samson, 2008), (3) determine possible impacts of the project per identified BU (e.g. which processes need to be adjusted, which manuals need to be extended, does personnel need to be hired or trained), and (4) specify which tasks need to be conducted by each BU, based on those impacts.

The first and second have been carried out together with **the project- and implementation managers in charge, knowledgeable about the organization (DP2).** Research from Salvador et al. (2021) shows that a project manager's experience is a driver of project performance. Moreover, one of the most important qualities of a project manager is a mature understanding of the way projects develop (Browning, 2010; Tatikonda et al., 2000). This allows for a better understanding of the nature of project activities, for problems to be seen in their proper perspective, and for the requirements of the project to be pre-emptively assessed (Morris, 2008).

This results in the identification of the affected **inter-organizational BUs (DP3)**. Subsequently, the impacts of the project on these identified BUs are determined in collaboration with their representatives during multiple interactive **expert sessions (DP4)**.

As such, this step is responsible for gathering the necessary information required in the IM process depicted in Figure 6.3.

6.4.3 Application Step 1: Defining the project scope for the construction of a new train stabling yard

The definition of the scope of this inter-organizational project, including the identification of the distinct actors and BUs impacted by the project has been carried out together with the project- and implementation managers in charge. This resulted in the identification of the inter-organizational affected BUs: Transport Control, Preservation of Operating Assets, Logistics Design, Preparing Operation, Transport Preparation, and Site Conservation.

Furthermore, the impacts of the project on these identified BUs have been determined in collaboration with their representatives during multiple interactive **expert workshops (DP4)**, which include i.e. impacts on budget, time, capacity, laws and regulations, personnel and competencies, guidelines, and technical systems. After this impact identification step, the corresponding tasks to be carried out within the project were defined based on the impacts.

6.4.4 IM process step 2: Organize information

Projects can consist of multiple domains, such as product, process, and organizational domains (Browning, 2016; Ramasesh & Browning, 2014), and a multitude of interfaces across these. As such, organizing and structuring the obtained expert-based information is necessary.

Because the coordination of tasks and activities among diverse BUs is necessary for successful integration, this paper organizes the obtained information by use of a **Multi Domain Matrix (DP5)**.

This matrix methodology allows for the simultaneous mapping of multiple domains to model entire systems consisting of organizational domains (e.g. business units, organizations), process domains (e.g. tasks), and technical domains (e.g. technical components), each containing multiple elements, connected by various interfaces.

One of the main functions of this visual matrix, in addition to interface identification, is pinpointing areas where conflicts may arise, so that integration in later stages can proceed efficiently (International Council on Systems Engineering, 2015).

To enable the exchange of information across different inter-organizational project parties, this paper proposes to extend the focus on the project interfaces mentioned in the second section of this article to include the inter-organizational context and **focus on inter-organizational project interfaces (DP3).** We explain this in Figure 6.4, which shows various tasks that require carrying out in the inter-organizational project. These are then granulated and allocated across organizations α and β. In this case, carrying out the different tasks can be the responsibility of different BUs, such as BU A in organization α (A_α), and BU B and C in organization β (B_β and C_β respectively).

Thus, in this research, the MDM consists of the process domain (tasks) and organizational domain (BUs across different organizations).

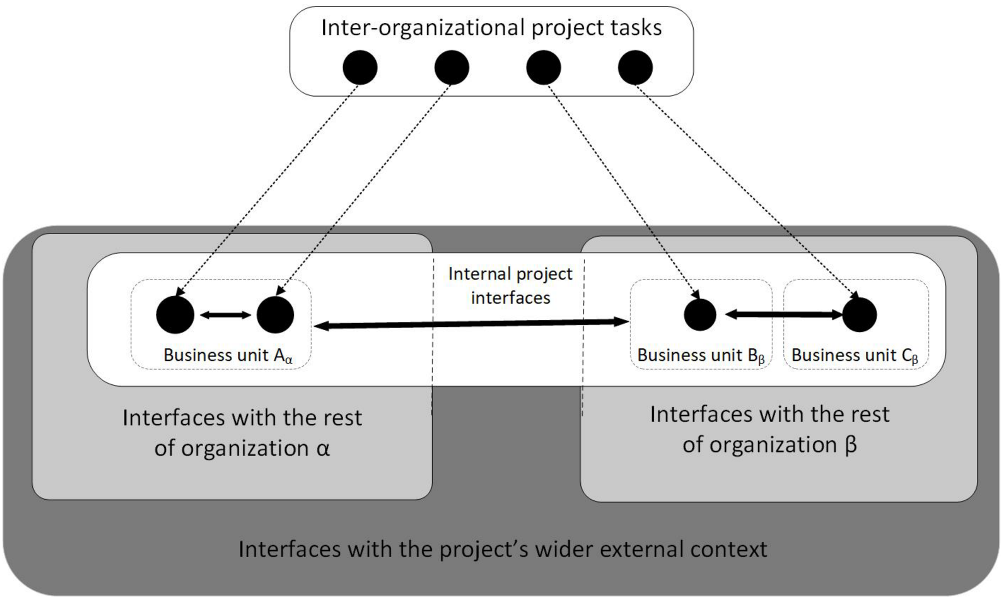


Figure 6.4 Inter-organizational project interfaces

Chapter 6

To build the MDM, the output obtained in step 1 is used. For every identified BU a matrix is built corresponding to Figure 6.5.

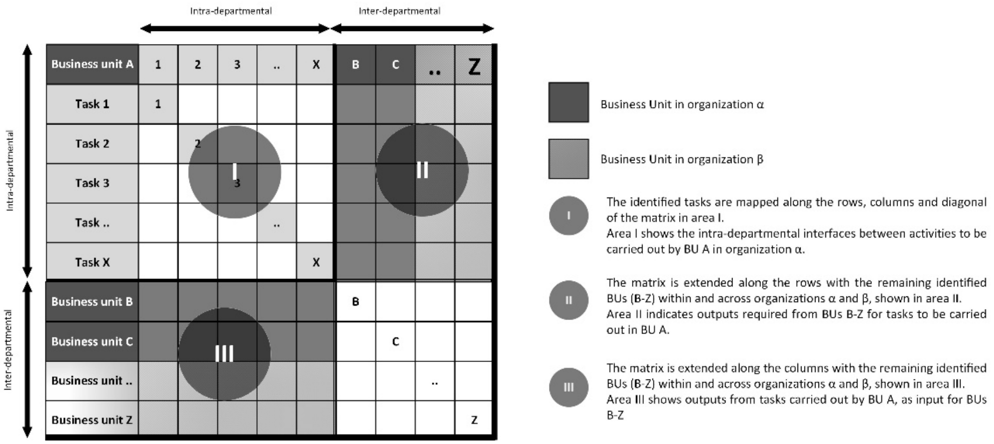


Figure 6.5: MDM layout mapping tasks against BUs, and enabling the identification of intra- and interdepartmental interfaces

As such, step 2 organizes and structures the information required for the IM process.

6.4.5 Application Step 2: Organizing information for the construction and implementation of a new train stabling yard

Due to the amount of information obtained throughout this research, we focus the remainder of the example application on solely the Site Conservation BU for illustrative purposes.

For the Site Conservation BU the MDM is built by mapping the established tasks onto the rows and columns as shown in Figure 6.6. Subsequently, the MDM is extended with the remaining identified BUs, shown in Figure 6.6, through areas II and III in the matrix. Furthermore, for all BUs identified in Step 1, the matrix is built in a similar fashion.

6.4.6 IM process step 3: Identify interfaces

Before interfaces can be coordinated and managed, they must be identified; both within and across different BUs in distinct organizations. To do this, **expert workshops (DP4)** are held with representatives from all identified BUs, with the aim to fill in the **MDM (DP5)** developed in step 2.

To aid in the mapping of the interfaces, the workshop facilitator can choose from the following guiding questions: (1) what input does the activity need to carry out the tasks listed in the matrix?; (2) where do these inputs come from (another activity or another BU)?; (3) what output must the task produce?; (4) what is the destination of this output (another task or another BU)?

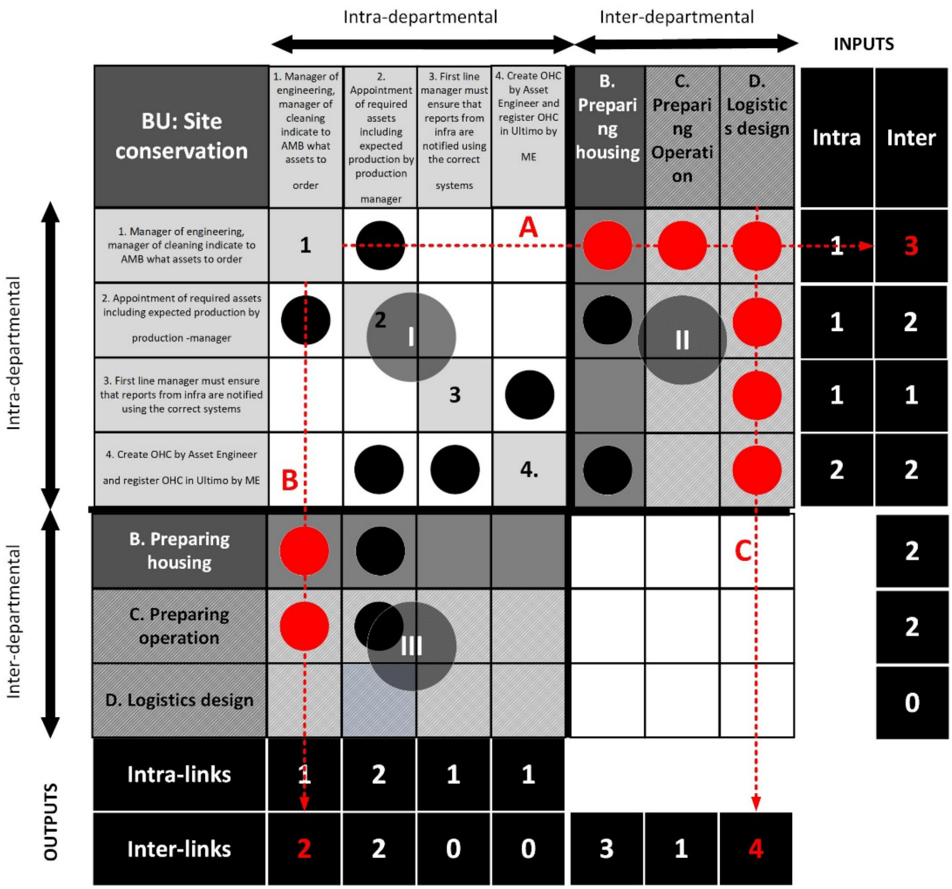


Figure 6.6: MDM example resulting from the workshop carried out with the Site Conservation BU in the project concerning the construction and implementation of a new train stabling yard

These workshops can be carried out in individual and/or group setting. The MDM filled out with identified interfaces shows, for example for BU A Figure 6.6: In area I, the interfaces between tasks carried out by BU A; In areas II and III, the interfaces between tasks and diverse BUs in the inter-organizational context, thus focuses **on inter-organizational project interfaces (DP3).**

This step aids in organizing and integrating information for the IM process, and provides analysis opportunities, as will be elaborated on in the next step.

6.4.7 Application Step 3: Identifying interfaces for the construction and implementation of a new train stabling yard

In the case study, the workshops aimed at identifying interfaces involved a representative from each BU in question, and, in the case of a group session, involved multiple representatives from that BU.

The workshops consisted of (1) a brief introduction regarding the goals of the session; (2) an explanation of the matrix methodology (including the matrix layout, rows and columns, and input-row convention); (3) interactive mapping of MDM interfaces; (4) discussing preliminary results.

Figure 6.6 shows an example section of an MDM with identified interfaces that resulted from the workshop with the Site Conservation BU. While this figure shows a matrix sized 7x7, the actual matrices which were built based on the input obtained in step 1, were matrices predominantly sized 21x21. This indicates how many tasks, and as such, interfaces can exist in such an inter-organizational project.

6.4.8 IM process step 4: Analyze the interfaces

After identifying the interfaces by means of workshops and then visualizing these in the MDM, they need to be analyzed to support their management. This analysis can include: identifying between which tasks and BUs interfaces are mapped, how many interfaces are mapped, and which/how many interfaces are connected to other BUs in the inter-organizational project. The analysis can aid in showing where collaboration is required on either side of the interface, and facilitate the information exchange between distinct BUs. One approach to doing this is by **interface aggregation (DP6).** This condenses the obtained information and highlights tasks with or without significant interfaces to other BUs, and as such, determines where close collaboration is required between distinct BUs in the inter-organizational context.

6.4.9 Application of Step 4: Analyzing interfaces for the construction and implementation of a new train stabling yard

Due to the size of some of the MDMs which resulted from the workshops, the amount of information may become overwhelming, so the authors propose looking at the analyzed MDMs at an aggregate level.

Figure 6.6 partly shows the interface aggregates in the MDM filled in with the Site Conservation BU using the numbers of both intra-, and interlinks to the right of, and below the matrix.

Moreover, because this paper uses the ‘input-row’ convention matrix, Figure 6.6 shows the following three examples indicated by red arrows:

(A) task 1 has three interfaces; with BU B, C, and D. Therefore, to carry out task 1, input, and as such, coordination is required between the Site Conservation BU and BUs B, C, and D.

The figure also shows that (B) task 1 provides two instances of output, to BUs B and C. In addition, the MDM aggregation illustrates that (C) BU D: Logistics Design, provides four instances of output to mapped tasks (1-4).

The last example (C) shows that close coordination is required between the Site Conservation BU and the Logistics Design BU due to the number of interfaces identified across the task- and organizational domains. Regarding this, workshop participant Z said:

"The Logistics Design department is at the front of the chain, so it has a lot of influence over the rest of the BUs. This assessment is confirmed by this process and the identified interfaces."

6.4.10 IM process step 5: Maintain interfaces

Once the interfaces are identified, these need to be maintained to enable coordination between parties on either side of the identified interfaces. This includes establishing roles and responsibilities between different inter-organizational parties on either side of the interface. This can aid in highlighting underlying critical issues much earlier in the process than they would otherwise be revealed (International Council on Systems Engineering, 2015). To do this, requesting, responding to, and tracing the required information between interrelated parties is necessary (Shokri, 2014), to create better alignment between project members and facilitate communication and cooperation.

It is important to keep in mind that so far in the IM process, the MDM has been filled out from the perspective and expertise of one BU, and thus highlights their perception of the interfaces regarding the input 'supplier' and output 'consumer' perspectives.

In order to create awareness of the identified interfaces and related 'supplier' and output 'consumer' perspectives, it is essential to also take into account the perspective of the remaining BUs on the other side of identified interfaces by **aligning perspectives (DP7)**. This can aid in ironing out discrepancies between the two perspectives and converging them in order to manage the interfaces appropriately.

Unless the interfaces have been carefully aligned, some BUs may view their interaction with other BUs as merely one of unilaterally providing information, whereas the other BUs may view the relationship as one involving bilateral information exchange (Browning, 2001). In other cases, one BU may note an interface with another, and the latter may not even recognize that the interface exists (Browning, 2001).

Only after perspectives have been aligned, it can be decided when, how often, and on which tasks coordination is necessary between relevant BUs. This includes determining the individuals responsible per BU on either side of the interfaces, for which tasks, and how often is necessary.

6.4.11 Application Step 5: Maintaining interfaces for the construction and implementation of a new train stabling yard

Up to this point in the case study example, the results have been viewed from the perspective of the Site Conservation BU. Figure 6.6 illustrates that numerous interfaces exist between the various BUs. A condensed overview of these interface aggregates is shown in Figure 6.7, in which layer 1 shows the interfaces as mentioned from the perspective of the Site Conservation BU.

To create alignment on the identified interfaces and ensure their maintenance, it is essential to also consider the perspective of the BUs on the other side of the interfaces, the suppliers and consumers. This can prevent the Site Conservation BU from noting the existence of interfaces with, for example, the Logistics Design BU, while that BU does not recognize that these interfaces exist.

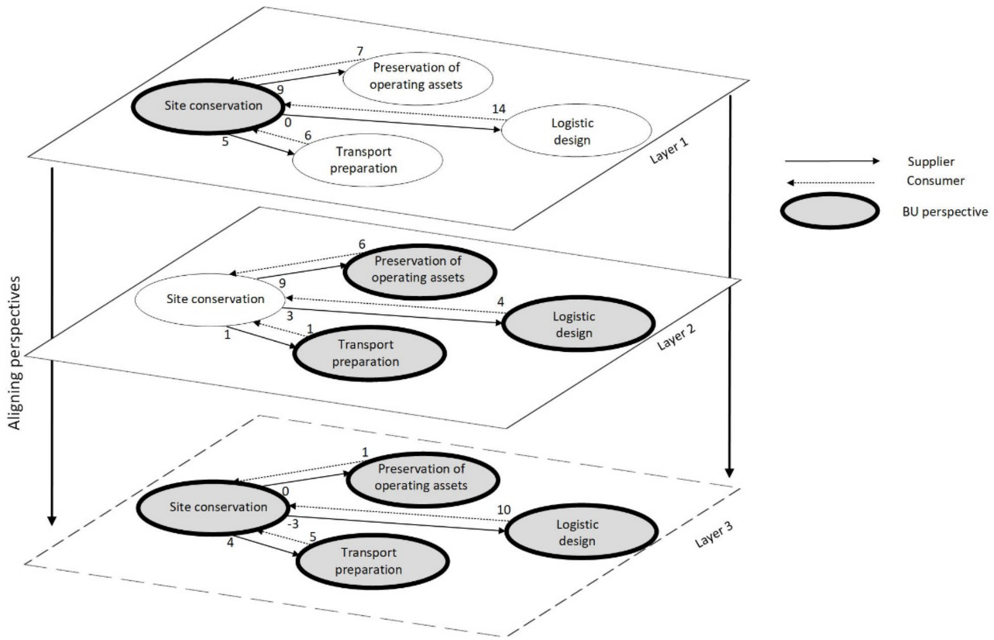


Figure 6.7: Aligning BU perspectives using interface aggregation (identifying mismatches of interfaces)

To support this process, a comparison was made between the interfaces identified by the various BUs with respect to each other. For example, layer 1 in Figure 6.7 shows, from the perspective of the Site Conservation BU, that there are 14 instances of input from the Logistics Design BU, while no output to this BU exists. Conversely, layer 2 shows the interface aggregates from the perspective of the Logistics Design, Preservation of Operating Assets, and the Transport Preparation BUs. For the Logistics Design BU, for example, layer 2 illustrates that this BU provides four instances of input to the Site Conservation BU, while also receiving 3 instances of input.

Ideally, the comparison of layers 1 and 2 should show similar interfaces, ensuring that all parties have a mutual understanding of the interfaces among other BUs. Aligning layer 1 and layer 2, in layer 3 however, shows significant discrepancies between the perceptions of interfaces. For example, it shows that there is a mismatch of ten interfaces where the Logistic design BU serves as a supplier to the Site Conservation BU. This also means, that there is no adequate coordination on those interfaces.

