Design structure matrix (DSM) based identification of reliability and availability risks within a lock's dependency structure: A case study on lock system Eefde

ing. M. Dijkstra

Report Number: DC 2015.074

Master thesis

Advisors TU/e: dr. ir. L.F.P. Etman
ir. T. Wilschut
em. prof. dr. ir. J.E. Rooda
prof. dr. ir. I.J.B.F. Adan

Advisors RWS: ir. A. Hijdra
ir. H. Vogel

Eindhoven University of Technology
Department of Mechanical Engineering

Rijkswaterstaat

Eindhoven, August 26, 2015

Preface

Seven years of studying for exams, working on projects, completing interesting internships, having amazing adventures, meeting inspiring people, doing crazy motorcycle trips and building lasting friendships, are concluded by my thesis: Design structure matrix (DSM) based identification of reliability and availability risks within a lock's dependency structure: A case study on lock system Eefde.

Mechanical engineering has always played a central role in my life; I've been taking apart equipment (including that of my parents) my entire childhood to figure out how it works and build a 5 meter tall half-pipe for skateboarding at the age of eleven.

Although my main interests during high school had been skateboarding, girls, partying, studying, and avoiding the consequences of this sequence. I always found time to spend the ever required time and effort on my 78' high maintenance Zundapp moped that still runs to this day. This included revising the engine for fun and ensuring my moped was the fastest Zundapp in the city.

Re-evaluating my interests and allowing the stories of my foster father to inspire me, quickly resulted in the decision to study mechanical engineering at the Fontys University of applied sciences. It turned out to be the right one, and resulted in amazing experiences like: an internship at PBH in Xi'an, China, an Erasmus exchange with the University of Leuven, many great trips that often compromised the margin for exam preparation and a highly interesting graduation project at VDL PMB-UVA.

Because compromising these margins rarely led to unsatisfactory results and because there was much more to be learned about the world of mechanical engineering, I joined the systems engineering group at the Eindhoven University of Technology to do my mechanical engineering master. This offered me the opportunity to both improve my knowledge and to put it into practice with an internship at Schlumberger in Bristol, England and finally this thesis.

Although words will never suffice to express my gratitude, I want to thank the following people for their support, without whom this would not have been possible:

My father Jan Dijkstra † and my mother Marjan van Rooij † for allowing the before mentioned half-pipe to be constructed in our backyard, for supporting me in every way possible and for planting the seed of my current academical interests,

My foster father Bert van Rooij † and my foster mother Margot van Rooij † for their incredible patience, endurance and persuasive capabilities that got me back on track and inspired me to make something of my life. Especially my foster father has been my anchor and provided unconditional support throughout the final phases of my adolescence, whether it governed a broken heart, tough decisions, thermodynamical problems or extremely stressful situations on the other side of the world.

Even though they were not around anymore during the completion of my studies, they were surely there in spirit.

Furthermore, I would like to thank: Emil Landman, Thomas Thijs, Remco van der Loo and Hugo van der Zandt for their uplifting spirits and ever positive attitude, Kaja Coenen for her wonderful smile, sexy figure and endless patience during the many evenings of writing this thesis, Nadine Dijkstra for her contagious enthusiasm, Ad van Rooij and Dori van Rooij for their warm hearts and cups of coffee, Ton Verkuijlen for his ever available assistance in fixing my chronically broken motorcycles, Lambert van Beukering for his commitment and highly inspiring talks during my Fontys period and after, Yvonne Vialle for her never closed door and ever filled table and Pascal Etman for guiding me through the final stages of my study!

Finally, I would like to thank the following people that have been directly involved with this thesis: Kees Nieuwstad for his guidance and impressing skill to allocate new data, Han Vogel and Arjan Hijdra for their inspiring meetings at both the TU/e and RWS, Cees Michielsen for his original viewpoints and ever constructive comments, Eefje van Dungen, Sander Wiendels, Jan Dirk Voorwinde, Herman van Manen and Bert van der Vegt for their much needed expert opinions that literally laid the foundation for this work, Tim Wilschut for his in-depth discussions and many useful comments, Koos Rooda for his guidance and detailed feedback on my work and Pascal Etman for his highly committed guidance and (impressively) many, in retrospect often needed, suggestions for improvement.

Thank you!

Summary

Rijkswaterstaat (RWS) is responsible for a total of 137 locks, of which 52 are due for renewal before the year 2040. The Multi Water Werken (MMW) project has been set up to overcome this challenge. MWW seeks standardization opportunities to increase reliability and availability (RA), decrease life-cycle cost (LCC), and decrease uncertainty of construction cost and time while maintaining market driven innovation. Hence, a standardization strategy is to be developed that determines a balance between innovation and standardization.

RWS contacted the Eindhoven University of Technology to assist in this challenge. This thesis is the first project within this collaboration and aims to identify specific areas in the lock system's design that pose a high reliability and availability risk.

Reliability and availability are characteristics of the whole system, and can not be solely attributed to its constituent components. The main idea of this thesis is that the way these components interact, i.e. the dependency structure that exists between them, is an important aspect in the RA risk identification. The Design Structure Matrix (DSM) and DSM based methods are used as a means to analyze this dependency structure and to subsequently identify RA risks within this structure.

The first part of this thesis governs the identification of the interactions between the components that form the lock's dependency structure.