The above explanation of the proposed IM process describes how the different design principles map out the individual process steps, these are summarized in Table 6.1.

Table 6.1 Summary of design principles mapped to the design steps

IM process steps	Design principles
Steps 1-5	(DP1) Expert-based process approach
Step 1: Define the project scope	(DP2) Project manager knowledgeable about the organization (DP3) Focus on inter-organizational project interfaces (DP4) Expert sessions/workshops
Step 2: Organize information	(DP5) Multi-domain matrix (MDM) (DP3) Focus on inter-organizational project interfaces
Step 3: Identify interfaces	(DP5) Multi-domain matrix (MDM) (DP3) Focus on inter-organizational project interfaces (DP4) Expert sessions/workshops
Step 4: Analyze interfaces	(DP5) Multi-domain matrix (MDM) (DP6) Interface aggregation
Step 5: Maintain interfaces	(DP6) Interface aggregation (DP7) Aligning perspectives

6.5 Evaluation and discussion

The next step in the DSR process presented in Figure 6.2 concerns the design evaluation. This involves comparing the objectives of the proposed solution to results gained through the use of the artifact in the case study. The designed IM process presented and demonstrated has been evaluated using information obtained through meetings, observations during the workshops, and structured evaluation sessions (Appendix B) with workshop participants after the workshops. The results will be discussed and linked to the design principles presented in the previous section.

6.5.1 Expert-based process approach (DP1)

The case study in the Dutch railway sector revealed that currently, several tools that encourage inter-organizational coordination across the boundaries of individual BUs are available in the organizations under consideration. Moreover, in some BUs some tools existed which focused on the identification of technical interfaces, however, no tool specifically focusing on interfaces and their management in inter-organizational projects existed in this context. As such, the evaluation showed that the proposed step-by-step process depicted in Figure 6.3 was regarded by project members as something distinctly different from existing tools within the organizations.

The proposed IM process breaks down IM into several manageable steps. This aided project members in regarding IM on a more practical level: 'Where is coordination needed with other BUs due to the existence of interfaces?', instead of merely a highly abstract one: 'What does the project mean for my BU?'.

Guiding project members through the process enabled effectively collecting of dispersed expert knowledge on the inter-organizational project impacts (requirements 2), structuring of gathered expert-based information (requirement 4), creating awareness of the existence of inter-organizational interface (requirement 6), and enabling the exchange of information across different inter-organizational parties (requirement 7).

By explicitly separating scope definition, organizing information, identifying interfaces, analyzing these interfaces, and finally maintaining these, the five-step IM process was proven to be well suited for gathering, organizing, integrating, and analyzing information to support IM in the inter-organizational project. Moreover, it was appreciated by project members that they themselves provided the information used throughout the IM process, from the very beginning. Project member A mentioned during an evaluation interview:

"We already knew the project was complex, doing this exercise makes the interfaces, and therefore the complexity, visible, which in turn could help to better manage it."

This statement is also an example of the perceived usefulness of the process by project members.

Moreover, by using the MDM layout, project members were encouraged to think in terms of input and output relationships with other BUs, which means that awareness of the existence of inter-organizational interfaces was created (requirement 6). However, during the workshops, it became evident that this way of thinking did not naturally come to the participants. During the workshops, participants needed time to become acquainted with the matrix layout and -conventions. One expert who joined a workshop mentioned:

"At the start of the workshop we needed to get acquainted with the methodology with help from the facilitator, but afterward, the session went quite smoothly."

Additionally, creating insight into interfaces in a structured manner, as well as demonstrating the presence of interfaces between distinct BUs, aided the project members in understanding that collaboration is necessary for the integration of dispersed project tasks, thus creating awareness of the existence of inter-organizational interfaces (requirement 6). These insights can be used by the project manager to steer discussions during instances of coordination between different BUs, thus, enabling the exchange of information across different inter-organizational parties (requirement 7). The project manager mentioned:

"This process adds value because precisely by conducting these exercises, people realize the importance of the project to involve colleagues. The perspective that arises from these kinds of processes, namely that there are different (inter)dependencies within the project, is very valuable to the progress of the project."

Thus, highlighting the perceived usefulness of the IM process. Furthermore, it was stated by a project member during the evaluation that the results from the proposed five-step IM process could be used as input to encourage the information exchange and coordination between different BUs, however, it does not directly enable it. This demonstrates that the IM process indirectly encourages the information exchange between different inter-organizational parties (requirement 7).

6.5.2 Project manager knowledgeable about the organization (DP2)

Before interfaces can actually be identified, it is essential to adequately define the project scope (requirement 1). In this step, it is necessary to: (1) establish the project context, (2) identify which BUs and actors are affected or affect this project (across all involved organizations) (Scott-Young & Samson, 2008), this has been carried out together with the project- and implementation managers in charge, knowledgeable about the organization.

Research from Salvador et al. (2021) shows that a project manager's experience is a driver of project performance. This means that based on their knowledge of the organizations under consideration, an initial scope is determined. This also means, that less experienced project managers will probably have more difficulties in this regard.

6.5.3 Focus on inter-organizational project interfaces (DP3) and Multi-domain matrix (DP5)

The MDM was used to map process- and inter-organizational domains. Furthermore, because the organizational domains of the MDM design encompassed BUs from both the infrastructure managing- and the main railway operating organization, both intra- and inter-departmental interfaces could be identified. Therefore, this matrix proved to be a practical tool for organizing and restructuring a significant amount of data in a compact and visually comprehensive manner and provided a balance between detailed tasks on the one hand, and high-level BUs on the other hand. Thus, the MDM enabled the structuring of gathered expert-based information (requirement 4). Additionally, building the matrix itself required limited resources once the project scope had been defined. Regarding this, project member Z stated:

"As far as I can recollect, this kind of exercise has never been done this way before, at this level of detail. It can really provide interesting results, and help to improve the integrality of the project."

This demonstrates the perceived usefulness of the MDM in the IM process among the project member.

Additionally, encouraging project members to think about input and output relationships with other BU across different organizations also enabled them to look beyond the boundaries of their own BU, thereby creating awareness of the existence of inter-organizational interfaces (requirement 6). Reflecting on this, participant C stated:

"Previously, representatives from different BUs did not know what everyone else was doing, each operating within their own little box. We are now trying to consider all facets of the project early on, which I think is a very positive development. We now try to consider everything, and involve everyone."

Although the MDM method itself proved to be useful, reflection during and after the workshops with participants revealed that attention should be paid to the descriptions in the matrix: (1) the description of, and the distinction between, mentioned BUs, (2) ambiguous description of tasks, (3) use of unfamiliar abbreviations, (4) outdated information.

Moreover, it became apparent that some tasks which were mentioned during the project scope definition were not necessarily the responsibility of the BU in question. This demonstrates that the structured IM approach allows project members to rethink previously defined tasks and their interfaces with other inter-organizational parties, guiding them to reconsider the ownership of and responsibility for, the tasks in the project. This is an unexpected positive outcome of the IM process, which emphasizes that the IM process should be iterative and updated continuously in order to remain valuable to the project, and, that a step-wise approach guides individuals and groups in their thought processes. Additionally, appropriate attention should be paid to the input and output relationships in the matrix. If these are confused in the process, interfaces can be incorrectly mapped in the matrix, resulting in less reliable matrices.

Due to the size of some of the MDMs which resulted from the workshops, however, the amount of information may become overwhelming, so the authors propose looking at the analyzed MDMs at an aggregate level.

6.5.4 Expert sessions/workshops (DP4)

This design principle was used in 2 instances. Firstly, this has been utilized in the first step of the proposed IM process, defining the project scope. This resulted in the identification of the affected inter-organizational BUs (DP3). Subsequently, the impacts of the project on these identified BUs were determined in collaboration with their representatives during multiple interactive expert sessions (DP6).

Secondly, expert workshops have been used in step 2 of the proposed IM process, to identify interfaces both within and across different BUs in distinct organizations. Here, representatives from all identified BUs joined the workshops in individual sessions with the aim to fill in the MDM (DP5).

These workshops were carried out in individual and/or group setting. Comparing these revealed multiple results.

During the individual sessions, (1) there was no discussion on the interfaces, (2) the session went smoothly, and (3) there was sufficient time to complete the MDM.

One attendee mentioned:

"This was a fun exercise, but made a bit tedious, by the facilitator asking the same question over and over again during the workshop. Nevertheless, it shows promising results: After the matrix was explained by the facilitator, I could easily continue the interface identification myself."

Conversely, during the group workshops, the interaction between members was encouraged (Linderman et al., 2004): lively discussion occurred between participants, which included discussions regarding (1) dependent or interdependent relationships, (2) (in)direct interfaces, and (3) the rationale behind interfaces. This enabled the unification of diverse mental models (requirement 3). However, due to this, insufficient time was available to complete the MDM. Regarding this, a participant from one of the workshops mentioned:

"It is certainly important to carry out this workshop with several experts simultaneously, that way you can discuss whether the interfaces exist or not, and also in which circumstances that is the case."

This highlights the fact that the perceived usefulness of the MDM increased when multiple experts joined the workshop simultaneously.

Additionally, based on the workshops, it can be concluded that all participants could easily identify from which other BUs input was required to carry out their tasks (Area II in Figure 6.6). However, it was more difficult for them to indicate which other BUs were consumers of their information (Area III in Figure 6.6), which illustrates differences between the supplier and consumer side. Due to this, some BUs may view their interaction with another BU as merely one of providing information, whereas, the other BU may view the relationship as a bilateral information exchange (Browning, 2001). In some instances, one BU noted an interface with another, while this other BU did not recognize that the interface existed. This emphasizes the necessity of aligning perspectives and maintaining interfaces (step 5), in order to create awareness on the existence on inter-organizational interfaces (requirement 6), which can support the information exchange in this context (requirement 7). In the end, this is also essential for effective coordination.

6.5.5 Interface aggregation (DP6) and Aligning perspectives (DP7)

As mentioned prior, some MDMs could become too large to easily comprehend, requiring further analysis to remain useful for IM in the project.

Subsequently, the MDMs were viewed from an aggregate level. This simplified the matrix results significantly and displayed instances of input from suppliers and instances of output to consumers regarding a specific BU. This interface aggregation aided in condensing interface information, aiding prioritization (requirement 5).

Furthermore, viewing the results at an aggregate level allowed for a comparison of the input and output from the perspectives of different BU. By first making the diverse mental models explicit in the form of MDMs, and then displaying and comparing differences, the unification of diverse mental models was enabled (requirement 3). These kinds of comparisons illustrated that in some cases, one BU's input was not recognized as an output of one or more supplying BUs. On the other hand, some BU's outputs were not recognized as input by consuming BUs. Regarding this, one expert mentioned during the evaluation:

"I did not expect this outcome of the MDM aggregates; I did not expect that the Preparing Housing department would have that many instances of input for my work."

A different BU representative mentioned the following regarding overviews, such as the one in Figure 6.6:

"These overviews clearly show differences, that definitely makes you more aware that attention should be paid to the interfaces in this context."

Thus, these high-level comparisons created awareness of the existence of inter-organizational interfaces (requirement 6) and the possible discrepancies between the views of various actors. Thus, making these differences explicit provided direction for communication, and supported the information exchange between different inter-organizational parties (requirement 7), ironing out discrepancies between perspectives.

Moreover, evaluation with project members indicates that the differences concerning the number of interfaces could be caused by several factors: (1) variations in knowledge and experience among project members regarding interfaces to other BUs, (2) availability of limited information during the project scope definition which was used as the starting point of the IM process, (3) some tasks not being mentioned during the defining of the project scope as they were deemed self-explanatory by some project members, (4) project members changing roles during the project and replacing members, bringing in different insights, and (5) it is possible that while filling out the MDM during the workshops, uncertainties about the interfaces already existed.

Additionally, project members indicated during workshops that the identified interfaces should be discussed with the BUs on the other side of the interface.

This would ensure alignment of the perspectives, and that all parties are aware of the existence of the interfaces (requirement 6), thereby enabling the unification of distinct mental models (requirement 3) and enabling the exchange of information across different inter-organizational parties (requirement 7). During the evaluation, it was mentioned by a workshop participant:

"It was definitely interesting viewing these differences from an aggregate level. Normally you don't look at the different project components in such a way. It forces you to look beyond boundaries and emphasizes that we have to do it together."

After there is awareness of these discrepancies, BUs under consideration need to engage with each other to clarify and agree on the identified interfaces. In this regard, the project manager stated:

"It does help to create insight and align perspectives, but here there is more to it, the coordination aspect. But such exercises can also help as input to really plan that coordination."

Further inquiry into the ideal strategies for maintaining the interfaces and coordinating across these lies beyond the scope of this research, and is an area for future research.

6.6 Implications and limitations

The application and evaluation of the proposed approach have multiple implications for practice:

- Combining the structured MDM tool with the softer expert-based process by inclusion of multiple experts in the development of the MDMs, provided a means for gathering, understanding, and dealing with the dispersed knowledge and information in the described contexts.
- It seemed that the proposed approach creates more awareness of the existence of interfaces, and might uncover more interfaces between BUs than expected. This indicates that the challenge proved greater than previously estimated. Subsequently, managing these might require more resources than initially expected.
- In this article, the MDMs resulting from the proposed IM process are not intended as end-products, but as instruments that increase an individual's ability to cope with, and understand complex circumstances by synthesizing multiple actors' perspectives and enhancing mutual understanding about the interfaces.

- In addition, by mapping the discrepancies in various actors' perspectives with regard to the interfaces, a debate is sparked. This facilitates the creation of shared understanding and consensus, aligning diverse perspectives so that mutual agreement can emerge about actions to be taken with regard to coordination.

As such, the proposed IM process does not necessarily enhance coordination on itself, rather, it provides a means to understand whether and where coordination among inter-organizational parties is necessary. Planning fitting coordination strategies remains a topic for further research.

6.7 Conclusion

The work required for a successful inter-organizational project depends on the integration of dispersed tasks among individuals, teams, organizations, and the interfaces between them. This can be challenging due to the dispersion of expertise and information, varied interpretations of the project's decomposition, and the multitude of interfaces present between BUs across different organizations.

We posited that in such projects, identifying interfaces is essential to indicate, on the one hand, whether coordination is needed, and on the other hand, where coordination is needed from actors from either side of the interface(s) to facilitate project integration.

Answering the research question opted in the introduction, focused coordination in the railway context can be achieved by facilitating a structured IM process within inter-organizational projects consisting of (1) defining the project scope by means of experienced project leaders and expert workshops, (2) organizing the obtained information in MDMs, (3) identifying interfaces through supervised workshops with experts, (4) analyzing interfaces by means of aggregate results, and (5) maintaining interfaces by synthesizing and aligning varied perspectives.

The proposed IM process balances the 'hard' MDM tooling with the 'soft' experts-based side. Evaluating the proposed process by application to a case study in the Dutch railway system shows that creating insight into interfaces in a structured way, and showing (inter)dependencies between distinct BUs, created awareness of the existence of interfaces and enabled understanding of the necessity of collaboration for the integration of dispersed project tasks. These insights can be used by the project manager to steer discussions during instances of coordination between different BUs.

Furthermore, the MDM consisting of both process- and organizational domains, proved to be a practical tool for organizing and (re)structuring a significant amount of information and compactly visualizing inter-organizational project interfaces.

Ultimately, the proposed approach did not necessarily lead to complete models which included all interfaces on the smallest detail level but aided in increasing the acceptance of these inter-organizational interfaces among project members, by raising awareness and by aligning views.

Chapter 7 Discussion and Conclusion

7.1 Overview

In the final chapter of this dissertation, particular emphasis is placed on answering the main research question that guided this dissertation and discussing how it was addressed in chapters two through six:

How can systems thinking support inter-organizational change integration in the Dutch railway system?

This question has been investigated and answered by following a strategy based on design science research. The data and information which were collected and processed during the iterative design cycles discussed in the previous chapters, are integrated into the designed artifacts which were implemented and evaluated through multiple case studies conducted within the Dutch railway system.

By reflecting on the design and application of these artifacts in their real-world contexts, it is possible to draw conclusions and make recommendations, thereby effectively answering the 'how'-type research question by using the findings of the research.

This chapter also provides a summarized overview of the key insights obtained during this research project. Although some of the information in this chapter has already been presented earlier in this dissertation, it is repeated here for emphasis and to guide the discussion and conclusion.

As such, this concluding chapter starts by answering the research questions posed in each chapter of this dissertation in Section 7.2. Furthermore, throughout this dissertation, systems thinking emerged in various forms, discussed separately in Section 7.3. This is followed by Section 7.4 which contains a discussion of the design principles which were used in the designing of the developed artifacts, including its resultant set of generalizable design principles. Subsequently, methodological considerations are discussed in Section 7.5, followed by implications of the research for theory and practice in Section 7.6. Lastly, this chapter ends by providing suggestions for future research in Section 7.7.

7.2 Answering the research questions

This section provides a brief overview of the answers to the research questions, as linked to individual chapters of this dissertation.

7.2.1 Main systems integration challenges in the Dutch railway system

To answer the main research question, the research commenced with the aim to understand the main integration challenges which the main railway operator and the infrastructure manager of the Dutch railway system currently face. The research question answered in Chapter 2 was:

What are currently the main systems integration challenges in the Dutch railway system?

While the existing literature mostly positions SI as a goal onto itself, this dissertation posits that SI should be regarded as a means to an end, performing SI should be aimed at maintaining or upgrading system-level performance qualities.

In order to gain insight into the integration challenges in practice, as well as to pinpoint the key factors that could enable more effective SI, semi-structured interviews were conducted in the Dutch railway context. This method offered sufficient flexibility to approach diverse respondents in a manner appropriate to them, while still collecting comparable data (Noor, 2008).

Through qualitative data analysis, the identified challenges were analyzed and mapped in three ways. The results of these mapping efforts show that the identified SI challenges are mainly concerned with the following:

Firstly, there seems to be a lack of mutual integral understanding of the railway system as a whole: the coherence of elements, subsystems, and interfaces currently making up the existing railway system. This was caused by the existence of diverse perspectives of the railway system, varying between organizations, departments, and individuals.

Secondly, as a consequence of the first point, it became apparent that when a change needs to be integrated, challenges to effectively determining the exact nature of the change, its scope, and the impacts of this change on the context exist. This includes determining how this change would fit within the existing railway system context, and not viewing the change as part of the system as a whole. It proved difficult to understand and consider all (sub)systems, organizations, regulations, and processes which may be impacted by the change(s) under consideration, and which need to be accounted for and eventually adapted, in order to facilitate the smooth integration of the change into the inter-organizational context. Moreover, it was mentioned in the interviews that the existence of varying objectives, silo mentality, as well as limited systems thinking among actors, could influence the goals and scope of the change(s) to be integrated.

Thirdly, due to the inter-organizational context, integrating changes would require coordination across organizational boundaries which are often considered to be a 'gray area,' where ownership and responsibilities are often ambiguous, which emphasized the need for insight into interfaces and interdependencies.

Lastly, there appeared to be no common, generally accepted approach in the inter-organizational context for determining the impacts of change(s) on the existing railway system. Not all relevant stakeholders would be involved early on in the SI process, and as such, the possibility exists that their experiences and perspectives on the effects of a change on their specific domains were not included early enough, which has a significant influence on the effective integration of the change at a later stage.

These challenges might hinder the effective integration of changes into the railway system; especially since changes are becoming increasingly complex, as is exemplified by planned innovations such as ATO and ERTMS discussed in the introductory chapter of this dissertation. Moreover, these challenges may hinder the overarching goal of achieving better railway system performance at the (inter)national level.

By pinpointing these integration challenges, it became apparent that possible solutions would require: the incorporation of multiple perspectives of actors; working with unclear boundaries and/or scope of the SOI; understanding the contexts of the change; identifying interfaces and interdependencies; and predicting the impacts of a change on the system. All of this patently points towards systems thinking as a solution (Squires et al., 2011).

Furthermore, as the research proceeded, it became apparent that both in theory and practice, significant attention is paid to diverse changes to be integrated into existing systems, for example, to achieve the desired levels of railway system performance. The success of these integration efforts (avoidance or anticipation of integration problems) is highly dependent on its advance planning and preparation, which is accomplished during the preceding system definition (SD) phase (Alexander et al., 2011). Existing literature also emphasizes that SDs that appropriately describe such changes are critical prerequisites for successful risk assessment and safe integration, and require systems thinking.

Moreover, due to existing rules and regulations in the railway sector, in order for changes to be safely integrated, SDs and their development are mandatory by law, and thus familiar to the Dutch railway sector. The consideration of these factors resulted in Chapter 3 of the dissertation, which examines how this well-known systems thinking approach is currently supported, and how it currently supports change integration in the Dutch railway system.

7.2.2 Systems thinking practices currently supporting change integration in the Dutch railway system

Although the development and understanding of an SD appear to be logical first steps for risk assessment, the existing literature concludes that this systems thinking step is not always conducted in practice. Furthermore, although the current literature, laws, and regulations stress the importance and prescribe the contents of SDs and what needs to be included in order to adequately describe the SOI, direct and thorough comparisons between theoretical best practices, and examples of industrial practice appear to be scarce. As such, Chapter 3 focused on answering the research question:

To what extent do existing systems thinking practices support change integration in the Dutch railway system currently?

To answer this question, Chapter 3 summarized the most prominent descriptions and assumptions present in the literature concerning SDs into five postulates, and compared them to empirical practices using thirteen case studies conducted in the Dutch railway system. The five postulates were either refuted, qualified, or elaborated on, based on the empirical findings from the case studies, as summarized in Table 7.1.

The results show that although CSM-REA provides insights into various aspects that should be included in SDs, there are no guidelines for how to actually apply them. Furthermore, the results indicated that there are divergent opinions regarding the usefulness and necessity of SDs. SD goals are often ambiguous, especially in the early development stages. As such, ambiguity needs to be addressed through the inclusion and alignment of the perspectives of multiple experts, and the creation of mutual understanding regarding any remaining ambiguity. Moreover, interfaces in particular are seen as critical to the SD, but are often perceived as ‘gray areas,’ making them difficult to manage and maintain. Furthermore, the majority of the interviewees agreed on the necessity of updating SDs, and indicated that SDs should be iterative in nature during their initial development. Although SDs are iteratively developed, they are rarely updated afterwards. Consequently, SDs start losing their relevance as changes occur.

Table 7.1: Summarized postulate results

CSM-REA postulate positioning		**Postulates**	**Results**
SD as basis for risk assessment (I)	1	A system definition is a critical success factor for risk assessment	Partially supported
SD content (II)	2	A system definition is focused on a clearly defined goal	Partially supported
	3	A developed system definition always has a clear scope	Not supported
	4	Interfaces between parties/stakeholders/subsystems are an essential part of the system definition	Fully Supported
SD's iterative nature (III)	5	A system definition is continuously updated based on information that becomes available during the development process	Supported

In addition to the results directly related to the postulates, the research revealed multiple other aspects that contribute to the usefulness and useability of an SD, which are not always followed up on in practice. These are synthesized in the proposed SD development process shown in Figure 7.1.

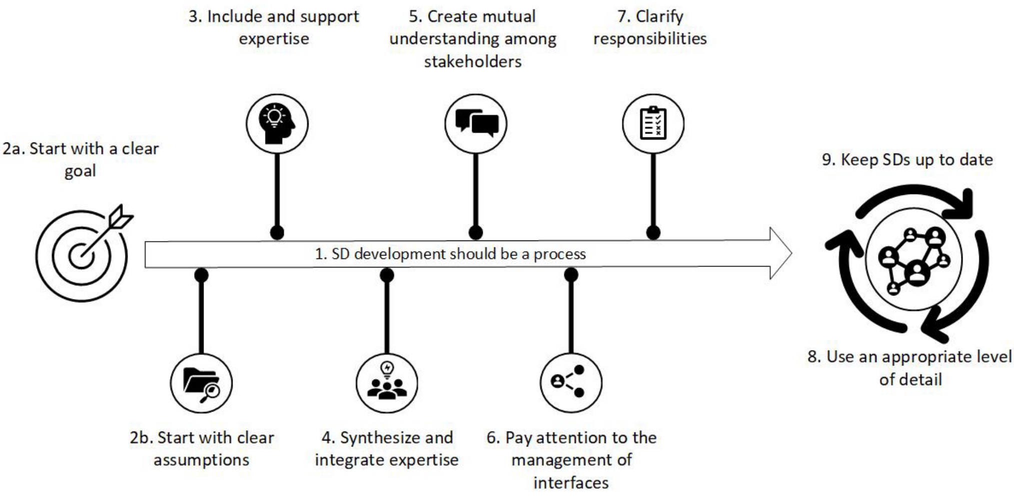


Figure 7.1 Proposed SD developed process

This shows that applying systems thinking in the SD creation process plays an important role in ensuring the SDs' usefulness. Despite their importance, however, the identified aspects are currently often considered on an ad hoc basis.

Therefore, as discussed in Chapter 3, more attention needs to be paid to these aspects, especially because changes are becoming increasingly complex and inter-organizational.

Furthermore, the findings from this chapter show that considerable attention is currently being paid to SDs and systems thinking from the safety perspective within the railway industry. However, the scope of integration in complex inter-organizational systems extends beyond safety, as reliability, capacity, and cost are becoming more important.

Railway systems involve multiple organizations that are often responsible for different aspects of the system, such as infrastructure, operations, maintenance, and safety. Prospective changes can vary widely in nature, and the impacts of these changes tend to affect multiple domains, often spanning across different organizations in the railway system. This extends into the field of systems integration, which is a key challenge to be mastered in the design and delivery of inter-organizational projects (Muruganandan et al., 2022).

In the railway system context, various organizations, disciplines, and individuals have their own insights, (mental) models, experiences, assumptions, expectations, and approaches to describing and understanding changes and their related impacts. As the scope of changes increases, more intense collaboration between people from different organizations, departments, and from diverse engineering and non-engineering backgrounds may be needed, in order to form a shared view of the change and its impacts on the system. Thus, the results from Chapter 3 formed the basis of several systems thinking features, which were to be included in the designed artifacts, connecting them to the results of Chapter 4 in this dissertation.

7.2.3 Design & development: Applying systems thinking to facilitate scope definition of inter-organizational changes

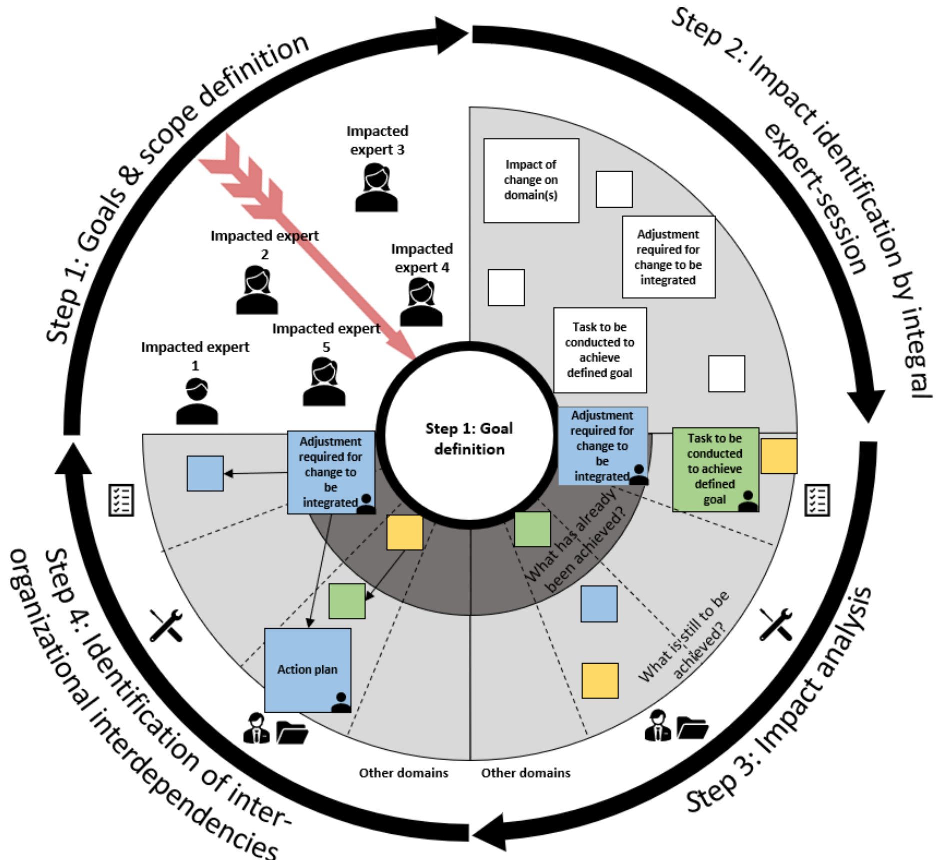
Change projects in complex sociotechnical systems such as railways can significantly impact other processes and/or multiple departments across organizations; thus, it is vital to set bounds on various aspects which may be of interest. A crucial aspect enabling the integration of changes in sociotechnical systems such as railways, is defining the scope of the changes, which is referred to as the SOI. This can be challenging due to: an inter-organizational environment, a multitude of diverse stakeholders, a multidomain environment, and an increasing number of interfaces. As such, concerns have been raised about the suitability of traditional tools and techniques developed for simple projects for use in complex inter-organizational projects (San Cristóbal et al., 2018).

Nevertheless, there is an increasing need for engineering managers to understand this complexity in order to identify how changes, and the projects that strive to realize them (Potts et al., 2021), can be integrated into the complex sociotechnical context.

As such, this chapter addresses the following research question:

How can systems thinking be applied to facilitate scope definition in order to enable inter-organizational change integration in the complex sociotechnical railway system?

By employing DSR, using iterative design science, and using design principles inferred from both theory and practice, this chapter proposes the MOSAIC analysis. It facilitates a structured, multidisciplinary assessment of system impacts and interdependencies, resulting in an SOI. This method is depicted in Figure 7.2.



.

Figure 7.2 Proposed MOSAIC analysis

By applying MOSAIC to an inter-organizational project concerning the implementation of a train-towing vehicle and evaluating it together with involved project members, this chapter demonstrated that the designed MOSAIC analysis contributes to reaching the goals of the project by: (1) focusing on a clear objective and including relevant actors; (2) providing a structured process and analysis for determining the SOI; (3) synchronizing the perspectives of inter-organizational and multidisciplinary experts through an integral expert session; (4) enabling an open, yet focused discussion, supported by guiding questions and visual aids; (5) identifying diverse impacts of the change across sociotechnical domains, and tasks required to be carried out by diverse stakeholders to achieve the determined objective; (6) highlighting ownership and responsibilities; and (7) identifying interdependencies across which collaboration is essential. Here, continuous evaluations can facilitate introduction of new experts and their late-arriving viewpoints to influence the scope, this was also highlighted previously by C. Haskins & Ruud (2017).

In addition to numerous changes which are introduced in order to improve the performance of the railway system, there are also external influences on the system which may negatively affect its performance. One of these factors is climate change, which leads us to the results of Chapter 5 of this dissertation, summarized in Section 7.2.4.

Furthermore, the execution of a successful inter-organizational project depends on numerous activities, individuals, teams, and organizations, as well as the relationships between them. This requires coordination among employees from different organizations (Browning, 2010; Milch & Laumann, 2016). However, the results from Chapter 4 showed that such inter-organizational projects often contain a significant number of tasks dispersed across the organizations, with possible interfaces between them. In such cases, there can be divergent interpretations of the decomposition of the project, many tasks to be conducted within an inter-organizational project do not have neat and easily identified interfaces to project participants (business units), and as a result, the interfaces can be 'hidden', or easily overlooked. This guided us to Chapter 6, discussed in Section 7.2.5.

7.2.4 Design & development: Changing system environments

The global climate is changing and the frequency of extreme weather events is increasing (Quinn et al., 2018). Because of this, the need to adapt assets to a changing climate has attracted increasing attention, both from a practical and theoretical perspective over the past decade. While the existing literature addresses, among other topics, risk identification and management, other essential aspects, such as the inclusion of synergetic opportunities, the process leading to adaptation strategies, the wider context, strategic adaptation inventory, and integrality, are not currently considered when managing CCA in infrastructures. Furthermore, the existing literature proposes processes which describe what needs to be done in order to create CCA strategies, but does not offer suggestions on how to achieve this.

Thus, this chapter developed a framework that aims to effectively take into account the identified theoretical aspects and limitations for managing CCA, and answered the research question:

How can systems thinking be applied in case of changing system environments: external influences like climate change on the Dutch railway system?

Using interviews, the existing scientific literature, and archival research on organizational reports, essential design principles for the framework were determined. This led to essential phases and key features, which were included in the initial version of the developed framework. This version was subsequently updated using expert input from involved key stakeholders, which resulted in the framework presented in Figure 7.3.

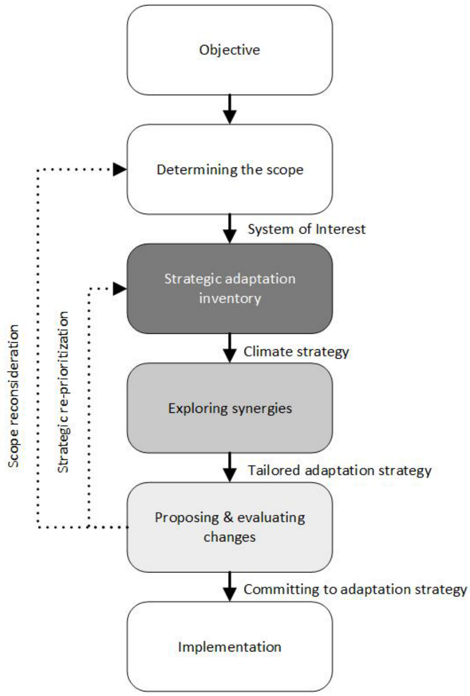


Figure 7.3 Proposed climate change adaptation framework

The evaluation of the preliminary framework suggested that it can assist railway infrastructural management organizations during the process of developing concrete climate adaptation strategies by determining a clear scope, focusing on the SOI, exploring synergies, and thereby, tailoring adaptation strategies. After a thorough analysis, these strategies can be either rescoped and reprioritized, or committed to and implemented.

7.2.5 Design & development: Systematic interface management in inter-organizational projects

Projects that aim to improve large systems such as railways, are often complex and inter-organizational because multiple organizations interact to create value together (Hass, 2008). These projects involve multiple actors with disparate goals, overlapping areas of responsibility, and differing levels of expertise (Jones & Lichtenstein, 2008).

Furthermore, the execution of a successful inter-organizational project depends on the alignment and coordination across interfaces between dispersed tasks. However, though this is vitally important, it can be difficult to achieve since knowledge and information are dispersed across various departments or organizations. Building on the existing literature, this research posits that identifying interfaces is essential for indicating whether and where coordination is needed from actors from either side of the interface(s), in order to facilitate project integration.

As such, this chapter addresses the following research question:

How to facilitate interface management within inter-organizational projects with the aim of achieving focused coordination in the railway context?

The applications of the DSR process resulted in the design of an IM process consisting of 5 subsequent steps, depicted in Figure 7.4.

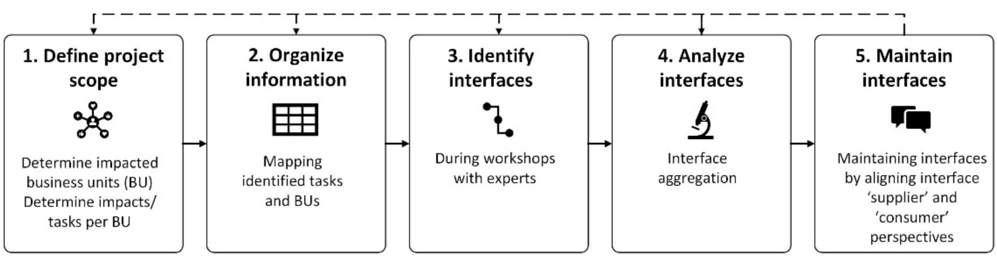


Figure 7.4 Proposed IM process in inter-organizational projects

By comparing the objectives of the proposed solution to results gained through the use of the artifact in the case study concerning the construction and implementation of a new train stabling yard, the results show that focused coordination in the railway context can be achieved by facilitating a structured IM process within inter-organizational projects consisting of (1) defining the project scope by means of experienced project leaders and expert workshops, (2) organizing the obtained information in MDMs, (3) identifying interfaces through supervised workshops with experts, (4) analyzing interfaces by means of aggregate results, and (5) maintaining interfaces by synthesizing and aligning varied perspectives.

The proposed IM process balances the 'hard' matrix tooling with the 'soft' experts-based side. Ultimately, the proposed approach did not necessarily lead to complete models which included all interfaces on the smallest detail level, but aided in raising awareness of these inter-organizational interfaces among project members, by aligning perspectives and creating transparency.

7.3 Systems thinking

When various systems ideas and techniques are brought together in an organized way and employed to improve a certain situation, systems thinking is used (Jackson, 2003). As such, systems thinking can be applied in almost any domain (Rosenhead, 2010). Throughout the chapters of this dissertation, systems thinking has been incorporated in various ways.

As mentioned in the introduction of this dissertation, hard system approaches such as systems engineering are often suggested as a suitable approach for managing complexity (Hitchins, 2007; International Council on Systems Engineering, 2015). Hard systems thinking was a breakthrough in terms of applying systems thinking to real-world problems because in many cases, it offered a methodology that proved to be the most appropriate way of tackling these (Jackson, 2003). Such 'hard practices' however, require a clear singular objective or goal (Hitchins, 2007), so that a (mathematical) model can be produced and an optimal solution to the problem can be recommended (Jackson, 2003). The reality faced by managers today, however, is so complex and subject to change, that it can be challenging to reduce problem situations to a form that would make them amenable to such modeling (Jackson, 2003). Additionally, hard systems thinking is unable to deal satisfactorily with multiple perceptions of reality (Mingers & Rosenhead, 2004; Rosenhead, 2010), which was often encountered during this research. It demands that the goal of the system of interest should be known or ascertained before analysis can proceed (Jackson, 2003).