RWS has various system decompositions in place that depict the components that comprise a lock system. By analyzing these decompositions and interviewing system experts, a decomposition is obtained that faithfully represents the most important aspects of the system.

The resulting decomposition and documentation governing the working principles of the lock system are used to build a preliminary DSM that is a first attempt to capture the occurring dependencies. This DSM, that is based on the physical dependencies, is improved via interviews with system experts.

As a complementary approach in identifying the interactions, the functional dependency structure is used to identify potential physical interactions. This is done by capturing the dependency structure between functions and components in a Design Matrix (DM). This DM is subsequently converted to a functional DSM that captures interaction between components based on functional dependencies.

By comparing the physical DSM and the functional DSM, a comparison DSM is build. This comparison DSM is used to identify potential interactions that are used to enhance the physical DSM. The comparison DSM is also be used to identify issues with the DM.

The identification of the interactions via the three methods: studying documentation, interviewing system experts and analyzing the functional dependency structure is successfully used in a complementary manner to obtain a DSM that faithfully represents the system's dependency structure.

The second part of this thesis governs the analyzes of the obtained dependency structure to expose the underlying coupling structure and the identification of high RA risk within this structure.

The enhanced DSM is modularized, i.e. its rows and columns are permuted in such a fashion that modules of tightly coupled components form. The first step of the modularization is the application of a clustering algorithm. The clustering resulting from the algorithm is manually adapted in a post processing step in which a bus module and overlapping components are introduced. The resultant modularization shows that other, more naturally emerging subsystems are present within the lock's dependency structure. The clustering furthermore shows that the coupling structure is modular, i.e. the resulting subsystems can be treated relatively disjunct.

The modularization is used as a base to identify high RA risk areas within the coupling structure. This is done by assigning impact values to the components of the DSM and increased risk values associated with the various interaction types and strengths. This results in a reliability DSM and an availability DSM that respectively represent the reliability and availability risks within the coupling structure.

These RA risk DSMs are analyzed from various perspectives to obtain increased insight in the different sources of RA risk. The R-DSM suggests that the reliability risks are mostly associated with the mechanical parts of the Navigation lock, and to a lesser extend the Front lock. Where as the A-DSM suggests that the availability risks are mostly associated with both its mechanical and civil parts.

The high risk areas are analyzed and a suitable standardization strategy is presented that distinguishes between component, interface and module standardization.

Samenvatting

Rijkswaterstaat (RWS) heeft 137 schutsluizen in beheer, waarvan er 52 moeten worden vervangen voor 2040. Het Multi Water Werken project (MWW) is opgericht binnen RWS om deze vervangingsopgave zo soepel mogelijk te laten verlopen. MWW is op zoek naar standaardisatie mogelijkheden die de beschikbaarheid en betrouwbaarheid verhogen, de life-cycle kosten verlagen en de onzekerheid omtrent bouwkosten en bouwtijd verlagen. Deze standaardisatie mag niet te veel invloed hebben op innovatie door de markt en moet daarom een balans weten te definiëren tussen innovatie en standaardisatie.

RWS heeft contact opgenomen met de Technische Universiteit Eindhoven om te assisteren bij deze uitdaging. Deze thesis is het eerste project binnen deze samenwerking en heeft tot doel het identificeren van delen binnen het ontwerp van een schutsluis die een hoog beschikbaarheids- en betrouwbaarheidsrisico dragen.

Beschikbaarheid en betrouwbaarheid zijn karakteristieken van het hele systeem en kunnen niet alleen worden toegewezen aan de individuele componenten. Het uitgangspunt van deze thesis is dat de manier waarop de componenten op elkaar inwerken, i.e. de afhankelijkheidsstructuur tussen de componenten, een belangrijk aspect is bij het identificeren van beschikbaarheids- en betrouwbaarheidsrisico's. De Design Structure Matrix (DSM) en op de DSM gebaseerde methoden worden gebruikt om deze afhankelijkheidsstructuur te analyseren en om binnen deze structuur beschikbaarheids- en betrouwbaarheidsrisico's te identificeren.

Het eerste deel van deze thesis gaat over het identificeren van de interacties tussen componenten die de afhankelijkheidsstructuur vormen.

RWS heeft verscheidenen decomposities die de componenten weergeven waar een schutsluis uit is opgebouwd. Door deze decomposities te bestuderen en systeemexperts te interviewen, wordt er een decompositie verkregen die de meest belangrijke aspecten van het systeem schutsluis belicht.

De resulterende decompositie wordt samen met documentatie over de sluis gebruikt om een preliminaire DSM te maken van het systeem. Deze DSM is een eerste poging om de bestaande afhankelijkheden te vangen. Deze DSM, die de fysieke afhankelijkheidsstructuur weergeeft, wordt verbeterd door interviews te houden met systeemexperts.

Als een aanvullende manier om interacties binnen het systeem te vinden, wordt de functionele afhankelijkheidsstructuur van de sluis bekeken. Dit wordt gedaan door de afhankelijkheid die bestaat tussen de functies van het systeem en zijn componenten te vangen in een Design Matrix (DM). Deze DM wordt vervolgens geconverteerd in een functionele DSM die de interacties tussen componenten weergeeft, gebaseerd op functionele afhankelijkheden.