This approach regards systems as "objective" aspects of reality, comprised of relatively "hard" (immutable), observable, and "real" objects (Junior & Da, 2020). In such situations, the understanding of systems is therefore considered largely independent of the observer (Junior & Da, 2020).

The research conducted and the results obtained throughout this dissertation clarified that these conditions do not always apply in the Dutch railway system. In this context, there appeared to be no individual or organization in the railway system that has a complete overview of the entire system, and of all the changes that are continuously integrated. In some instances, various groups in the sector aimed to develop overarching railway system models. However, these were not generally accepted, let alone used by practitioners to solve integration challenges. Furthermore, the knowledge and information about the system, and any changes with their related impacts, are not centralized but dispersed across different organizations and different experts, all of whom have their own understanding and perspectives. Furthermore, due to the size of the organizations involved and the silo mentality, as described by involved practitioners, finding those experts would be a challenge in itself. Thus, in such contexts, hard systems thinking approaches have shortcomings (Jackson, 2003; Mingers & Rosenhead, 2004).

In response to the perceived shortcomings of hard systems thinking, soft systems thinking was developed (Mingers & Rosenhead, 2004; Rosenhead, 2010), which proves especially relevant to the challenges described in this dissertation. In many situations, the questions 'what is the objective?' and 'what are we trying to achieve' were part of the problem (Mingers & White, 2010). Without an agreement on objectives, or when the objectives are poorly defined, the results of traditional systems engineering may cause a loss of confidence in the model, and, most likely, would lead to dissatisfaction on the part of those whose perspective on those objectives is not implemented (Rosenhead, 2010).

In situations like those described in this dissertation, reaching agreements on objectives is often central to the core problem to be tackled (Jackson, 2003). Throughout chapters 4, 5, and 6, this became increasingly evident, mostly due to the use of iterative DSR methodologies. Thus, for all artifacts designed and produced during the course of this dissertation, focusing on the objectives of the change(s) under consideration was an essential starting point. By promoting a shared understanding of the change and related goals, facilitating effective collaboration between involved actors was stimulated.

Soft systems thinking was developed as a means to understand and address the diversity of perspectives and interests when analyzing complex situations (Mingers & White, 2010). Soft systems thinking emphasizes collaboration and stakeholder engagement, bringing together multiple perspectives and encouraging dialogue and learning. Furthermore, it emphasizes the importance of subjective interpretation and human perception in understanding complex systems.

The core ideas of soft systems thinking can be used both for general problem-solving and the management of change (Rosenhead, 2010), as was done in Chapter 4 and Chapter 6. In these chapters, soft systems thinking was employed in order to incorporate the various perspectives of the stakeholders and experts involved. Moreover, we used the notion of a 'system' as an interrogative device, by jointly creating an SOI, which facilitated discussion amongst the involved actors (Rosenhead, 2010). Additionally, by focusing the MOSAIC analysis on multiple sociotechnical domains, experts were encouraged to look beyond the technical aspects of the change, and to also consider the regulatory and social impacts. This can result in more comprehensive insights which can address underlying systemic aspects.

Systems thinking was used more generally in Chapter 5. Depending on the level of abstraction, CCA strategies can range from a complete system redesign to a mere handful of simple improvements to a specific asset, and as such, the system is viewed at different levels. This emphasizes the importance of focusing on an SOI in this context, especially as related to the relevant climate effects, affected asset(s), geographical location, and the expected lifespan of the asset(s), which were all deemed important input for the strategic adaptation inventory in Figure 7.3. Additionally, the SOI-specific risk-based CCA strategies should be compared and adapted to existing and proposed programs from both internal (company) and external sources. By mapping and adapting CCA strategies to these existing plans, synergetic and/or collective efforts can be identified which may reduce the burden of implementing CCA strategies, and even solve multiple problems simultaneously. Therefore, in this case, systems thinking is used to aid in identifying synergetic opportunities.

Projects that are characterized by a high number of interfaces and components particularly benefit from systems thinking (Sheffield et al., 2012). In these situations, soft systems thinking aims to unfold relationships within projects to enable better decision-making (Jackson, 2003). This corresponded to the focus of Chapter 6, in which a structured IM process was developed, in order to support practitioners in gathering, organizing, and analyzing dispersed information aimed at identifying interfaces, to achieve focused coordination across organizational boundaries. This chapter also demonstrated that several hard analysis methods and tools exist which can aid IM.

These typically require the systems engineers to generate complete definitions of all the system interfaces in a rigid fixed framework (International Council on Systems Engineering, 2015). In Chapter 6, MDMs were used to organize the obtained information and identify inter-organizational project interfaces concerning tasks.

While these hard systems thinking tools can be applied in a fairly straightforward manner in cases of physical products or changes, where a limited number of diverging interpretations among actors exist, this is often not the case for inter-organizational projects, where varied interpretations of the decomposition exist. As such, this dissertation combined aspects of soft systems thinking by including multiple experts in the development of the MDMs, making their mental models explicit, and synchronizing these. Additionally, by mapping the discrepancies between the perspectives of various actors regarding the interfaces, discussion was facilitated, which is key to the success of soft systems thinking (Jackson, 1991). Shared understanding and consensus were created, and diverse perspectives were aligned, so that mutual agreement about actions to be taken could emerge. This emphasizes the importance of collaboration and communication between different actors across the interfaces.

Another feature of soft systems approaches is that they stress the importance of organizational and individual learning (Rosenhead, 2010), however, they do not guarantee that a definite product will emerge from a project. In this research, both the MOSAIC analysis and the proposed IM process are artifacts, however, the SOIs resulting from the MOSAIC analysis, and the MDMs resulting from the IM process, are also not definite products. The MOSAIC and IM analyses provide opportunities for people to understand and cope with complex circumstances so that their performance can be improved. Therefore, soft systems approaches tend to be presented as cyclical, as depicted in Figure 7.2 and Figure 7.4. As such, the designed artifacts discussed in Chapter 4 and Chapter 6 encourage individual and organizational learning by combining various stakeholder perspectives, thus enhancing mutual understanding of the SOIs and interfaces in the inter-organizational projects and context.

As demonstrated above, systems thinking can support inter-organizational change integration in railway systems by: (1) making the objectives of a change explicit to facilitate focused discussions, (2) using and synchronizing dispersed expert knowledge to gain holistic integral insight into the impacts and scope of change(s), (3) taking a multidomain perspective to organize the collection of information, (4) making inter-organizational interfaces transparent, and (5) condensing interface information by aggregating and visualizing information concerning critical interfaces.

7.4 Discussion and generalization of the adopted design principles

7.4.1 Discussion of design principles

The artifacts developed in this dissertation have been designed using established design principles, related to the identified design goals and requirements. As stated in Chapter 1, an important characteristic of DSR is that it allows for a deeper reflection at the level of design principles, and their generalizability for other contexts. This subsection discusses why the proposed design principles included in the proposed MOSAIC analysis in Chapter 4 and the IM process in Chapter 6, were effective in the railway system context.

While the first section of this concluding chapter answered the core research question of this dissertation by explaining ‘how’ systems thinking can support inter-organizational change integration in the sociotechnical railway system, this section elaborates further on the research results by discussing ‘why’ the developed artifacts were effective from a design perspective. The following paragraphs, discuss the generalizable design principles that underpin the research presented in this dissertation.

7.4.1.1 (DP 1) Explicating a change’s objectives to facilitate focused discussions

In temporary organizational systems such as projects, independent and interdependent entities cooperate for a limited period to achieve specific objectives (Pezzillo Iacono et al., 2012). The objective is typically a short statement outlining the purpose and function of the change (Safety & Standards Board, 2014). According to Foster-Fishman et al. (2001), creating mutual goals and objectives is important for enhancing inter-organizational collaboration and facilitating the exchange of information and resources across organizational boundaries. In such cases, all project participants must be clear about their goals and objectives (San Cristóbal et al., 2018). Thus, the objective provides useful context and clarifies the main reasons for the change and the requirements for a successful assessment.

As previously stated in chapters two to six, unclear objectives, and ambiguity in ‘what are we trying to achieve’ were identified as part of the problem. Thus, by making the objective(s) of the change(s) under consideration explicit in the designed artifacts in Chapter 4, 5, and 6, the involved actors were encouraged to engage with these, without assuming that all involved actors had a similar understanding of them.

Furthermore, discussing the objective aids in jointly producing a mutually valued outcome. Without agreement on the objective, or when the objective is poorly defined, a loss of confidence in the SOI developed at the end of the

MOSAIC analysis may occur, and, most likely, lead to dissatisfaction on the part of those whose perspectives of the objective(s) were not implemented.

7.4.1.2 (DP 2) Using and synchronizing dispersed expert knowledge to gain holistic integral insight into the impacts and scope of change(s)

This DP was established as a result of the findings of Chapter 2, 3, 4, and 6. The structure and behavior of a complex system are impossible to fully understand from a single point of view (Browning, 2009). The context described throughout this dissertation is characterized by the existence of multiple actors, multiple perspectives, incommensurable and/or conflicting interests, prominent intangibles, and key uncertainties (Jackson, 2003; Mingers & Rosenhead, 2004). As such, knowledge and information are dispersed, the actors involved have varying views on the railway system and on the diverse changes to be integrated, and experts from various disciplines and organizations have their own insights, models, and approaches to describing and understanding these. As such, the information and knowledge of experts from different organizations, and from diverse engineering and non-engineering disciplines, needed to be synchronized in order to create an integral overview of the change(s) and its impacts. To overcome these challenges, input from experts was used in various ways.

In Chapter 4, integral expert sessions were used. Ruitenburg (2017) illustrated that these sessions improve stakeholder engagement, close the gaps between experts, and combine scattered resources. These sessions included experts from multiple disciplines, who provided collective expertise, exchanged information, and discussed the impacts of a change. Thus, deploying tacit knowledge, and synchronizing multiple stakeholder perspectives into an SOI. In this case, the shared overview could be used to test and align participants' mental models through discussion, which led to a mutual understanding of, and consensus on the SOI (Danilovic & Browning, 2007).

Additionally, in Chapter 6, an expert-based process approach was designed, with inherent expert sessions. These were utilized to gather expert knowledge concerning the impacts of a change on various domains, related tasks required to be conducted by various business units in the inter-organizational project, and identify the various interfaces in the inter-organizational project, based on the obtained information. Also, by conducting the latter session multiple times with various experts, their views with respect to the interfaces could be contrasted from 'supplier' and 'consumer' perspectives, as well as revealing possible discrepancies in and between their views. As such, this not only raised awareness of the existence of interfaces but also aided in creating alignment among the involved actors.

7.4.1.3 (DP 3) Taking a multidomain perspective to organize the collection of information

Qureshi et al. (2007) explain that sociotechnical systems should be viewed as encompassing at minimum human, technical, and organizational domains, with intrinsic complexity arising from interactions and interdependencies between components. While a prospective change may appear to have only technical impacts at first glance, this can turn out to be more complex when attention is paid to the sociotechnical context into which it must be integrated. Describing multiple domains provides a sound basis for structured analysis during the later stages of a project (Rail Safety & Standards Board, 2014).

Experts involved in the MOSAIC analysis had different perspectives on the impacts of the change(s), based on their backgrounds and experiences. As previously mentioned, by utilizing expert sessions and displaying and categorizing the impacts identified during these, into various sociotechnical domains, such as social, process, technical, and regulatory domains, the resulting overview would indicate whether a certain domain received an abundance of focus, or whether impacts of a certain domain were underreported. This could indicate that the included experts did not have expertise concerning, or experience with, impacts on that specific domain (e.g. regulations), thus requiring additional experts from those domains to confirm this. This indicates that this method encourages learning, as discussed in Section 7.3.

The evaluation revealed that the MOSAIC analysis created an understanding among the group of participants that multiple domains play a role in reaching the defined objective. Despite this, reorganizing the information according to the sociotechnical quadrants did not proceed smoothly, since this mode of thinking did not come naturally to them.

7.4.1.4 (DP 4) Making inter-organizational interfaces transparent to facilitate focused coordination

In order to cope with complexities that arise from inter-organizational projects and enable effective project management, organizations often attempt to decompose a project (Davies & Mackenzie, 2014; Healey, 1997). This decomposition results in the granulation of work into numerous diverse tasks, which are executed by different individuals and by different departments across organizations (Healey, 1997). In such projects, identifying interfaces can indicate where a collaborative approach is needed from actors on either side of the interface, thus revealing which tasks require coordination across organizations for their successful execution. In complex inter-organizational contexts, however, coordination among diverse groups becomes more challenging as their number and interdependencies increase. Regardless of how tasks are divided, linking various parts is always complicated (Long & Spurlock, 2008).

In Chapter 4, the identification of inter-organizational interdependencies was the last step of the MOSAIC analysis. By asking guiding questions during the workshops, interfaces between the previously mentioned tasks could be made explicit. In this case, the identification of interdependencies significantly aided in clarifying (1) how different tasks fit into the project as a whole, (2) how different tasks are linked to each other, and (3) how a change in adjacent tasks could impact dependent tasks, and as such, should be planned accordingly. This demonstrates that making these insights explicit facilitates the structured exchange of inter-organizational knowledge and information concerning specific tasks/impacts. However, since substantial discussion preceded this last step of the MOSAIC analysis, interdependencies between different tasks had already been referred to, albeit indirectly. Moreover, because a significant number of tasks with possible interfaces were identified in the inter-organizational projects, these required more focused attention.

Chapter 6 discussed IM and emphasized both that in inter-organizational projects it is crucial to understand and explore interfaces, as well as the need for information exchange across these. The challenge for managers lies in finding the appropriate method to organize individuals, appropriately pace the assignment of work, facilitate communication, and synchronize activities (Danilovic & Browning, 2007).

Thus, in an inter-organizational project where the tasks are carried out by actors from BUs across distinct organizations, it is essential that the related interfaces are identified. The included project members should be aware of these in order to account for coordination between parties on either side of the identified interfaces. This includes establishing roles and responsibilities between different inter-organizational parties on either side of the interface (International Council on Systems Engineering, 2015).

However, though identifying and managing interfaces is vitally important, it can be difficult to achieve, since knowledge and information are dispersed across various departments or organizations, and many tasks to be conducted within an inter-organizational project do not have neat and easily identified interfaces to project participants.

As a result, the interfaces can be ‘hidden’, or easily overlooked. Chapter 6 addressed this by aiming to achieve mutual understanding concerning these interfaces in inter-organizational projects, by viewing the identified interfaces from both consumer and provider perspectives. Moreover, the discrepancies between perspectives could be identified by viewing the interfaces from an aggregate level. These differences sparked discussions, which created shared understanding and consensus, aligning diverse perspectives so that mutual agreement could be established about actions to be taken on either side of an interface. Moreover, it provided a means by which to identify on which tasks inter-organizational coordination is necessary.

7.4.1.5 (DP 5) Condensing interface information by aggregating and visualizing information concerning critical interfaces

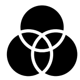
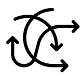
Models that attempt to contain everything about a project are cumbersome to build, maintain, understand, and use (Little, 1970). Furthermore, attempting to provide all information in such a model can cause information overload, which is more often than not detrimental to providing information, owing to the false assumption that effective communication has occurred (Browning, 2009). In keeping with this, Little (1970) noted that managers prefer simple models, which they understand and trust, over more realistic ones.

In Chapter 6, after identifying and visualizing the interfaces in the inter-organizational project concerning the MDMs, the number of interfaces identified in the matrix quickly proved to be too large to deal with. This did not decrease the complexity but did make it more transparent, as was also pointed out by the project members. In order to discuss this, the identified interfaces were subsequently viewed from an aggregate level. This high-level, visual overview revealed tasks with or without significant interfaces to other inter-organizational BUs. This facilitated the understanding of a large number of interfaces, by creating awareness of their existence, and indicated where collaboration would be required on either side of the interface.

7.4.2 Generalizable design statements

One advantage of DSR is that achieving a successful design outcome goes beyond solving a practical problem. It also generates valuable knowledge regarding the nature of the problem and the specific solutions employed to address it. The design principles discussed in Section 7.4.1 can be summarized into five concise and generalized statements that can be transferred to other designs, and tested in contexts other than the one outlined in this dissertation.

Table 7.2: Generalizable design statements

#	Statement	
1	Making the objectives of a change explicit facilitates focused discussions among actors, which is essential for a mutual starting point	
2	Using and synchronizing dispersed expert knowledge can provide holistic, integral insight into the impacts and scope of change(s)	
3	By taking a multidomain perspective to organize the identified impacts of a change, existing tendencies towards certain domains are made explicit and can be compensated for accordingly	
4	Making inter-organizational interfaces transparent can create awareness of the fact that focused coordination is necessary across organizations	
5	Condensing interface information by aggregating and visualizing information emphasizes (the lack of) critical interfaces where coordination is crucial for effective integration	

7.5 Methodological considerations

As with any research, the outcomes of this dissertation have limitations. While the specific limitations have already been discussed in chapters 2 through 6, the most significant limitations of the PhD project and methodological considerations will be elaborated on in this section.

7.5.1 Focus on a single system

The research, and the designed and evaluated artifacts as presented in this dissertation focus on a single system, namely the Dutch railway system. This focus has an advantage over more detached forms of research in that it allows for a rich, contextualized, and empirical understanding of the research problem. This focus on a single system, however, also results in limitations, one of which is the difficulty of generalizing findings.

The conducted research is based on case studies, which are qualitative in nature, and have the advantage of obtaining a thorough empirical understanding of the rich problem context (Yin, 2003). A common mistake when conducting case studies is thinking of statistical generalization as a method of generalizing (Yin, 2003). This is because cases are not sampling units, rather, individual cases are to be selected as a laboratory investigator selects the topics of a new experiment (Yin, 2003). Under these circumstances, analytic generalization is employed: focusing on developing conceptual insights and theoretical understanding based on the detailed examination of particular cases. A detailed description of how the quality of the cases was ensured is provided separately in chapters 2 through 6.

7.5.2 Triangulation

To address the challenges resulting from focusing on a single system, triangulation was employed. Multiple sources of evidence have been used, as is recommended for case studies (Yin, 2003). This is also considered a major strength, as it provides the opportunity to use many different sources of evidence, allowing investigators to develop converging lines of inquiry (Campbell et al., 2020). Campbell et al. (2020) distinguish triangulation into data triangulation, investigator triangulation, theory triangulation, and methodological triangulation. In this dissertation, these triangulation methods were applied in multiple complementary ways, which will be discussed in more detail in the following paragraphs.