Door de fysieke DSM en de functionele DSM te vergelijken, wordt een zogenaamde vergelijkings DSM gemaakt. Deze vergelijkings DSM wordt gebruikt om kandidaatinteracties te identificeren. Deze kunnen worden gebruikt om de fysieke DSM te verbeteren. De vergelijkings DSM wordt ook gebruikt om problemen met de DM te kunnen identificeren.

Het identificeren van interacties op de drie manieren, door documentatie te bestuderen, systeem experts te interviewen en de functionele structuur te analyseren, is succesvol op een complementaire

manier gebruikt. Het resultaat is een DSM die de fysieke afhankelijkheidsstructuur tussen de componenten waarheidsgetrouw weergeeft.

Het tweede deel van deze thesis gaat over het analyseren van de verkregen afhankelijkheidsstructuur om de onderliggende koppelingsstructuur te onderzoeken. Daarnaast worden de beschikbaarheids- en betrouwbaarheidsrisico's binnen deze structuur geïdentificeerd.

De verbeterde fysieke DSM wordt gemodulariseerd, i.e. de rijen en kolommen worden verwisseld totdat modules van sterk gekoppelde componenten te voorschijn komen. De eerste stap van deze modularizatie is het toepassen van een clusterings algoritme. De verkregen clustering wordt handmatig aangepast door een busmodule en overlappende componenten te introduceren. De resulterende modularizatie laat zien dat andere, meer natuurlijk aanwezige subsystemen bestaan binnen de afhankelijkheidsstructuur. De modularizatie laat ook zien dat de koppelingsstructuur vrij modulair is, i.e. de resulterende subsystemen kunnen vrij disjunct worden behandeld.

De modularisatie wordt gebruikt als een basis om de beschikbaarheids- en betrouwbaarheidsrisico's te identificeren binnen de afhankelijkheidsstructuur. Dit wordt gedaan door impactwaarden aan de componenten toe te wijzen en verhoogde risicowaarden aan de verschillende interactie typen en sterkten toe te wijzen. Dit resulteert in een beschikbaarheids DSM en een betrouwbaarheids DSM die respectievelijk de beschikbaarheids- en betrouwbaarheidsrisico's binnen de afhankelijkheidsstructuur weergeven.

Deze beschikbaarheids en betrouwbaarheids DSMs worden geanalyseerd vanuit verschillende invalshoeken om inzicht te krijgen in de verschillende vormen van risico. De betrouwbaarheids DSM suggureert dat de betrouwbaarheidsrisico's vooral aanwezig zijn in de mechanische delen van de schutsluis, en in mindere mate de voorsluis. De beschikbaarheids DSM suggereert dat de beschikbaarheidsrisico's vooral te wijden zijn aan de civiele delen.

De gebieden binnen de afhankelijkheidsstructuur die een hoog risico krijgen toegewezen door de DSMs worden geanalyseerd en een passende standaardisatie strategie wordt gepresenteerd die onderscheid maakt tussen component, raakvlak en module standaardisatie.

Lock dictionary of terms

English	Dutch
1. Vertical lift gates	Hefdeuren
2. Actuators vertical lift gates	Bewegingswerken hefdeuren
3. Leveling system	Nivelleersysteem
4. Actuators leveling system	Bewegingswerken nivelleersysteem
5. Lock head construction	Sluishoofd constructie
6. Seepage screens	Onder- en achterloopheidsschermen
7. Ice prevention system	IJsbestrijdingssysteem
8. Lock chamber wall	Kolkwand
9. Soil protection	Bodembescherming
10. Shipping facilities	Scheepsvaartvoorzieningen
11. Funnel	Fuik
12. Positioning area	Opstelruimte
13. Waiting area	Wachtruimte
14. Run-out zone	Uitlooplengte
15. Soil protection outport	Bodembescherming voorhaven
16. Bank protection	Oeverbescherming
17. Grid connection	Energy aansluiting
18. Low voltage supply	Laagspanningsinstallatie
19. High voltage supply	Hoogspanningsinstallatie
20. Emergency power supply	Noodstroominstallatie
21. Regular control system	Bediensysteem regulier procces
22. Maintenance control system	Bediensysteem onderhoud
23. Emergency shutdown	Noodstop
24. Emergency control system	Bediensysteem noodbediening
25. Supervisory control system	Besturingssyteem
26. Operator/maintenance personnel	Bedienaar/onderhoudspersoneel
27. Telephone	Telefoon
28. Control building	Bediengebouw
29. Site lighting system	Objectverlichting
30. Lightning and over voltage protection	Bliksem- overspanningsbeveiliging
31. Safety equipment (incl. detection)	Veiligheidsmiddelen (incl. scheepsvaart detectie)
32. Fire alarm system	Brandmeldinstallatie
33. Acoustic and visual signs	Akoustische en visuele signalering
34. Broadcast installation	Omroepinstallatie
35. Emergency phone installation	Praatpaal installatie
36. Intercom installation	Intercom installatie
37. VHF radio installation	Marifooninstallatie
38. CCTV installation	CCTV installatie
39. Radar installation	Radarinstallatie