7.5.2.1 Data Triangulation

Data triangulation is the use of a variety of data sources, including time, space, and persons (Campbell et al., 2020). Findings can be corroborated and any weaknesses in the data can be compensated for by the strengths of other data, thereby increasing the validity and reliability of the results.

Multiple cases were investigated throughout this dissertation, varying in scope and complexity, and involving different actors. For example in Chapter 3 a wide range of cases and related SDs were investigated, which varied in scope, costs, novelty, complexity, inter- and intra-organizational natures, duration, reversibility, and impacts. Thus, different factors were analyzed to offer sufficient diversity to draw reliable conclusions (Yin, 2003).

7.5.2.2 Investigator Triangulation

Investigator triangulation refers to the use of more than one investigator, interviewer, observer, researcher, or data analyst in a study (Archibald, 2016).

Firstly, in Chapter 2, the conducted interviews were analyzed by multiple analysts. In this chapter, data processing and coding based on SI issues mentioned during the documented interviews, and structuring and regrouping the analyzed data for pattern matching have been carried out with multiple researchers in order to decrease bias and improve the validity of the analysis.

Secondly, in Chapter 3, a structured interview protocol was developed in order to gather data for the study. The protocol was pre-tested with researchers to ensure that the questions were unambiguous.

Thirdly, in Chapter 4, investigator triangulation was used by means of having several observers or interviewers present during data collection. Additionally, several observers were present during the workshop and the evaluation of the developed MOSAIC approach. This proved to be useful to ensure that the recorded information was understood correctly as well.

Fourthly, in Chapter 6, multiple observers were present during the workshops which were conducted to fill in the MDMs aimed at identifying interfaces within inter-organizational projects. This proved to be useful for determining the success of the workshops, and establishing where improvement was possible in future design iterations.

Additionally, the developed artifacts were never applied by the author alone, but in practice, always performed in multidisciplinary groups of people. Moreover, the results obtained in this dissertation were discussed thoroughly in numerous meetings, which involved University researchers, the SIRA project steering committee, and representatives from NS and ProRail.

7.5.2.3 Theory Triangulation

Theory triangulation is the use of multiple theories or hypotheses when examining a situation or phenomenon: looking at a situation/phenomenon from different perspectives, through different lenses, and/or with different questions in mind (Campbell et al., 2020).

In this dissertation, this has mainly been applied in Chapter 6, in which IM and the designed tools were viewed both from the system engineering perspective, focusing on the identification of interfaces, and from the coordination perspective. This demonstrated that interface identification and management are essential within the context described in this dissertation, however, their subjective interpretations should be accounted for in order to encourage coordination across BUs and organizations.

7.5.2.4 Methodological Triangulation

Methodological triangulation is the use of multiple methodologies to study a situation or phenomenon.

Firstly, in Chapter 3, multiple methodologies were used to supplement the findings (Yin, 2003). These included documentation on the development and use of SDs in the Dutch railway system, a longitudinal case study, research of archival documents, exploratory- and semi-structured interviews, and joining and observing multiple expert sessions held within the respective organizations where SDs were developed or used.

Secondly, in Chapter 4, triangulation was used by means of interviews, observations of expert sessions within the industry, and archival research on existing models and modeling approaches in the industry.

Thirdly, in Chapter 5, exploratory interviews, the existing scientific literature, and archival research of organizational reports were employed in order to determine essential design principles for the developed framework. This led to important phases and key features included in the initial version of the developed framework.

Lastly, in Chapter 6, methodological triangulation was achieved by means of semi-structured interviews, observation of multiple project meetings, and archival research. This triangulation revealed that several tools enabling inter-departmental cooperation were already available within the studied organizations. However, a standardized process aimed at gathering, organizing, integrating, and analyzing information to support IM in this context did not yet exist.

7.5.2.5 Deductive and inductive reasoning

This dissertation employs both deductive and inductive reasoning. In Chapters 2 and 3, deductive reasoning is utilized to examine the challenges from both a theoretical and practical standpoint. This influenced the development of the coding schemes for qualitative data analysis. Inductive reasoning was employed during the evaluation of the implemented design principles.

7.6 Research implications

The implications of the research conducted throughout this dissertation are divided into reference-, theoretical-, practical-, and general implications elaborated on in the following paragraphs.

7.6.1 Reference implications

Two decades ago, Rasmussen (1997), had mentioned rapid change, globalization, fierce competition, rising customer expectations, and rapid advancement of technology to characterize the society at that point in time. He mentioned a fast pace of technology within the domains of transport and process industry, steadily increasing scales of industrial installations, and rapid development of information and communication technology, all leading to a degree of integration and coupling of systems.

A decade later, Bartolomei et al. (2012) still mentioned the scope and complexity of engineered systems to be ever-increasing as unprecedented technological capabilities, rising consumer expectations, and ever-changing social requirements presented difficult design challenges that often extend beyond the traditional engineering paradigm. These challenges required engineers and managers to treat the technological systems as a part of a larger whole (Bartolomei et al., 2012), as technological advancements spawn system after system, each increasingly interdependent with other, preceding systems (Arnold & Wade, 2015).

Currently, several characteristics in the 'Industry 4.0' trends are notable which include (Ahmed et al., 2022; Hermann et al., 2016b; Xu et al., 2021): (1) the large number of companies that are affected by changes, (2) interconnection, (3) the exponential speed at which industries are affected, (4) the collection of immense amounts of data and information. As such, modern systems become ever more connected and interdependent, causing an increase in complexity, and a need to evaluate it (Potts et al., 2022).

The latest trend is further development named 'Industry 5.0', which is understood to recognize the power of industry to achieve societal goals, by making production respect the boundaries of our planet and placing the well-being of the industry worker at the center of the production process (Xu et al., 2021). For this, the industry needs to be sustainable, reducing waste and environmental impact, ultimately leading to better resource efficiency and effectiveness (Breque et al., 2021), by integrating social and environmental European priorities into technological innovation and shifting the focus from individual technologies to systematic approaches (Xu et al., 2021). Providing some concrete examples, the European Union has ambitious goals for mobility and railway transport, such as establishing clear milestones for transport in reducing greenhouse gas emissions (Railtech, 2020b). Additionally, Guerrieri (2022) mentions that in recent years several innovative technology systems have been conceived within rail transport, with the purpose of producing ever faster and more efficient transportation systems such as the Hyperloop, providing key benefits of speed and flexibility, comfort, and safety as well as sustainability. Another frequently recurring example in this dissertation is ATO, aimed at among other increasing capacity by stronger utilization of existing rail tracks, reduction of operational costs, and increasing energy efficiency.

In these trends, ever growing inter-organizational complexity can be observed because of among others the increased outsourcing of production and operations (Bugalia et al., 2021). Multiple specialized organizations are increasingly managing the functions of manufacturing and operations, leading to an increased need for inter-organizational coordination (Pilbeam et al., 2020). Bugalia et al. (2021) show that recent studies have continued to raise concerns about the trends in various modern-day complex systems due to enhanced inter-organizational complexity, which can cause for example fragmented decision-making.

Here, one decision or change could have possible extreme effects that could propagate rapidly and widely through the interconnected systems and organizations. As a result, systems integration has also been evolving.

While early research established that systems integration, created in the 1960s, was one of the core technical engineering tasks within systems engineering performed during the design and execution of large, complex projects (Muruganandan et al., 2022), it has nowadays become a core capability of organizations responsible for coordinating large networks of stakeholders involved in the design, production and integration of interdependent component parts of complex products, project, and systems ((Hobday et al., 2005) as cited in (Muruganandan et al., 2022)).

This includes how well the project activities are coordinated across the different stakeholders, and demands at least alignment on documentation, coordination, and communication (Siriram, 2022). In addition, alignment in terms of the project's perspectives, clear objectives, project scope, cross-functional team involvement, risk measures, and technical specifications and performance are important (Siriram, 2022). In increasingly complex systems and projects, however, this can become challenging due to among others the range of perspectives that can be taken on what constitutes the System of Interest (Potts et al., 2022).

It's becoming essential to determine what constitutes the SoI; whether it is purely the technical system or also includes the socio-technical system that realizes the SoI (Potts et al., 2022). The current reality faced by managers, however, is so complex and subject to change, that it can be challenging to reduce such situations to a form that would make them amenable to (mathematical) modeling to solve social-technical problems (Hossain et al., 2020; Jackson, 2003). Thus, this requires integrating a multitude of perspectives into a coherent, useful, and actionable evaluation (Potts et al., 2022). All of this highlights the importance of communication and systems thinking in increasingly interconnected changes and systems, as underpinned in this dissertation.

7.6.2 Theoretical implications

The findings of this dissertation contribute to the fields of systems integration, risk assessment, inter-organizational project management, and systems thinking in various ways.

The first contribution concerns systems integration and its challenges related to integrating diverse changes into complex sociotechnical systems such as railways. This dissertation posited integration as a means to an end, thereby shifting the focus from integration itself to the steps leading up to it.

This focus aided in identifying the need for various independent actors in the inter-organizational environment to obtain an integral view of the change(s) under consideration, as well as its associated impacts on the environment, in order to facilitate change integration, which pointed to the field of systems thinking. Additionally, as a result of the in-depth analysis of the conducted interviews, several aspects emerged that highlighted why this is not commonly applied in practice.

The second contribution is related to Chapter 3. Existing literature (Mauborgne et al., 2016; Roe & Schulman, 2018) emphasized that the priority placed on applying systems thinking in the form of SDs in risk assessments is not new. Additionally, it was emphasized that although in theory, SDs are essential, in practice they are often skipped in practice. As such, this research explored why organizations tend to deviate from what is generally assumed in the literature, thereby revealing several essential factors inherent to the SD development process, ensuring higher quality SDs that can be more usable and useful.

By combining the identified factors into a generally applicable process, as shown in Figure 7.1, this process was useful beyond risk assessments, and (can be/was) used as a basis to develop artifacts supporting change integration.

The third contribution is related to the field of systems thinking. By obtaining insight into the railway system and its context, inherent characteristics, and envisioned modifications, it became apparent that although systems thinking appears to be the self-evident solution for the identified challenges, its application is not. One possible reason for this is that generally, hard systems approaches such as systems engineering are the guiding principle in the railway context, which makes sense considering its technical origins. However, these approaches are less suitable for addressing the needs of all stakeholders, especially those from non-engineering fields (Madni et al., 2014b). Additionally, the shortcomings of these approaches and assumptions are becoming more obvious as systems become more complex (Jackson, 2003). As such, the research confirmed the existing theory on soft systems thinking (Mingers & Rosenhead, 2004; Mingers & White, 2010), and extends the theory on systems thinking by developing generalizable design principles to deal with the diversity of perspectives present in the analysis of complex situations. Moreover, such approaches stress the importance of organizational and individual learning. This also contributes to sociotechnical systems thinking (Davis et al., 2014).

The fourth contribution is related to Chapter 6, which finds that identifying interfaces in inter-organizational projects is essential to indicate whether and where coordination is needed from actors on either side of the interface(s), in order to facilitate integration. In doing so, the hard systems thinking approach to interface identification was combined with the 'softer' coordination approach, by designing an artifact that utilizes the strengths of both.

7.6.3 Practical implications

In addition to theoretical contributions and implications, this research also aimed to make pragmatic contributions. As such, the research developed practically applicable artifacts, and experience with these revealed that there are also practical implications to consider if these artifacts are to be transferred to other, similar contexts.

The artifacts were developed to deal with the integration of inter-organizational changes in sociotechnical systems which (1) involve multidisciplinary experts with varying perspectives; (2) concern a variety of (non)engineering stakeholders who are required to collaborate for effective change integration; (3) require information that is dispersed across (multiple) departments and organizations; and (4) concern a sociotechnical system change, where multiple domains play a role.

Firstly, hard systems thinking approaches are generally well known within the industry, as they were initially a breakthrough in terms of applying systems thinking to real-world problems (Jackson, 2003) and are rooted in disciplines such as engineering, operations research, and management science. However, soft systems thinking aims to involve multiple stakeholders with diverse perspectives and goals, emphasizing qualitative methods and participatory processes to understand and address complex problems. While soft systems thinking approaches have gained recognition and acceptance in certain domains, such as organizational development, and social sciences, they are not as widely adopted in traditionally engineering-based industries that prioritize quantitative analysis and optimization. Industries with rigid and established processes may be hesitant to adopt 'softer' approaches due to concerns about efficiency, feasibility, and the perceived lack of concrete outcomes.

As such, the aim of the proposed approaches is not to create complete models which include the smallest possible level of detail, but to synchronize expert knowledge, align perspectives, increase awareness of the existence of interfaces among actors, emphasizing whether and where coordination is needed from actors from either side of the interface(s), to facilitate integration.

Secondly, by bringing together experts from different backgrounds and different organizations during the expert session, with a clear, explicit goal and supported by visual aids, the impacts of the change on their respective disciplines and domains can be mapped and discussed. This ensures that diverse insights can be combined into an integral overview, thus facilitating multidisciplinary group communication and sharing of information across organizational boundaries. However, these sessions need to be organized and facilitated appropriately.

Thirdly, in Chapter 4 and Chapter 6, the research was aided by project leaders who provided an initial indication of the BUs impacted by a change under consideration. Based on that initial indication, the specific impacts on those BUs were determined by experts from the identified BUs. This means that the quality of the initial indication is highly dependent on the project leader's experience and knowledge concerning the organization. Moreover, in the case of an inter-organizational project, it should be considered if the project leader can indicate impacted BUs from other organizations to a sufficient extent, or whether a representative from other organizations is necessary to complement this information.

Fourthly, taking a multidomain perspective to organize the identified impacts of a change can highlight existing tendencies toward certain domains. However, organizations should describe carefully how they interpret those domains, as the research illustrated that thinking in terms of sociotechnical domains did not come naturally to all involved practitioners.

Fifthly, in Chapter 3 it was explored why organizations often skip the SD phase or develop it on an ad-hoc basis. It became apparent that in practice, this step is generally carried out because it is mandatory by law, and not necessarily because all practitioners see its added value. By combining the results of this chapter's findings into several essential factors of the SD development process, as shown in Figure 7.1, practitioners can use the process as a guideline in their

SD development, ensuring higher quality SDs that are more usable and useful. However, this might require more resources than are generally spent on the SD development step in practice.

Lastly, after identifying and visualizing the interfaces in the inter-organizational project by use of MDMs in Chapter 6, the project members pointed out the complexity did not decrease, but was made more transparent. As such, the resulting overview from the proposed IM process created awareness of existing interfaces. Subsequently, this could lead to involved actors requiring to consider more interfaces and interdependencies than they initially envisaged, thus requiring more resources. Additionally, appropriate attention should be paid to the input and output relationships in the proposed interface management matrix. If these are mixed up during the process, interfaces can be incorrectly mapped, resulting in less reliable matrices; having a workshop facilitator is highly recommended.

7.6.4 General implications

Based on this research, some more general implications have emerged:

Integrating inter-organizational changes in the working railway system does not happen automatically. It requires understanding and carrying out the activities and processes in a coherent manner to realize the objectives. However, because of the railway system's inter-organizational and sociotechnical nature, and lack of a designated system-level change integrator, more focused integration efforts are required.

The principles described in this dissertation can help to assess the systemic implications and consequences of diverse changes under consideration that may arise across the railway system. This involves considering the ripple effects that can occur as a result of changes in one organization affecting others. By anticipating and addressing potential impacts early on, the integration of changes can be more effectively managed.

By understanding how changes in one organization can impact others, it can aid to plan and coordinate change efforts. By applying systems thinking principles, actors are forced out of their functional silos, and the integration of changes among the various organizations can be enhanced. This involves mapping out the impacts of a change, flows of information, and interfaces across organizations.

Due to the complexity of the system and the lack of a central integrator, integration efforts could be dealt with in a decentral way, by for example deploying the developed artifacts on inter-organizational project level. In this way, the inter-organizational and multidisciplinary actors can converge. By recognizing the interdependencies among them, organizations can work together to share information, coordinate efforts, and align their activities.

Regular communication channels, such as working groups, or joint meetings, can be established to promote collaboration and communication among the organizations involved.

‘Working on integration together’ might require an initial investment in time and resources, however, the sooner systems thinking is applied and the integration context is considered, the more coherence arises, and possible modifications can be accounted for and incorporated more easily and at a lower cost.

7.7 Suggestions for future research

Based on the findings presented in this dissertation, several opportunities for future research have presented themselves. These include:

- Investigating how the proposed artifacts could be adapted and applied to different sociotechnical contexts, such as energy systems. Understanding the specific challenges and dynamics of each context can help tailor the artifacts to facilitate effective change integration.
- Exploring the possible integration of soft systems thinking methods with more traditional approaches in order to address the challenges discussed in this dissertation.
- Developing frameworks and metrics to assess the outcomes and impact of applying systems thinking tools to facilitate change integration. This could involve both qualitative and quantitative approaches to measure the effectiveness, efficiency, and sustainability of changes implemented within sociotechnical systems.
- Examining strategies for knowledge transfer and learning from successful applications of systems thinking to facilitate change integration. This can involve developing best practices, guidelines, and case studies to support practitioners, policymakers, and researchers in applying systems thinking principles effectively in different sociotechnical contexts.
- Examining fitting strategies for enhancing stakeholder engagement and coordination on the interfaces which are identified by using the proposed IM process. This can, for example, include planning and control, or relationship-building, as discussed by Jakubeit (2023).

References

Abbas, Y., Martinetti, A., Houghton, R., & Majumdar, A. (2022). Disentangling Large Scale Technological Projects: Learning from ERTMS Roll-Out Case study in the Netherlands. *Research in Transportation Business and Management*, *45*. https://doi.org/10.1016/j.rtbm.2022.100856

Abbas, Y., Martinetti, A., Rajabalinejad, M., Frunt, L., & van Dongen, L. A. M. (2020). *Tacit Knowledge Sharing for System Integration* (pp. 70–83). https://doi.org/10.4018/978-1-7998-3904-0.ch004

Ahmed, R., Shaheen, S., & Philbin, S. P. (2022). The Role of Big Data Analytics and Decision-Making in Achieving Project Success. *Journal of Engineering and Technology Management*, *65*, 101697. https://doi.org/10.1016/j.jengtecman.2022.101697

Ahn, S., Shokri, S., Lee, S., Haas, C. T., & Haas, R. C. G. (2017). Exploratory Study on the Effectiveness of Interface-Management Practices in Dealing with Project Complexity in Large-Scale Engineering and Construction Projects. *Journal of Management in Engineering*, *33*(2). https://doi.org/10.1061/(ASCE)ME.1943-5479.0000488

Alexander, K., William N., S., Samuel J., S., & Steven M., B. (2011). Systems Engineering Principles and Practices. In *Systems Engineering* (second). Wiley. https://doi.org/10.1002/9780470518762.ch17

Alin, P., Maunula, A., Taylor, J., & Smeds, R. (2013). Aligning Misaligned Systemic Innovations: Probing Inter-Firm Effects Development in Project Networks. *Project Management*, *44*, 77–93. https://doi.org/10.1002/pmj

Archibald, M. M. (2016). Investigator Triangulation: A Collaborative Strategy With Potential for Mixed Methods Research. *Journal of Mixed Methods Research*, *10*(3), 228–250. https://doi.org/10.1177/1558689815570092

Argyroudis, S. A., Mitoulis, S. A., Hofer, L., Zanini, M. A., Tubaldi, E., & Frangopol, D. M. (2020). Resilience Assessment Framework for Critical Infrastructure in a Multi-Hazard Environment: Case Study on Transport Assets. *Science of The Total Environment*, *714*. https://doi.org/10.1016/j.scitotenv.2020.136854

Arnold, R. D., & Wade, J. P. (2015). A Definition of Systems Thinking: A Systems Approach. *Procedia Computer Science*, *44*, 669–678. https://doi.org/10.1016/j.procs.2015.03.050

Association of European Railway Industries. (2010). InteGRrail-Intelligent Integration of Railway Systems. In *InteGRail Consortium*.