English	Dutch
40. Meteo installation	Meteo installatie
41. Shipping signs	Scheepsvaart tekens
42. Level measurement system	Niveaumeetsysteem
43. Logging	Logging
44. Mitre gates front lock	Puntdeuren voorsluis
45. Actuators mitre gates front lock	Bewegingswerken puntdeuren voorsluis
46. Leveling system front lock	Nivelleersysteem voorsluis
47. Actuators leveling system front lock	Bewegingswerken nivelleersysteem voorsluis
48. Lock head construction front lock	Sluishoofd constructie voorsluis
49. Seepage screens front lock	Onder- en achterloopheidsschermen voorsluis
50. Vessel	Schip
Bollard	Bolder
Communication systems	Communicatiesystemen
Control systems	Bediensystemen
Energy supply	Energievoorziening
Front lock	Voorsluis
Hawsers	Tros
Information systems	Informatie systemen
Lock	Sluis
Lock chamber	Sluiskolk
Lock head	Sluishoofd
Navigation lock	Schutsluis
Safety equipment	Veiligheidsvoorzieningen

Contents

Preface iii

Summary v

Samenvatting vii

Lock dictionary of terms ix

1 Introduction 1

1.1 Lock system Eefde 1

1.2 Objective 4

1.3 Available data 4

1.4 Approach 5

1.5 Thesis outline 6

2 Related work 7

2.1 Decomposition of systems in components and functions 7

2.2 Interactions, their representation and coupling structure analysis 9

2.3 Development of the Design Structure Matrix 10

2.4 Case study: The NASA Pathfinder 13

2.5 Conclusion 14

3 Method 17

3.1 Building the physical DSM 19

3.2 Building the functional DSM 19

3.3 Enhancing the physical DSM and analyzing its structure 20

3.4 Exploring the resulting DSM in RA context 20

4 Decomposition of the system **23**

4.1 System boundary 23

4.2 Existing decompositions 25

4.3 Decomposition of lock system Eefde 27

4.4 Conclusion 29

5 Building the physical DSM **31**

5.1 Interaction rating scheme 31

5.2 Building the preliminary DSM 35

5.3 Reviewing the DSM via interviews 38

5.4 Conclusion 41

6 Building the functional DSM **43**

6.1 Properties of the conversion method 44

6.2 Building the DM from data 45

6.3 Conversion of the DM 47

6.4 Conclusion 51

7 DSM comparison and enhancement **53**

7.1 The comparison DSM 53

7.2 Feedback on the DM 55

7.3 Suggested interactions 56

7.4 Conclusion 60

8 Coupling structure analysis **61**

8.1 Structural aggregation of the interaction types and strengths 61

8.2 Clustering the physical DSM 63

8.3 Coupling structure review 65

8.4 Conclusion 75

9 Reliability and availability coupling structure analysis **77**

9.1 Reliability and availability interaction strengths 78

9.2 Determination of component R and A impact values 79

9.3 The reliability DSM 82

9.4 The availability DSM 87

9.5 Conclusion 91

10 Towards standardization **93**

10.1 Standardization for high reliability and availability risk component pairs 93

10.2 Standardization for high reliability and availability risk components 95

10.3 Standardization for high reliability and availability risk modules 96

10.4 Conclusion 97

11 Conclusion **99**

12 Future work **103**

12.1 Elaborating on results 103

12.2 Suggestions for related work 104

Bibliography **105**

A Latin hypercube sampling for DSM modularization **109**

Chapter 1

Introduction

Navigation locks for ships have been built in the Netherlands in large quantities, mostly during the last century. Rijkswaterstaat (RWS) is responsible for a total of 137 locks, of which 52 are due for renewal before the year 2040.

In order to overcome this challenge, the Multi Water Werken (MWW) project has been set up. MWW seeks standardization opportunities to increase reliability and availability (RA), decrease life-cycle cost (LCC), and decrease uncertainty of construction cost and time while maintaining market driven innovation. Hence, a standardization strategy is to be developed that determines a balance between innovation and standardization.

To this end, RWS contacted the Eindhoven University of Technology. This study is the first project within this collaboration. Its objective is to identify specific areas in the lock system's design that pose a high reliability and availability risk, i.e. a high RA risk with respect to the function: providing ship passage.

Since reliability and availability are characteristics of the whole lock system and can not be solely attributed to its comprising components, both the contribution of the components and the way they interact with each other needs to be analyzed. Hence, the dependency structure of the lock components needs to be investigated.

To explore the potential of system structure analysis, a case study has been performed on lock system Eefde. This lock system exhibits interesting features, has a high amount of readily available data and a representative complexity. Furthermore, Eefde is currently subject to an expansion process in which a second lock is being constructed. Since this allows future coupling structure comparison, it makes Eefde an ideal candidate.

1.1 Lock system Eefde

The lock system in Eefde is part of a lock complex. It connects the upstream Twentekanaal to the downstream IJssel, see Figure 1.1 and Figure 1.3.

The ship passage function is performed by the navigation lock system. If the water level in the IJssel is too low to exit the lock system, an additional set of gates, the Front lock is used to increase the water level on the IJssel side of the lock and enable stepwise passage.

The volume of water that is transferred from the Twentekanaal to the IJssel during ship passage is significant (about 35 passages per day), hence two Pumphouses have been installed. Their function is to reduce the water losses during passage by pumping the water from the IJssel back to the Twentekanaal.

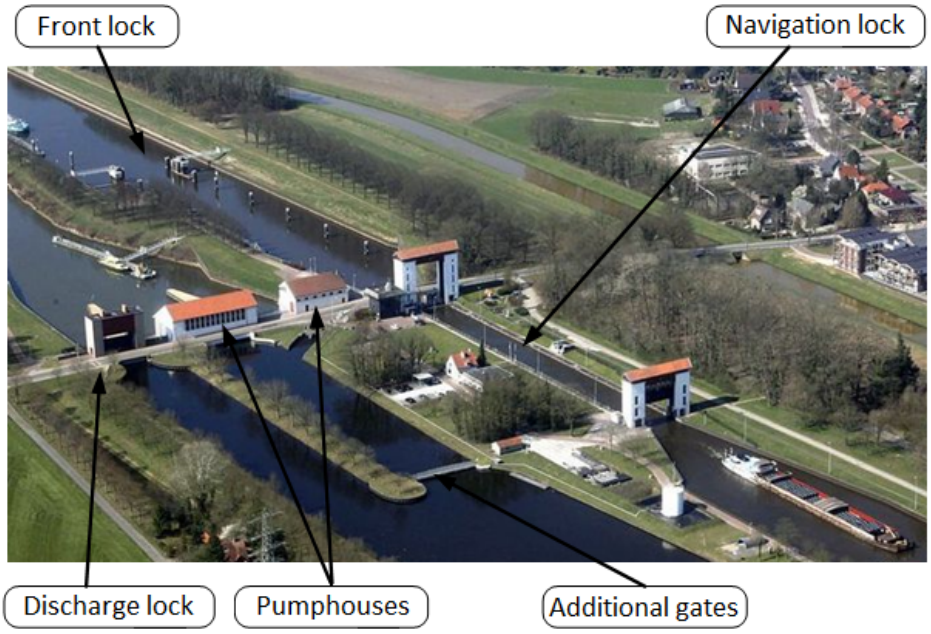


Figure 1.1: Layout of the lock complex Eefde, photograph by Ab Hakeboom.

For the rare event that the Pumphouses fail to stop the flow of water from the Twentekanaal to the IJssel, an additional set of gates is placed in front of them. During normal operational conditions, they are redundant.

In the opposite situation, i.e. the water level in the Twentekanaal becomes too high, water needs to be released from the Twentekanaal to the IJssel. The Discharge lock is used to release the excess water in a controlled manner.

Principle of operation

The water level on the IJssel dictates the way the ship passage operates. If the water level is too low, the Front lock is employed to raise it (scenario 1). If the water level slightly increases, the Front lock is not used, but ship passage may still be limited (screnario 2). On the contrary, if the water level is too high, the ship passage is limited by the hight of the lock construction(scenario 4). The regular ship passage is performed between the water levels NAP +3,20 and NAP +8,20 , see Figure 1.2 for an overview of possible scenarios.

Waterlevel IJssel		Scenario
Lower	Upper	
-	NAP +3,00 m	1. Passage with the use of the Front lock possible limitation for ship immersion
NAP +3,00 m	NAP +3,20 m	2. Possible limitation for ship immersion
NAP +3,20 m	NAP +8,20 m	3. Regular ship passage
NAP +8,20 m or above	-	4. Ship passage limited due to high water level

Figure 1.2: Overview of possible scenarios for ship passage.

The process of ship passage using the Front lock from the IJssel to the Twentekanaal (upstream), goes as follows:

1. The water level of the Front lock is leveled to the water level of the IJssel by the Leveling system in the Mitre gates of the Front lock.
2. The Mitre gates of the Front lock are opened and the ships enter the Front lock. After the last ship has entered, the Mitre gates are closed.
3. The Lock chamber is leveled to the Twentekanaal.
4. The water from the Lock chamber is released to the Front lock. The level in the Front lock hereby increases.
5. The Vertical lift gate of the Lock head east is opened and ships enter the Lock chamber.
6. If all ships entered the lock, the Vertical lift gate is closed and the Vessel detection system is used to prevent the door from closing too early.
7. The Lock chamber is leveled with the Twentekanaal.
8. The Vertical lift gate of the Lock head east is opened and the ships exit the lock.

For regular ship passage, scenario 4 in Figure 1.2 , the Front lock is not required, and steps 1 to 4 can be replaced by "The Lock chamber is leveled with the IJssel". For ship passage from the Twentekanaal to the IJssel, the process is executed in reverse order.

System boundary

Since the lock's RA with respect to the function: 'providing ship passage', is the focus of this thesis, solely the systems required for this function are incorporated in the analysis, i.e the Navigation lock and the Front lock, see Figure 1.3.

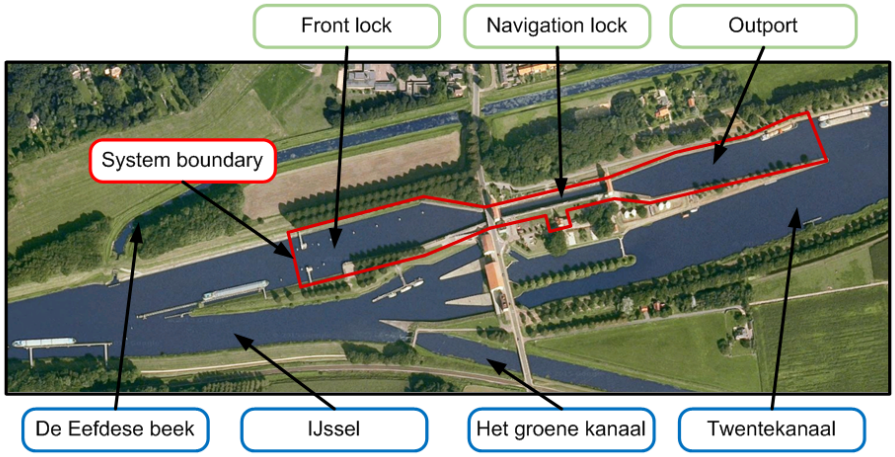


Figure 1.3: Layout of the lock complex Eefde, satellite image adapted from Google maps.