Atkinson, R. (1999). Project Management: Cost, Time and Quality, Two Best Guesses and a Phenomenon, Its Time to Accept Other Success Criteria. *International Journal of Project Management*, *17*(6), 337–342. https://doi.org/10.1016/S0263-7863(98)00069-6

Baccarini, D. (1996). The Concept of Project Complexity - A Review. *International Journal of Project Management*, *14*(4), 201–204. https://doi.org/10.1016/0263-7863(95)00093-3

Barnatt, N., & Jack, A. (2018). Safety Analysis in a Modern Railway Setting. *Safety Science*, *110*(August), 177–182. https://doi.org/10.1016/j.ssci.2018.08.005

Bartolomei, J. E., Hastings, D. E., de Neufville, R., & Rhodes, D. H. (2012). Engineering Systems Multiple-Domain Matrix: An Organizing Framework for Modeling Large-Scale Complex Systems. *Systems Engineering*, *15*(1), 41–61. https://doi.org/10.1002/sys.20193

BBC News. (2014, May 21). *French Red Faces Over Trains That Are "Too Wide."* https://www.bbc.com/news/world-europe-27497727

Bearfield, G., & McDonald, R. (2013). Use of a Generic Hazard List to Support the Development of Re-Usable Safety Arguments in the Rail Industry. *Safety and Reliability*, *33*(3), 18–28. https://doi.org/10.1080/09617353.2013.11690973

Blanchard, B., & Fabrycky, W. (1998). Systems Engineering and Analysis. In *Boston* (Vol. 4). Prentice hall.

Boardman, J., & Sauser, B. (2008). *Systems Thinking: Coping With 21st Century Problems*. CRC Press.

Bocong, L. (2015). Engineering Action in Micro-, Meso-, and Macro-contexts. In S. H. Christensen, C. Didier, A. Jamison, M. Meganck, C. Mitcham, & B. Newberry (Eds.), *Engineering Identities, Epistemologies and Values: Engineering Education and Practice in Context*. Springer International Publishing. https://doi.org/10.1007/978-3-319-16172-3

Bollinger, L. A., Bogmans, C. W. J., Chappin, E. J. L., Dijkema, G. P. J., Huibregtse, J. N., Maas, N., Schenk, T., Snelder, M., van Thienen, P., de Wit, S., Wols, B., & Tavasszy, L. A. (2014). Climate Adaptation of Interconnected Infrastructures: A Framework for Supporting Governance. *Regional Environmental Change*, *14*(3), 919–931. https://doi.org/10.1007/s10113-013-0428-4

Borches, P. D. (2010). *A3 Architecture Overviews: A Tool for Effective Communication in Product Evolution*. University of Twente.

Botchkarev, A., & Finnigan, P. (2015). Complexity in the Context of Information Systems Project Management. *Organisational Project Management*, *2*(1), 15. https://doi.org/10.5130/opm.v2i1.4272

Braaksma, J. (2012). *Asset Information for FMEA-Based Maintenance*. University of Groningen.

Braband, J., & Siems AG Transportation Systems. (2002). Risk Assessment in Railroad Signaling: Experience Gained and Lessons Learned. *Proceedings of* *the Annual Reliability and Maintainability Symposium*, 147–152. https://doi.org/10.1109/rams.2002.981633

Braun, T. (2018). Configurations for Interorganizational Project Networks: The Interplay of the PMO and Network Administrative Organization. *Project Management Journal*, *49*(4), 53–61. https://doi.org/10.1177/8756972818781710

Breque, M., De Nul, L., & Petridis, A. (2021). Industry 5.0: Towards a Sustainable, Human-Centric and Resilient European Industry. *Luxembourg, LU: European Commission, Directorate-General for Research and Innovation*.

Browning, T. R. (2001). Applying the Design Structure Matrix to System Decomposition and Integration Problems: A Review and New Directions. *IEEE Transactions on Engineering Management*, *48*(3), 292–306. https://doi.org/10.1109/17.946528

Browning, T. R. (2002). Process Integration Using the Design Structure Matrix. *Systems Engineering*, *5*(3), 180–193. https://doi.org/10.1002/sys.10023

Browning, T. R. (2009). The Many Views of a Process: Toward a Process Architecture Framework for Product Development Processes. *Systems Engineering*, *12*(1), 69–90. https://doi.org/10.1002/SYS.20109

Browning, T. R. (2010). On the Alignment of the Purposes and Views of Process Models in Project Management. *Journal of Operations Management*, *28*(4), 316–332. https://doi.org/10.1016/j.jom.2009.11.007

Browning, T. R. (2016). Design Structure Matrix Extensions and Innovations: A Survey and New Opportunities. *IEEE Transactions on Engineering Management*, *63*(1), 27–52. https://doi.org/10.1109/TEM.2015.2491283

Bugalia, N., Maemura, Y., & Ozawa, K. (2021). Characteristics of Enhanced Safety Coordination Between High-Speed Rail Operators and Manufacturers. *Reliability Engineering and System Safety*, *216*. https://doi.org/10.1016/j.ress.2021.107995

Campbell, R., Goodman-Williams, R., Feeney, H., & Fehler-Cabral, G. (2020). Assessing Triangulation Across Methodologies, Methods, and Stakeholder Groups: The Joys, Woes, and Politics of Interpreting Convergent and Divergent Data. *American Journal of Evaluation*, *41*(1), 125–144. https://doi.org/10.1177/1098214018804195

CELENEC. (2017). *NEN-EN 50126-2 Railway Applications - The Specification and Demonstration of Reliability, Availability, Maintainability and Safety (RAMS) - Part 2: Systems approach to Safety* (Vol. 2).

CENELEC. (2015). *NEN-EN 50126-1 Railway Applications - The Specification and Demonstration of Reliability, Availability, Maintainability and Safety (RAMS) - Part 1: Generic RAMS Process. 1.*

Chen, Q., Reichard, G., & Beliveau, Y. (2008). Multiperspective Approach to Exploring Comprehensive Cause Factors for Interface Issues. *Journal of Construction Engineering and Management*, *134*(6), 432–441. https://doi.org/10.1061/(ASCE)0733-9364(2008)134:6(432)

Chen, Q., Reichard, G., & Beliveau, Y. (2010). Object Model Framework for Interface Modeling and IT-Oriented Interface Management. *Journal of Construction Engineering and Management*, *136*(2), 187–198. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000120

Clemson, B. A., & Lowe, E. (1993). Which Way to Rome?: Choosing a Path for Change. *EMJ - Engineering Management Journal*, *5*(4), 26–40. https://doi.org/10.1080/10429247.1993.11414754

Coyote, B. L., & Thompson, J. D. (1967). *Organizations in Action: Social Science Bases of Administrative Theory* (Vol. 10). McGraw-Hill College.

Cropper, S., Ebers, M., Huxham, C., & Ring, P. S. (2008). *The Oxford Handbook of Inter-Organizational Relations*. Oxford Handbooks.

Cumming, G. S., & Collier, J. (2005). Change and Identity in Complex Systems. *Ecology & Society*, *10*(1). http://www.jstor.org/stable/26267756

Danilovic, M., & Browning, T. R. (2007). Managing Complex Product Development Projects With Design Structure Matrices and Domain Mapping Matrices. *International Journal of Project Management*, *25*(3), 300–314. https://doi.org/10.1016/j.ijproman.2006.11.003

Dao, B., Kermanshachi, S., Shane, J., Anderson, S., & Hare, E. (2017). Exploring and Assessing Project Complexity. *Journal of Construction Engineering and Management*, *143*(5), 04016126. https://doi.org/10.1061/(asce)co.1943-7862.0001275

Daouk, M., & Leveson, N. G. (2003). Towards Safe Change in Transportation Systems. *IFAC Proceedings Volumes*, *36*(14), 167–172. https://doi.org/10.1016/S1474-6670(17)32414-X

Dasher, G. T. (2003). The Interface Between Systems Engineering and Program Management. *EMJ - Engineering Management Journal*, *15*(3), 11–14. https://doi.org/10.1080/10429247.2003.11415210

Davies, A., & Mackenzie, I. (2014). Project Complexity and Systems Integration: Constructing the London 2012 Olympics and Paralympics Games. *International Journal of Project Management*, *32*(5), 773–790. https://doi.org/10.1016/j.ijproman.2013.10.004

Davis, M. C., Challenger, R., Jayewardene, D. N. W., & Clegg, C. W. (2014). Advancing Socio-Technical Systems Thinking: A Call for Bravery. *Applied Ergonomics*, *45*(2 Part A), 171–180. https://doi.org/10.1016/j.apergo.2013.02.009

De Leeuw, A. C. J. (2002). Bedrijfskundig Management. In *Primair proces, strategie en organisatie. Assen, Koninklijke Van Gorcum* (2nd ed.). Koninklijke Van Gorcum BV.

Dépoues, V. (2017). Organisational Uptake of Scientific Information About Climate Change by Infrastructure Managers: The Case of Adaptation of the French Railway Company. *Climatic Change*, *143*(3–4), 473–486. https://doi.org/10.1007/s10584-017-2016-y

Dumolo, R. N. (2007). Application of Systems Engineering to Railway Projects. *International Journal of Performability Engineering*, *3*(1), 25–34. https://doi.org/10.23940/ijpe.07.1.p25.mag

Edkins, A., Geraldi, J., Morris, P., & Smith, A. (2013). Exploring the Front-End of Project Management. *Engineering Project Organization Journal*, *3*(2), 71–85. https://doi.org/10.1080/21573727.2013.775942

Euronews. (2023). *"Unspeakable Botch": Spain Spends €258 Million on Trains That Are Too Big for Its Tunnels*. https://www.euronews.com/travel/2023/02/10/unspeakable-botch-spain-spends-258-million-on-trains-that-are-too-big-for-its-tunnels

European Committee for Electrotechnical Standardization. (2015). *NEN-EN 50126-1* (Vol. 1).

European Railway Agency. (2009a). *Collection of Examples of Risk Assessments and of Some Possible Tools Supporting the CSM Regulation*.

European Railway Agency. (2009b). *Guide for the Application of the Commission Regulation on the Adoption of a Common Safety Method on Risk Evaluation and Assessment as Referred to in Article 6(3)(a) Of the Railway Safety Directive*.

European Union Agency for Railways. (2020). *Clarification Note on Safe Integration*. https://www.era.europa.eu/sites/default/files/applicants/docs/era_1209-063_clarification_note_on_safe_integration_en.pdf

Fageha, M. K., & Aibinu, A. A. (2013). Managing Project Scope Definition to Improve Stakeholders' Participation and Enhance Project Outcome. *Procedia - Social and Behavioral Sciences*, *74*, 154–164. https://doi.org/10.1016/j.sbspro.2013.03.038

Fageha, M. K., & Aibinu, A. A. (2014). Prioritising Project Scope Definition Elements in Public Building Projects. *Australasian Journal of Construction Economics and Building*, *14*(3), 18–33. https://doi.org/10.5130/ajceb.v14i3.4155

Foster-Fishman, P. G., Salem, D. A., Allen, N. A., & Fahrbach, K. (2001). Facilitating Interorganizational Collaboration: The Contributions of Interorganizational

Alliances. *American Journal of Community Psychology*, *29*(6), 875–905. https://doi.org/10.1023/A:1012915631956

Geels, F. W. (2002). Technological Transitions as Evolutionary Reconfiguration Processes: A Multi-Level Perspective and a Case-Study. *Research Policy*, *31*(8–9), 1257–1274. https://doi.org/10.1016/S0048-7333(02)00062-8

Geyer, A., & Davies, A. (2000). Managing Project–System Interfaces: Case Studies of Railway Projects in Restructured UK and German Markets. *Research Policy*, *29*(7–8), 991–1013. https://doi.org/10.1016/S0048-7333(00)00116-5

Girgin, S., & Krausmann, E. (2013). RAPID-N: Rapid Natech Risk Assessment and Mapping Framework. *Journal of Loss Prevention in the Process Industries*, *26*(6), 949–960. https://doi.org/10.1016/j.jlp.2013.10.004

Gregor, S., & Hevner, A. R. (2013). Positioning and Presenting Design Science Research for Maximum Impact. *Source: MIS Quarterly*, *37*(2), 337–355. https://www.jstor.org/stable/43825912

Guerrieri, M. (2022). Hyperloop, Helirail, Transrapid and High-Speed Rail Systems. Technical Characteristics and Cost-Benefit Analyses. *Research in Transportation Business and Management*, *43*. https://doi.org/10.1016/j.rtbm.2022.100824

Guerriero, F., Rocchi, S., Iazzolino, G., & Manfredi, W. (2022). An Empirical Assessment of Pricing Efficiency Across the European Rail Market. *Research in Transportation Business and Management*, *43*. https://doi.org/10.1016/j.rtbm.2022.100782

Guillerm, R., Demmou, H., & Sadou, N. (2012). Safety Evaluation and Management of Complex Systems: A System Engineering Approach. *Concurrent Engineering: Research and Applications*, *20–2*. https://doi.org/10.1177/1063293X12446665

Haanstra, W. (2021). *Life Cycle Valuation* [University of Twente]. https://doi.org/10.3990/1.9789036551847

Haanstra, W., Braaksma, A. J. J., & van Dongen, L. A. M. (2021). Designing a Hybrid Methodology for the Life Cycle Valuation of Capital Goods. *CIRP Journal of Manufacturing Science and Technology*, *32*, 382–395. https://doi.org/10.1016/j.cirpj.2021.01.017

Hackl, J., Adey, B. T., Heitzler, M., & Iosifescu-Enescu, I. (2017). An Overarching Risk Assessment Process to Evaluate the Risks Associated With Infrastructure Networks Due to Natural Hazards. *International Journal of Performability Engineering*, *11*(2), 153–168. https://hal.science/hal-01575239

Hagan, G., Bower, D., & Smith, N. (2011). Managing Complex Projects in Multi-Project Environments. *Association of Researchers in Construction*

Management, ARCOM 2011 - Proceedings of the 27th Annual Conference, *2*(September), 787–796.

Haji-Kazemi, S., Andersen, B., & Petter Krane, H. (2013). A Review on Possible Approaches for Detecting Early Warning Signs in Projects. *Project Management Journal*, *44*, 55–69. https://doi.org/10.1002/pmj

Harvey, C., & Stanton, N. A. (2014). Safety in System-Of-Systems: Ten Key Challenges. *Safety Science*, *70*, 358–366. https://doi.org/10.1016/j.ssci.2014.07.009

Haskins, B., & Striegel, J. (2006). Integration Challenges of Complex Systems. *16th Annual International Symposium of the International Council on Systems Engineering, INCOSE 2006*, *2*, 1531–1545. https://doi.org/10.1002/j.2334-5837.2006.tb02831.x

Haskins, C., & Ruud, K. S. (2017). Systems Engineering: Making People Talk! In *Disciplinary Convergence in Systems Engineering Research* (pp. 1081–1093). Springer International Publishing. https://doi.org/10.1007/978-3-319-62217-0_75

Hass, K. B. (2008). *Managing Complex Projects: A New Model*. Berrett-Koehler Publishers.

Hatfield, A. J., & Hipel, K. W. (2002). Risk and Systems Theory. *Risk Analysis*, *22*(6), 1043–1057. https://doi.org/10.1111/1539-6924.00272

Haveman, S. (2014). *COMBOS: Communicating Behavior of Systems. Incorporating Simulations in Conceptual System Design* [University of Twente]. https://ris.utwente.nl/ws/portalfiles/portal/6051543/thesis_S_Haveman.pdf

Healey, P. (1997). *Project Management: Getting the Job Done on Time and in Budget*. Routeledge.

Hendrick, H. W. (1997). Organizational Design and Macroergonomics. *Handbook of Human Factors and Ergonomics*, *2*, 594–627.

Hermann, M., Pentek, T., & Otto, B. (2016a). Design Principles for Industry 4.0 Scenarios. *Proceedings of the Annual Hawaii International Conference on System Sciences*, *2016-March*, 3928–3937. https://doi.org/10.1109/HICSS.2016.488

Hermann, M., Pentek, T., & Otto, B. (2016b). Design Principles for Industry 4.0 Scenarios. *Proceedings of the Annual Hawaii International Conference on System Sciences*, *2016-March*, 3928–3937. https://doi.org/10.1109/HICSS.2016.488

Hevner, A., & Chatterjee, S. (2010). Design Science Research in Information Systems. In *Design Research in Information Systems* (pp. 9–22). Springer. https://doi.org/10.1007/978-1-4419-5653-8_2

Hevner, A., Park, J., & March, S. (2004). Design Science in Information Systems Research. *Management Information Systems Quarterly*, *28*(1), 6. https://www.researchgate.net/publication/201168946

Hitchins, D. K. (2005). Systems Methodology. *CSER Conference*. http://www.hitchins.net/SysMethodology.html

Hitchins, D. K. (2007). *Systems Engineering: A 21st Century Systems Methodology*. John Wiley & Sons, Ltd. https://doi.org/10.1002/9780470518762

Hobday, M., Davies, A., & Prencipe, A. (2005). Systems Integration: A Core Capability of the Modern Corporation. *Industrial and Corporate Change*, *14*(6), 1109–1143. https://doi.org/10.1093/icc/dth080

Høj, N. P., & Kröger, W. (2002). Risk Analyses of Transportation on Road and Railway From a European Perspective. *Safety Science*, *40*(1–4), 337–357. https://doi.org/10.1016/S0925-7535(01)00053-4

Hossain, N. U. I., Dayarathna, V. L., Nagahi, M., & Jaradat, R. (2020). Systems Thinking: A Review and Bibliometric Analysis. *Systems*, *8*(3), 23. https://doi.org/10.3390/systems8030023

Huisman, D., Kroon, L. G., Lentink, R. M., Vromans, M. J. C. M., Huisman, D., Kroon, L. G., Lentink, R. M., & Vromans, M. J. C. M. (2005). Operations Research in Passenger Railway Transportation. *Statistica Neerlandica*, *59*(4), 467–497. https://doi.org/10.1111/j.1467-9574.2005.00303.x

International Council on Systems Engineering. (2015). *Systems Engineering Handbook- A Guide for System Life Cycle Processes and Activities* (E. David D. Walden, E. Garry J. Roedler, E. Kevin J. Forsberg, R. Douglas Hamelin, & C. Thomas M. Shortell, Eds.). John Wiley & Sons, Inc. All.