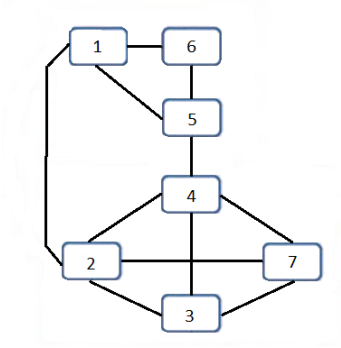
The bridge across the lock complex is not part of the analysis. More details about the system boundary are provided in the Chapter 4.

1.2 Objective

To decide on a standardization strategy that maintains market driven innovation, specific areas of the design need to be identified that have a high impact on the RA of the ship passage function. Since these are characteristics of the whole system, as opposed to characteristics of the individual components, the effect of the lock's coupling structure on the RA of the ship passage function is investigated.

The objective of this study is to identify components and modules of components that have a significant influence on the reliability and availability (RA) of the lock system in Eefde with respect to providing ship passage. The critical components and modules resulting from this study, can subsequently be used for deciding on a standardization strategy.

To do so, Design Structure Matrices (DSMs) and DSM based methods are investigated as a means to reveal the underlying coupling structure of the lock components. A DSM is a square matrix that provides a clear and compact representation of the coupling structure that exists between the components of a system, see Figure 1.4.



(a)

	1	2	3	4	5	6	7
1		X			X	X	
2	X		X	X			X
3		X		X			X
4		X	X		X		X
5	X			X		X	
6	X				X		
7		X	X	X			

(b)

Figure 1.4: (a) Graph representation of dependency structure between components of a system (b) DSM representation of the dependency structure.

A dependency between a component pair is represented by an edge in the graph representation. In the DSM representation, this dependency is represented by an 'X' in the DSM. Since all dependencies are symmetrical in this example, the resulting DSM is also symmetrical.

DSM based methods seem promising techniques to identify critical components and modules. The objective of this study can consequently be split in two sub objectives:

1. obtain a representative DSM of the dependency structure between the lock components, and
2. use this DSM to explore the underlying coupling structure and to identify areas within the lock's dependency structure that pose a high reliability and availability risk for the ship passage function.

1.3 Available data

Knowledge about the available data regarding the coupling structure of lock Eefde is required to determine an optimal approach for this study, hence an overview is provided.

Rijkswaterstaat has numerous databases, containing information about a great variety of subjects. A selection hereof, containing information about the coupling structure has been investigated.

- As-built drawings describe the as-built situation of the lock for various disciplines like mechanical engineering and electrical engineering.
- System manuals providing schematics for operation and general working principles.
- Photographic material of the complex depicting the orientation of various system elements.
- A Failure Mode and Criticality Effect Analysis (FMECA) report denoting the various risks of the complex by analyzing its functional structure and investigating the state of the matching physical component (Rijkswaterstaat (2012a))
- A 'Gecoördineerde Regionale Incidentensbestrijdingsprodeduren (GRIP)' printout (Rijkswaterstaat (2015)). GRIP is a database providing cross reference of "standard lock functions" and physical components.

The available data is consequently able to partly describe the coupling structure between components and between functions and components.

1.4 Approach

The DSM is used as a means to analyze the coupling structure of the systems and to identify areas in the design that pose a high reliability and availability risk. The available data dictates both limitations and possibilities to obtain a representative DSM of the lock system. These have been used to define an approach to meet the objectives. The approach can be divided into four main steps: build the physical DSM, build the functional DSM, enhance the physical DSM and analyze its structure, and finally exploring the resulting DSM in RA context.

- *Build the physical DSM*: The physical DSM of lock system Eefde needs to represent its physical coupling structure. Two methods found in literature are combined to acquire a representative DSM: eliciting the coupling structure from data and performing interviews with system experts.

  A decomposition that describes the components of the lock system is and interactions that exists between these components are determined by studying product documentation. Both the decomposition and the interactions are reviewed by system experts.

  A preliminary DSM is constructed by investigating the working principles of the system, design drawings and as-build drawings and referencing the results with the obtained decomposition and the interactions. This DSM is also reviewed by system experts.

- *Build the functional DSM*: The components of the lock system are used to fulfill particular functions of the lock system. The functional DSM is build by using the insight that if two components share a function, an interaction between these components must also exist.

  There are two data sources that describe the coupling structure of functions and components. Both of them are used in a complementary manner to obtain a Design Matrix (DM). This DM appears to be incomplete and some manual improvements are made.

  The DM is subsequently converted to a DSM by the use of a conversion algorithm developed by Wilschut (2015). Since the conversion is made via the functional coupling structure of the system, the resultant DSM is called a functional DSM.

- *Enhance the physical DSM and analyzing its structure*: The functional DSM is used to enhance the physical DSM. This is done by constructing a comparison DSM in which both DSMs are depicted. The comparison DSM is used to suggest improvements for the DM, to verify the interactions obtained by constructing the physical DSM and to suggest new interactions.

The enhanced physical DSM is modularized in order to reveal the underlying coupling structure of the system. This is done by applying a clustering algorithm to the enhanced physical DSM and by subsequently manually post processing the results.

- *Explore the resulting DSM in RA context*: The improved and modularized DSM, which faithfully represents the coupling structure of lock system Eefde, is used as a base to identify components and modules with a high impact on the RA characteristics of the system.

  The different interaction types and strengths are aggregated to obtain a representative RA innteraction strength (RRAIS). The RRAIS value denotes the importance of an interaction with respect to the RA analysis.

  Subsequently, a relative RA impact value (RRAI) is determined for each of the components. This value is a characteristic of a component, in contrary to the RRAIS which is a characteristic of a component pair. These values and DSM are used to obtain the relative RA impact DSM. The RRAI DSM depicts interaction with a high RA impact. By identifying the clusters in which these interactions reside, the high RA impact modules can be identified.

1.5 Thesis outline

In Chapter 2, relevant literature is presented that describes decomposition strategies and coupling structure representation. Special attention is paid to the practical issues regarding DSM development like interaction identification methods an maintaining objectiveness.

Via an investigation of the available data and the knowledge obtained in Chapter 2, a method is developed. Chapter 3 provides a detailed overview on how the techniques encountered in literature can be applied to complete the objectives of this study.

The decomposition strategies obtained in Chapter 2, are used to determine a suitable and representative decomposition of lock system Eefde. This process is described in Chapter 4.

In Chapter 5, the resultant decomposition is used as a base to construct a physical DSM of the lock system. A preliminary DSM is constructed via documentation, and subsequently improved by interviews with system experts.

A functional DSM of the lock system is developed by converting a DM into a DSM in Chapter 6. The principles governing this conversion process and its implications are elaborated.

In Chapter 7, the functional DSM is used to enhance the physical DSM. Furthermore, the differences between the physical and functional DSM are investigated and implications for the DM are elicited.

The coupling structure analysis via clustering techniques of the improved physical DSM is described in Chapter 8. The errors that surface during the in-dept analysis are resolved and the modularized coupling structure representation of lock system Eefde is obtained.

Chapter 9 describes the RA orientated analysis of the modularized DSM. The main research question is answered by identifying components and modules with a significant impact on the RA characteristics of the lock.

The conclusions of the preceding chapters are summarized and reflected in Chapter 11.

In Chapter 12 recommendations for future research are provided.

Chapter 2

Related work

A literature review has been performed to identify means to determine the existing dependency structure between the lock components, and to identify high RA impact components and modules within this structure.

First, decomposition techniques to systematically determine these components are reviewed. The dependency structure formed by the interactions that exist between the components of the lock system are essential in its description. Various types of interactions and means to represent them are investigated. The Design Structure Matrix (DSM) appears as an attractive representation of the dependency structure. Various procedures to develop a DSM are reviewed. It is investigated how the reliability and availability of a system can be studied from the perspective of DSMs. Finally, a case study is reviewed that employs a similar approach to determine risks in the design of the NASA Pathfinder.

Reliability and availability are defined by Birolini (2007): "If n statistically identical and independent items are put into operation at time $t = 0$ to perform a given mission and $N < n$ of them accomplish it successfully, then the ratio N/n is a random variable which converges for increasing n to the true value of the reliability." Thus, reliability is a characteristic of a system expressed by the probability that it will perform its required function under given conditions for a stated time interval. Availability is defined as the proportion of time a system performs its required function for a stated time interval and can be calculated by:

$$A = \frac{MTTF}{MTTF+MTTR}$$

where $MTTF$ denotes the Mean Time To Failure and $MTTR$ denotes the Mean Time To Repair. The availability of a system is therefore a function of its reliability ($MTTF$) and its maintainability ($MTTR$).

2.1 Decomposition of systems in components and functions

To investigate the dependency structure between the components of a system, first these components have to be determined. Chiriac et al. (2011b) suggest three distinct approaches in decomposing systems into their constituent components: assembly based decomposition, service based decomposition and function based decomposition. Suh (1990) proposed a technique known as zigzagging to systematically decompose the components and functions of a system simultaneously, see Figure 2.1.

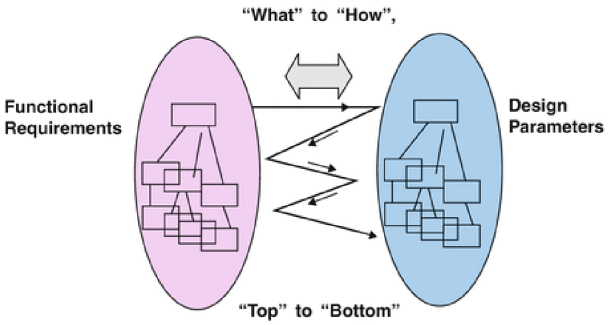


Figure 2.1: Zigzagging decomposition process.