International Standardization Organization. (2015). *NEN-ISO/IEC/IEEE 15288 Systems and Software Engineering - System Life Cycle Processes* (Issue 1st). Nederlands Normalisatie-instituut.

Jackson, M. C. (1991). The Origins and Nature of Critical Systems Thinking. In *Systems practice* (Vol. 4). Wiley.

Jackson, M. C. (2003). *Systems Thinking: Creative Holism for Managers*. John Wiley & Sons Ltd.

Jakubeit, N. (2023). *Coordinated Interorganizational Decision-Making: Dealing With Project Complexity in the Dutch Railway Context*. University of Twente.

Jones, C., & Lichtenstein, B. (2008). Types of Inter-Organizational Projects: Managing Uncertainty Through Temporal and Social Embeddedness. In *The Oxford handbook of inter-organizational relations* (Issue January, pp. 231–255). Oxford. https://www.researchgate.net/publication/233857227

Junior, C., & Da, J. (2020). *A Systems Design Approach to Sustainable Development: Embracing the Complexity of Energy Challenges in Low-income Markets*. https://doi.org/https://doi.org/10.4233/uuid:8bbf71f1-48bd-4844-84f5-fe8c7ca5398c

Keating, C. B., Padilla, J. J., & Adams, K. (2008). System of Systems Engineering Requirements: Challenges and Guidelines. *EMJ - Engineering Management Journal*, *20*(4), 24–31. https://doi.org/10.1080/10429247.2008.11431785

Kiridena, S., & Sense, A. (2017). Profiling Project Complexity: Insights from Complexity Science and Project Management Literature. *Project Management Journal*, *47*(6), 56–74.

Klüppelberg, C., Straub, D., & Welpe, I. (2014). *Risk - A Multidisciplinary Introduction*. Springer International Publishing. https://doi.org/10.1007/978-3-319-04486-6

Krane, H. P., Olsson, N. O. E., & Rolstadås, A. (2012). How Project Manager–Project Owner Interaction Can Work within and Influence Project Risk Management. *Project Management Journal*, *43*(2), 54–67. https://doi.org/10.1002/pmj.20284

Kroes, P., Franssen, M., Van De Poel, I., & Ottens, M. (2006). Treating Socio-Technical Systems as Engineering Systems: Some Conceptual Problems. *Systems Research and Behavioral Science*, *23*(6), 803–814. https://doi.org/10.1002/sres.703

Lagay, R., & Adell, G. M. (2018). The Autonomous Train: A Game Changer for the Railways Industry. *2018 16th International Conference on Intelligent Transportation Systems Telecommunications (ITST)*, 1–5.

Leijten, M., & Koppenjan, J. F. M. (2010). Asset Management for the Dutch Railway Infrastructure. *International Conference on Next Generation Infrastructure Systems for Eco-Cities*, *November*. https://doi.org/10.1109/INFRA.2010.5679222

Linderman, K., Schroeder, R. G., Zaheer, S., Liedtke, C., & Choo, A. S. (2004). Integrating Quality Management Practices With Knowledge Creation Processes. *Journal of Operations Management*, *22*(6), 589–607. https://doi.org/10.1016/j.jom.2004.07.001

Lindgren, J., Jonsson, D. K., & Carlsson-Kanyama, A. (2009). Climate Adaptation of Railways: Lessons from Sweden. *European Journal of Transport and Infrastructure Research*, *9*(2), 164–181. https://doi.org/10.18757/ejtir.2009.9.2.3295

Little, J. D. C. (1970). Models and Managers: The Concept of a Decision Calculus. *Management Science*, *16*(8), B-466.

Liu, C., Yang, S., Cui, Y., & Yang, Y. (2020). An Improved Risk Assessment Method Based on a Comprehensive Weighting Algorithm in Railway Signaling Safety Analysis. *Safety Science*, *128*. https://doi.org/10.1016/j.ssci.2020.104768

Long, S., & Spurlock, D. G. (2008). Motivation and Stakeholder Acceptance in Technology-Driven Change Management: Implications for the Engineering Manager. *EMJ - Engineering Management Journal*, *20*(2), 30–36. https://doi.org/10.1080/10429247.2008.11431764

Lustenbergerent, F. (2012). Types of Organizational Interfaces. *IEEE Engineering Management Review*, *40*(3), 9–10. https://doi.org/10.1109/EMR.2012.2206960

Luther, B., Gunawan, I., & Nguyen, N. (2023). Identifying Effective Risk Management Frameworks for Complex Socio-Technical Systems. *Safety Science*, *158*. https://doi.org/10.1016/j.ssci.2022.105989

Madni, A. M. (2007). Transdisciplinarity: Reaching Beyond Disciplines to Find Connections. *Journal of Integrated Design & Process Science*, *11*(1), 1–11.

Madni, A. M., Nance, M., Richey, M., Hubbard, W., & Hanneman, L. (2014). Toward an Experiential Design Language: Augmenting Model-Based Systems Engineering With Technical Storytelling in Virtual Worlds. *Procedia Computer Science*, *28*, 848–856. https://doi.org/10.1016/j.procs.2014.03.101

Madni, A. M., & Sievers, M. (2010). Systems Integration: Key Perspectives, Experiences, and Challenges. *Systems Engineering*, *14*(3), 305–326. https://doi.org/10.1002/sys

Madni, A. M., & Sievers, M. (2014). System of Systems Integration: Key Considerations and Challenges. *Systems Engineering*, *17*(3), 330–347. https://doi.org/10.1002/sys.21272

Maier, M., & Rechtin, E. (2000). Architecture Frameworks. *The Art of Systems Architecting, 2nd Ed. CRC Press, Florida*, 229–250.

Mateu, J. M., Martínez Fernández, P., & Insa Franco, R. (2021). Setting Safety Foundations in the Hyperloop: A First Approach to Preliminary Hazard Analysis and Safety Assurance System. *Safety Science*, *142*. https://doi.org/10.1016/j.ssci.2021.105366

Mauborgne, P., Deniaud, S., Levrat, E., Bonjour, E., Micaëlli, J.-P., & Loise, D. (2016). *Operational and System Hazard Analysis in a Safe Systems Requirement Engineering Process-Application to Automotive Industry*. https://doi.org/10.1016/j.ssci.2016.04.011

Maylor, H., Meredith, J. R., Söderlund, J., & Browning, T. (2018). Old Theories, New Contexts: Extending Operations Management Theories to Projects. In *International Journal of Operations and Production Management* (Vol. 38, Issue 6, pp. 1274–1288). Emerald Group Holdings Ltd. https://doi.org/10.1108/IJOPM-06-2018-781

Maylor, H., & Turner, N. (2017). Understand, Reduce, Respond: Project Complexity Management Theory and Practice. *International Journal of Operations and Production Management*, *37*(8), 1076–1093. https://doi.org/10.1108/IJOPM-05-2016-0263

Merkus, S., Willems, T., Schipper, D., Van Marrewijk, A., Koppenjan, J., Veenswijk, M., & Bakker, H. (2017). A Storm Is Coming? Collective Sensemaking and Ambiguity in an Inter-organizational Team Managing Railway System Disruptions. *Journal of Change Management*, *17*(3), 228–248. https://doi.org/10.1080/14697017.2016.1219380

Milch, V., & Laumann, K. (2016). Interorganizational Complexity and Organizational Accident Risk: A Literature Review. *Safety Science*, *82*, 9–17. https://doi.org/10.1016/j.ssci.2015.08.010

Mingers, J., & Rosenhead, J. (2004). Problem Structuring Methods in Action. *European Journal of Operational Research*, *152*(3), 530–554. https://doi.org/10.1016/S0377-2217(03)00056-0

Mingers, J., & White, L. (2010). A Review of the Recent Contribution of Systems Thinking to Operational Research and Management Science. *European Journal of Operational Research*, *207*(3), 1147–1161. https://doi.org/10.1016/j.ejor.2009.12.019

Mirza, M. N., Pourzolfaghar, Z., & Shahnazari, M. (2013). Significance of Scope in Project Success. *Procedia Technology*, *9*, 722–729. https://doi.org/10.1016/j.protcy.2013.12.080

Morris, P. W. G. (2008). Managing Project Interfaces—Key Points for Project Success. *Project Management Handbook*, 16–55. https://doi.org/10.1002/9780470172353.ch2

Moser, S. C., & Ekstrom, J. A. (2010). A Framework to Diagnose Barriers to Climate Change Adaptation. *Proceedings of the National Academy of Sciences*, *107*(51), 22026–22031. https://doi.org/10.1073/pnas.1007887107

Mostashari, A., & Sussman, J. M. (2009). A Framework for Analysis, Design and Management of Complex Large-Scale Interconnected Open Sociotechnological Systems. *International Journal of Decision Support System Technology*, *1*(2), 53–68. https://doi.org/10.4018/jdsst.2009040104

Muller, G. (2007). Coping With System Integration Challenges in Large Complex Environments. *17th Annual International Symposium of the International Council on Systems Engineering, INCOSE 2007 - Systems Engineering: Key to Intelligent Enterprises*, *2*, 1373–1387. https://doi.org/10.1002/j.2334-5837.2007.tb02930.x

Muruganandan, K., Davies, A., Denicol, J., & Whyte, J. (2022). The Dynamics of Systems Integration: Balancing Stability and Change on London's Crossrail Project. *International Journal of Project Management*, *40*(6), 608–623. https://doi.org/10.1016/j.ijproman.2022.03.007

Nakamura, E., & Sakai, H. (2022). Control and Coordination in Railway Business: Implications for Intermediate Organisational Forms Between Vertical Separation and Integration. *Research in Transportation Business & Management*, *45*, 100905. https://doi.org/10.1016/j.rtbm.2022.100905

NASA. (2007). *NASA Systems Engineering Handbook*. Diane Publishing. www.sti.nasa.gov

Nogal, M., O'Connor, A., Caulfield, B., & Brazil, W. (2016). A Multidisciplinary Approach for Risk Analysis of Infrastructure Networks in Response to Extreme Weather. *Transportation Research Procedia*, *14*, 78–85. https://doi.org/10.1016/j.trpro.2016.05.043

Noor, K. B. M. (2008). Case Study: A Strategic Research Methodology. *American Journal of Applied Sciences*, *5*(11), 1602–1604. https://doi.org/10.3844/ajassp.2008.1602.1604

Oliveira, N., & Lumineau, F. (2017). How Coordination Trajectories Influence the Performance of Interorganizational Project Networks. *Organization Science*, *28*(6), 1029–1060. https://doi.org/10.1287/orsc.2017.1151

Ouyang, M., & Wang, Z. (2015). Resilience Assessment of Interdependent Infrastructure Systems: With a Focus on Joint Restoration Modeling and Analysis. *Reliability Engineering & System Safety*, *141*, 74–82. https://doi.org/10.1016/j.ress.2015.03.011

Parraguez, P., Eppinger, S., & Maier, A. (2016). Characterizing Design Process Interfaces as Organization Networks: Insights for Engineering Systems Management. *Systems Engineering*, *19*(2), 158–173. https://doi.org/10.1002/sys.21345

Pasquini, A., Pozzi, S., & Save, L. (2011). A Critical View of Severity Classification in Risk Assessment Methods. *Reliability Engineering & System Safety*, *96*(1), 53–63. https://doi.org/10.1016/j.ress.2010.06.029

Pavitt, T. C., & Gibb, A. G. F. (2003). Interface Management within Construction: In Particular, Building Facade. *Journal of Construction Engineering and Management*, *129*(1), 8–15. https://doi.org/10.1061/(ASCE)0733-9364(2003)129:1(8)

Peffers, K., Tuunanen, T., Rothenberger, M. A., & Chatterjee, S. (2007). A Design Science Research Methodology for Information Systems Research. *Journal of Management Information Systems*, *24*(3), 45–77. https://doi.org/10.2753/MIS0742-1222240302

Perrow, C. (1999). *Normal Accidents: Living With High Risk Technologies*. Princeton university press.

Pezzillo Iacono, M., Martinez, M., Mangia, G., & Galdiero, C. (2012). Knowledge Creation and Inter-Organizational Relationships: The Development of Innovation in the Railway Industry. *Journal of Knowledge Management*, *16*(4), 604–616. https://doi.org/10.1108/13673271211246176

Pilbeam, C., Denyer, D., & Doherty, N. (2020). Safety Risk Factors in Two Different Types of Routine Outsourced Work: a Systematic Literature Review. *Policy and Practice in Health and Safety*, *18*(2), 140–154.

Pinto, J. K., & Prescott, J. E. (1988). Variations in Critical Success Factors Over the Stages in the Project Life Cycle. *Journal of Management*, *14*(1), 5–18.

Potts, M., Harvey, D., Johnson, A., & Bullock, S. (2022). The Complexity Register: A Collaborative Tool for System Complexity Evaluation. *Engineering Management Journal*, *34*(1), 157–173. https://doi.org/10.1080/10429247.2020.1858643

Preston, B. L., Westaway, R. M., & Yuen, E. J. (2011). Climate Adaptation Planning in Practice: An Evaluation of Adaptation Plans From Three Developed Nations. *Mitigation and Adaptation Strategies for Global Change*, *16*(4), 407–438. https://doi.org/10.1007/s11027-010-9270-x

Pritesh, S., & Konnur, B. A. (2019). Interface Management and its Effect on Project Complexity in Construction Management. *International Research Journal of Engineering and Technology*, *6*(5), 2415–2419.

Proehl, R. A. (1996). Enhancing the Effectiveness of Cross-Functional Teams. *Leadership & Organization Development Journal*, *17*(5), 3–10. https://doi.org/10.1108/01437739610127450

Quinn, A. D., Ferranti, E. J. S., Hodgkinson, S. P., Jack, A. C. R., Beckford, J., & Dora, J. M. (2018). Adaptation Becoming Business as Usual: A Framework for Climate-Change-Ready Transport Infrastructure. *MDPI Infrastructures*, *3*(2). https://doi.org/10.3390/infrastructures3020010

Qureshi, Z. H., Ashraf, M. A., & Amer, Y. (2007). Modeling Industrial Safety: A Sociotechnical Systems Perspective. *IEEM 2007: 2007 IEEE International Conference on Industrial Engineering and Engineering Management*, 1883–1887. https://doi.org/10.1109/IEEM.2007.4419519

Rail Safety & Standards Board. (2014). *GEGN8641: Guidance on System Definition*. RSSB Rail Safety and Standards Board Limited.

Rail Safety & Standards Board. (2017). GEGN8646: Guidance on the Common Safety Method for Risk Evaluation and Assessment. In *GEGN8646*.

Railtech. (2020a). *European Railways Highlight Key Priorities for Sustainable and Smart Mobility*. https://www.railtech.com/policy/2020/06/30/european-railways-highlight-key-priorities-for-sustainable-and-smart-mobility/

Railtech. (2020b, July 13). *Four Key Goals for Railway Based Mobility in Europe*. https://www.railtech.com/policy/2020/07/13/four-key-goals-for-railway-based-mobility-in-europe/?gdpr=accept

Railway supply. (2023, February 8). *The Train Is Too Big for the Tunnels*. Railway Supply - Industry Publication for Railway Transport Specialists. https://www.railway.supply/en/the-train-is-too-big-for-the-tunnels/

Rajabalinejad, M. (2018). System Integration: Challenges and Opportunities. *13th Annual Conference on System of Systems Engineering (SoSE)*, 471–476.

Rajabalinejad, M., Frunt, L., Klinkers, J., & van Dongen, L. A. M. (2019). *Systems Integration for Railways Advancement* (pp. 27–40). https://doi.org/10.1007/978-981-32-9323-6_3

Rajabalinejad, M., & van Dongen, L. A. M. (2018). Framing Success: The Netherlands Railways Experience. *International Journal of System of Systems Engineering*, *8*(4), 313. https://doi.org/10.1504/ijsse.2018.10015811

Rajabalinejad, M., van Dongen, L., & Ramtahalsing, M. (2020). Systems Integration Theory and Fundamentals. *Safety and Reliability*, *39*(1), 83–113. https://doi.org/10.1080/09617353.2020.1712918

Ramasesh, R. V, & Browning, T. R. (2014). A Conceptual Framework for Tackling Knowable Unknown Unknowns in Project Management; A Conceptual Framework for Tackling Knowable Unknown Unknowns in Project Management. *Journal of Operations Management*, *32*, 190–204. https://doi.org/10.1016/j.jom.2014.03.003

Ramtahalsing, M., Haanstra, W., Braaksma, J., Rajabalinejad, M., & van Dongen, L. (2022). MOSAIC: A Structured Multidisciplinary Analysis for Managing the Integration of Inter-Organizational Changes. *Engineering Management Journal*, 1–15. https://doi.org/10.1080/10429247.2022.2143709

Ramtahalsing, M., Jafari, M., Braaksma, J., Rajabalinejad, M., & Van Dongen, L. (2020). The System (of Interest) Definition Phase: Key Features and Challenges in the Dutch Railway System. *SOSE 2020 - IEEE 15th International Conference of System of Systems Engineering, Proceedings*, 229–234. https://doi.org/10.1109/SoSE50414.2020.9130473

Rasmussen, J. (1997). Proactive Risk Management in a Dynamic Society Proactive Risk Management. *Safety Science*, *27*(2), 183–213.

Rehak, D., Senovsky, P., & Slivkova, S. (2018). Resilience of Critical Infrastructure Elements and Its Main Factors. *MDPI Systems*, *6*(2). https://doi.org/10.3390/systems6020021

Reiman, T., & Oedewald, P. (2007). Assessment of Complex Sociotechnical Systems - Theoretical Issues Concerning the Use of Organizational Culture and Organizational Core Task Concepts. *Safety Science*, *45*(7), 745–768. https://doi.org/10.1016/j.ssci.2006.07.010

Roe, E., & Schulman, P. R. (2018). A Reliability & Risk Framework for the Assessment and Management of System Risks in Critical Infrastructures With Central Control Rooms. *Safety Science*, *110*, 80–88. https://doi.org/10.1016/j.ssci.2017.09.003

Rosenhead, J. (2010). A Review of the Recent Contribution of Systems Thinking to Operational Research and Management Science. *European Journal of Operational Research*, *207*(3), 1147–1161. https://doi.org/10.1016/j.ejor.2009.12.019

Rouse, W. B. (2007). Complex Engineered, Organizational and Natural Systems: Issues Underlying the Complexity of Systems and Fundamental Research Needed to Address These Issues. *Systems Engineering*, *10*(3), 260–271. https://doi.org/10.1002/sys.20076

Ruitenburg, R. J. (2017). *Manoeuvring Physical Assets Into the Future* [University of Twente]. https://doi.org/10.3990/1.9789036543958

Sage, A. P., & Lynch, C. L. (1998). Systems Integration and Architecting: An Overview of Principles, Practices, and Perspectives. *The Journal of The International Council on Systems Engineering*, *1*(3), 176–227. https://doi.org/10.1002/(SICI)1520-6858(1998)1:3<176::AID-SYS3>3.0.CO;2-L

Salvador, F., Alba, C., Madiedo, J. P., Tenhiälä, A., & Bendoly, E. (2021). Project Managers’ Breadth of Experience, Project Complexity, and Project Performance. *Journal of Operations Management*, *67*(6), 729–754. https://doi.org/10.1002/joom.1140

San Cristóbal, J. R., Carral, L., Diaz, E., Fraguela, J. A., & Iglesias, G. (2018). Complexity and Project Management: A General Overview. *Complexity*. https://doi.org/10.1155/2018/4891286

Sauser, B., & Boardman, J. (2015). Systemigram Modeling for Contextualizing Complexity in System of Systems. In *Modeling and Simulation Support for System of Systems Engineering Applications* (pp. 273–302). John Wiley & Sons, Inc. https://doi.org/10.1002/9781118501757.ch11

Sawhney, R. (2006). Interplay Between Uncertainty and Flexibility Across the Value-Chain: Towards a Transformation Model of Manufacturing Flexibility. *Journal of Operations Management*, *24*(5), 476–493. https://doi.org/10.1016/j.jom.2005.11.008

Scott-Young, C., & Samson, D. (2008). Project Success and Project Team Management: Evidence From Capital Projects in the Process Industries. *Journal of Operations Management*, *26*(6), 749–766. https://doi.org/10.1016/j.jom.2007.10.006

Shokri, S. (2014). *Interface Management for Complex Capital Projects*. University of Waterloo.

Siriram, R. (2022). Inter-Organizational Integration, Transition, and Collaboration in the Project Front-End, and Project Initiation Phase. In *Project Management - New Trends and Applications [Working Title]*. IntechOpen. https://doi.org/10.5772/intechopen.102798

Smith, A. M., & Hinchcliffe, G. R. (2003). *RCM: Gateway to World Class Maintenance*. Elsevier.

Sosa, M., Eppinger, S., & Rowles, C. (2007). Are Your Engineers Talking to One Another When They Should? *Harvard Business Review*. https://hbr.org/2007/11/are-your-engineers-talking-to-one-another-when-they-should

Sousa-Poza, A., & Kovacic, S. (2008). Research Agenda for Complex Situations. *EMJ - Engineering Management Journal*, *20*(4), 32–39. https://doi.org/10.1080/10429247.2008.11431786

Spoorpro. (2019, August 29). *ProRail luidt noodklok over tekort aan stroom*. https://www.spoorpro.nl/spoorbouw/2019/08/29/prorail-luidt-noodklok-over-tekort-aan-stroom/

Spoorpro. (2023, March 31). *Uitrol ERTMS gaat sneller in België, maar ProRail trekt eigen plan*. https://www.spoorpro.nl/spoorbouw/2023/03/31/uitrol-ertms-gaat-sneller-in-belgie-maar-prorail-trekt-eigen-plan/

Squires, A., Wade, J., Dominick, P., & Gelosh, D. (2011, April). Building a Competency Taxonomy to Guide Experience Acceleration of Lead Program Systems Engineers. *Proceedings from the Ninth Annual Conference on Systems Engineering Research (CSER)*.

Sterman, J. D. (2002). System Dynamics Modeling: Tools for Learning in a Complex World. *IEEE Engineering Management Review*, *30*(1), 42–42. https://doi.org/10.1109/EMR.2002.1022404

Stretton, A. (2016). Series on Project Integration, Interfaces And Context Management: Project Interfaces and Their Management. *Project Management World*, *V*(Vii), 1–12.

Tatikonda, M. V, Rosenthal, S. R., & Rosenthal, S. R. (2000). Successful Execution of Product Development Projects: Balancing Firmness and Flexibility in the Innovation Process. In *Journal of Operations Management* (Vol. 18). https://doi.org/10.1016/S0272-6963(00)00028-0

The Verge. (2014, May 22). *France Pays $20 Billion for Trains That Don't Fit Its Stations*. https://www.theverge.com/us-world/2014/5/22/5740588/french-trains-error-sncf-too-wide-for-stations

Treinreiziger.nl. (2019). *ProRail: Tekort aan stroom op het spoor, 60 knelpunten*. https://www.treinreiziger.nl/prorail-te-kort-aan-stroom-op-het-spoot-60-knelpunten/

University of Cambridge dictionary. (2022, December 22). *Cambridge dictionary*.

van Aken, J., Chandrasekaran, A., & Halman, J. (2016). Conducting and Publishing Design Science Research: Inaugural Essay of the Design Science Department of the Journal of Operations Management. *Journal of Operations Management*, *47–48*, 1–8. https://doi.org/10.1016/j.jom.2016.06.004

Van Aken, J. E. (2005). Management Research as a Design Science: Articulating the Research Products of Mode 2 Knowledge Production in Management. *British Journal of Management*, *16*(1), 19–36. https://doi.org/10.1111/j.1467-8551.2005.00437.x

van Dongen, L. A. M., Frunt, L., & Rajabalinejad, M. (2019). *Issues and Challenges in Transportation* (pp. 3–17). https://doi.org/10.1007/978-981-32-9323-6_1

Visser, C. (2013). The Origin of the Solution-Focused Approach. *International Journal of Solution-Focused Practices*, *1*(1), 11–17. https://doi.org/10.14335/ijsfp.v1i1.10

Wang, F., & Hannafin, M. J. (2005). Design-Based Research and Technology-Enhanced Learning Environments. *Educational Technology Research and Development*, *53*(4), 5–23. https://doi.org/https://doi.org/10.1007/BF02504682

Wearne, S. (2014). Evidence-Based Scope for Reducing "Fire-Fighting" in Project Management. *Project Management Journal*, *45*(1), 67–75. https://doi.org/10.1002/pmj.21395

Whyte, J., & Davies, A. (2021). Reframing Systems Integration: A Process Perspective on Projects. *Project Management Journal*, *52*(3), 237–249. https://doi.org/10.1177/8756972821992246

Williams, T., Vo, H., Samset, K., & Edkins, A. (2019). The Front-End of Projects: A Systematic Literature Review and Structuring. *Production Planning and Control*, *30*(14), 1137–1169. https://doi.org/10.1080/09537287.2019.1594429

Wilson, J. R. (2014). Fundamentals of Systems Ergonomics/Human Factors. *Applied Ergonomics*, *45*(1), 5–13. https://doi.org/10.1016/j.apergo.2013.03.021

Wren, D. A. (1967). Interface and Interorganizational Coordination. *The Academy of Management Journal*, *10*(1), 69–81.

Wu, L., Weng, Y., Shen, W., & Tang, W. (2021). Effects of Boundary-Spanning Roles and Interface Management Practices on Inter-Organizational Communication in Construction Projects: Perspective of the Owner. *International Symposium on Advancement of Construction Management and Real Estate*, 361–371.

Wu, S. K., Braaksma, A. J. J., & van Dongen, L. A. M. (2019). Innovation Management in Outsourced Railway Maintenance: The Case of a Dutch Railway Service Provider. In *Transportation Systems* (pp. 133–170). https://doi.org/10.1007/978-981-32-9323-6_9

Xu, X., Lu, Y., Vogel-Heuser, B., & Wang, L. (2021). Industry 4.0 and Industry 5.0—Inception, Conception and Perception. *Journal of Manufacturing Systems*, *61*, 530–535. https://doi.org/10.1016/j.jmsy.2021.10.006

Yang, Q., Yu, J., & Yang, N. (2020). Analysing Organization-To-Project Interfaces in Construction Integration Management. *IOP Conference Series: Materials Science and Engineering*.

Yin, R. (2003). *Case Study Research - Design and Methods* (Vol. 5, Issue 3). Sage Publications. https://doi.org/10.1300/J145v03n03_07

Appendix A

Appendix A-1: Interview protocol

Interviewee:

Organization:

Function:

Project/case:

Interview date:

---

(1) Interviewee
  a. What is your function within NS/ProRail?
  b. What is your knowledge of/experience with CSM-REA?

(2) SDs to be discussed
  a. Have you had to use, or seen the SD for any specific project or modification which was implemented?
  b. What did this modification/project involve?
  c. What did the SD look like? (document, block diagram, Excel document...)
  d. Is this the same for all SDs you have encountered, or did any look different?
  e. What do you think causes this?

(3) An SD is a critical success factor for risk analysis
  a. Agree/disagree.
  b. Why do you think it is of critical importance or not?
  c. What was the reason for starting with an SD?
  d. Of course the SD is the starting point, but how is the original SD used further on during the process (e.g., risk analysis and evaluation)?
  e. Would the SD be re-used and modified, in case of a similar modification? (Why yes/no)?

(4) An SD is focused on a clearly defined goal
  a. Agree/disagree.
  b. What was the goal of this SD (in case one or multiple are discussed within the interview)?
  c. Were the goals clear (from the beginning)?
  d. Does everyone have the same goal?
  e. Is this goal clear to everyone?
  f. Has the goal changed over time? (Why yes/no)?

(5) An SD always has a clear scope and includes details important for the risk analysis
    a. Agree/disagree.
    b. What kind of elements are included in the SD?
    c. How is what is inside the scope of an SD typically determined?
    d. Is this SD static, or has it been adjusted over time? Have the scope and/or level of detail changed?
    e. Does the scope sometimes include other organizations?
    f. Are these also included in the development of the SD? (Why yes/no)?
(6) Interfaces between parties/stakeholders/subsystems are of great importance in an SD
    a. Agree/disagree.
    b. Were interfaces also included in the SD that you have experience with?
    c. What kind of interfaces? (e.g., technical, organizational)
    d. How are those interfaces typically determined?
    e. Is this static, or adjusted over time?
    f. Has it ever occurred that there were interfaces with other organizations?
    g. How are those interfaces managed?
(7) An SD is iterative, i.e., continuously adjusted based on information that becomes available in the process
    a. Agree/disagree.
    b. What is typically modified during this iterative process?
    c. The following questions concern the development of SDs
(8) How are SDs typically developed?
    a. Who is in charge of these developments? What is their function within the organization?
    b. Are other people involved in this development process?
    c. How is it decided which other people should be included?
    d. Do those people give feedback, or actively help to develop the SD?
(9) After the SD is developed, what is the SD used for?
(10) By whom are the SDs typically managed?
(11) Will this SD be reused after implementation of the change?
(12) Are there other aspects regarding SDs that you think could be improved?

Appendix A-2: Case study scoring

Criterium	Scales
Scope	small change, affecting 1 department medium change, affecting multiple departments multiple changes, affecting several organizations multiple changes, affecting the whole sector
Approximate costs associated with the change (€)	<1 Million Between 1 and 10 mil Between 10 and 100 mil > 100 mil
Novelty	No Novelty Low Novelty Medium Novelty High Novelty Very High Novelty
Complexity	Not complex Somewhat complex Complex Very Complex
Intra-organizational or Inter-organizational	Inter-organizational Intra-organizational
Project duration	<1 year Between 1 and 5 years >5 years
Reversibility	Reversible Somewhat reversible Not reversible
Technical, Organizational, and Operational Impacts	Technical Organizational Operational Multiple

Appendix B

Proposed Interface Management approach - Evaluation questions

1. To what extent does this process help identify the interfaces in inter-organizational projects?
2. To what extent does this process help reveal complexity?
3. To what extent does this help to collect, organize, integrate, and analyze information in a structured way?
4. To what extent does this help to combine and align different perspectives?
5. To what extent does this process encourage information exchange between different (inter-organizational) parties?
6. To what extent does this help project control/progress?
7. To what extent does this process create more awareness about interfaces?
8. How could this method/process be improved?

Acknowledgment

This four-year journey has certainly been an eventful one with many noteworthy experiences, to say the least.

If anyone could have attempted to tell me at the start of this journey how much sweat, tears, and frustration would go into it, how many times I would have to go far beyond my comfort zone, how many times I would experience feelings of great uncertainty, and how many times I would almost quit, I am quite sure this dissertation would not exist. That is also why I can confidently say that there were numerous people included in my journey without whom I would never have dared to do this, and without whom reaching this milestone would have been impossible. Therefore, I dedicate this part of my dissertation to you.

First and foremost, I would like to express my sincere gratitude to my promotor Leo van Dongen: Leo, thank you for always expressing confidence in me, especially at times I was lacking it most. You were always approachable, and would always help come up with quick, pragmatic solutions. You have given me much valuable advice and helped me follow my gut feeling multiple times. Your leadership style, openness, encouragement, and honesty have greatly influenced not only my PhD trajectory but also my personal development during the years I have known you. Additionally, to my second promotor, Jan Braaksma: Jan, your enthusiasm is contagious, something I noticed already in 2017 when we were discussing my master's internship project. You have always created an open, understanding, and encouraging atmosphere, even at times when it was somewhat difficult. Your stakeholder management skills saved this project, and your positivity, encouragement, and trust in me often gave me a nudge in the right direction. I don't remember ever having a phone call or meeting with you that lasted shorter than an hour, but I do know that all of those left me a lot more confident and energized than at the start. Furthermore, to my co-promotor Willem Haanstra: Willem, your eye for detail, extremely focused attention, and clear to-the-point feedback have helped enormously to make significant improvements in my writing and thinking processes along this journey. I can't think of a better PhD supervisor than you, which is why I'm happy we also got that formalized!

To Nina Jakubeit (Trauernicht) and Yawar Abbas, there are several reasons I chose you to be my paranymphs. You preceded me in the SIRA project, however, at a certain point in the past 4 years, we were certainly in the same boat, in the same turbulent waters.

There were a lot of facets to our PhD journey which I think only the three of us experienced to a certain extent and had to deal with. I will always remember our discussions at the UT, at the KTT, on the train, and all other places, about our research, about our life, and everything that came along with it.. our dinners, coffee breaks, walks, lunches, and occasional boat trip with Surinamese beer and food. Both of you organically grew from colleagues to my friends, with whom I shared countless personal stories, doubts, thoughts, and ideas. You became my anchor in the SIRA journey, and I am certain that without both of you, I would have never reached the end of this journey (and would have ended less sane than I currently am). No matter the routes we will individually take in life, I hope we will always stay in contact.

Furthermore, to my colleagues Henrike Holwerda, Ashrith Jain, Arno Kok, Alberto Martinetti, Jan-Jaap Moerman, Nikola Petrova (Nizamis), and Sara Scheffer, thank you for all the uplifting talks and entertaining coffee breaks, making my time in the group a joyous one. I often brag about the Maintenance group because I can't imagine a more inclusive, supporting, and understanding group of colleagues. I hope for many years to come, more researchers will have a similar experience.

Additionally, to Annemarie Bos-Lubbers, Inge Dos Santos-Smit, Saskia Groenendijk, and Bianca Dibbelink: You make sure the whole operation is running smoothly and that everyone can do their work on a daily basis. Moreover, you have been an important support for me, not only in organizing activities, guiding in processes, and finding the right people within the UT, but also personally. With some of you, I could always express my concerns about anything, and vice versa. You were always the first to know about the latest news and developments, and have certainly made my years at the UT easier and more enjoyable.

To all of you at the UT, working with you has brought me so much joy, so much peace of mind, so much confidence, so much support, so many opportunities, so many experiences, and so many laughs, all of which shaped me into a version of myself I am very proud of and am eager to develop further. This was also among the reasons why deciding not to pursue the assistant professor position in our group was a very difficult one for me. Only time will tell whether I made the right decision in doing so, but for now, I am content with my choice and I do know that I will always look back at my years at the University of Twente with eternal gratitude for the experiences, the people, and the lessons learned.

The research conducted throughout this dissertation would have been impossible without the NS and ProRail. I am therefore grateful for the efforts of my coaches Marion Post from the NS and Onno Hazelaar from ProRail during these past 4 years. Our frequent update sessions and your critical, constructive feedback always kept me sharp and forced me to continuously translate my ideas and results into more pragmatic language and tools for the industry. Moreover, within both NS and ProRail, there are people who have made a significant practical contribution to my project and provided me with opportunities to conduct my research. Special thanks to: Quincy Bink, Lex Frunt, Marcel Grob, Paul Hendriks, Jorren ter Hofstede, Jeroen Klinkers, Arno Kok, Marco Kuijsten, Andrea Langerak, Edwin Luidjes, Martin Morsman, Peter van de Nieuwendijk, Ruben Rulf, Eddy Schakelaar, Damy Snel, Bruno van Touw, Annelies van Unen, Bas van Vliet, Doesjka Warmerdam, Jasper de Wit, and Sander Wolf. Moreover, to all others from 'Programma Hoog-Frequent Spoor Amsterdam', 'the Unimog', 'Amsterdam Westhaven', 'ERTMS', and other cases who were involved in various ways during my PhD trajectory, your willingness to participate in the research made this dissertation possible.

Moving on to my family and friends, mostly residing in the Netherlands and Suriname, to all of you, especially Dada Narain & Tante Hermien, Nani Jeanette, Phoewa Lien & Phoepha Anton, and Nani, thank you for always welcoming me with open arms, for showing so much interest in my journey, for always encouraging me to keep going, and for often expressing how proud you are of me.

Furthermore, essential on this journey were my mom, dad, brother Raveen, sister Roshni, and my niece Lynah. It is not always easy for me to live life at a distance of 8000 km from you, that is also why the time we do get to spend together on holidays is so precious to me. Thank you for providing me with a solid foundation for life, for always being there for me (also in digital form), for believing in me, and for giving me the opportunity to pursue my life decisions. I can't imagine my life without any one of you, and I am so happy I get to celebrate this milestone with you.

Finally, there is only one person who experienced my day-to-day rollercoaster moods these past 4 years from up close, my partner Quin. You were there during the first tears (of relief) of this journey, when after months of contemplating and doubting, I decided to pursue this PhD. You were there for the last tears (of joy) of this journey - until time of writing - when I received my official greenlight, and you were there for all the four years in between, with its inherent highs and lows.

Countless times I would complain, explain, and think out loud about something related to this journey, and you would (seemingly) listen carefully. Thank you for often reminding me that I was doing great, that everything would always be all right, to take breaks, and to focus also on the more positive aspects of this journey. Also, thank you for joining me on many holidays, and for taking me out to dinner and drinks, every time we had something to celebrate, and every time we had nothing to celebrate. We have grown so much, both individually and together these past years, and I am so grateful to have you in my life.

This journey left me with many life lessons: to celebrate all the small milestones included in any journey; to never write a dissertation in Word; to trust my instinct and gut feeling, even though their source is often unknown; and most importantly, that the days we silently wipe our tears - take a deep breath - and continue, are the days that make a difference.

Merishna Merilyn Ramtahalsing
Rotterdam
September 2023

UNIVERSITY OF TWENTE.

ProRail