The design parameters in Figure 2.1, refer to the components of a system, and the functional requirements are its functions. The decomposition process starts by defining the main function of the system. The system is then coupled to this function by the first horizontal arrow. The subfunctions of this system are defined and all subsystems required for these functions are determined. The subfunctions of these subsystems are determined and the process is repeated on one increased level of detail. By following these steps until a satisfying degree of detail is obtained, the system can be systematically decomposed.

Two important characteristics of a decomposition are:

- The decomposition level of detail i.e. their granularity[1] should be consistent for all components (Chiriac et al., 2011a), and
- The components must be non-overlapping, i.e. their respective definitions should not include other components (Tilstra et al., 2012).

A non consistent granularity distribution over the components of a system causes a not evenly distributed focus over the various aspects of the system. By ensuring the non overlapping nature of components, their non ambiguous definition is promoted and miscommunication is prevented.

Browning (2001) furthermore suggests to "decompose the system one step lower than the subsystems of interest". This allows the subsequent coupling structure analysis to define naturally emerging subsystems. Eppinger and Browning (2012) suggests to limit the decomposition to a maximum of 50 components to prevent intractability.

Chiriac et al. (2011a) show that different decomposition strategies, arising from varying viewpoints, yield a different set of components. It is therefore important to, during investigation of an existing decomposition, be aware of the various possible viewpoints that could have been used to develop it.

Some examples of decompositions resulting from varying strategies and viewpoints can be found in literature: Pimmler (1994) used a mix of functional and physical components to describe a climate control system. Sosa et al. (2003) decomposed a jet engine into 8 major subsystems and subsequently split these subsystems in 54 components. Brady (2002) analyzed the components and modules of the Mars Pathfinder that possibly have a technology risk before incorporating them in the decomposition. Alizon et al. (2007) disassembled Kodak cameras to determine the components.

As stated by Suh (1990), a system can also be decomposed into functions instead of components. Stone and Wood (2000) stress the importance of unambiguous function definition. They defined a

[1] The "grain" size or detail of the decomposition level.

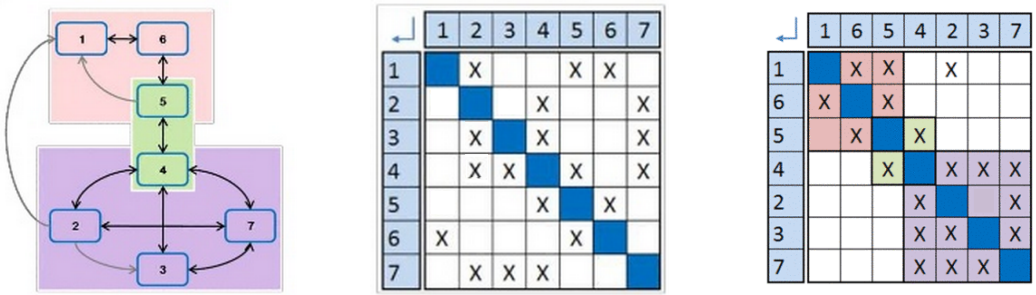
function as an input/output relation stated in verb-object form and worked on a functional basis to aid in the systematical functional decomposition of a system. Hirtz et al. (2002) elaborated on this functional basis to make it more explicit.

2.2 Interactions, their representation and coupling structure analysis

The components of a lock need to work together to enable ship passage, i.e. the lock components need to interact to provide the desired functionality. These interactions may vary in type (e.g. electrical, spatial, etc.) and in strength. The interactions define the structure of a system. Various representations, used to visualize and analyze this structure can be found in literature.

There exist a great variety of interaction representation methods, most of which can be categorized under matrix based representations (Incidence Matrix, Design Matrix, Design Structure Matrix) or graph based representations (Directed Graph, Undirected Graph). Park and Cutkosky (1999) state that graph representations are more intuitive and easier to construct whereas matrix representations are more suited for system analyses. The Design Structure Matrix (DSM) is an intuitive matrix representation of the occurring interactions. A large variety of analysis techniques is readily available for DSMs.

In Figure 2.2a a directed graph visualization of a system is depicted. The arrows in this visualization depict the directed nature of some interactions. The arrow between component 5 and component 1 for example, shows that component 5 exerts a non reciprocal influence on component 1. This graph visualization can also be depicted in a matrix representation, see Figure 2.2b for the DSM representation of the directed graph.



(a) (b) (c)

Figure 2.2: (a) A directed graph (b) The DSM representation (c) The clustered DSM

The row elements in Figure 2.2b represent the input, and the column elements the output. The directed nature of an interaction is represented by a non symmetrical entry in the DSM and the undirected interaction by a symmetrical entry. Element 1 shows interactions with element 2, 5 and 6. Since element 2 and 5 only provide input, these interactions are represented by a non symmetrical entry in the DSM. The interaction between element 1 and element 6 however shows a undirected or reciprocal interaction and thus is represented by a symmetrical entry in the DSM.

The term Design Structure Matrix (DSM) was first introduced by Steward (1981) when using matrix based techniques to analyze the structure of a system. The DSM is a square $N \times N$ matrix mapping the interactions amongst N system elements. Since its introduction it has seen a broad range of applications from the analyses of electronic systems and buildings to aircraft and auto-mobiles (Eppinger and Browning (2012); Yassine and Braha (2003)).

It is safe to consider the DSM a proven technology. There exist several types of DSMs, each with their own specific analysis techniques, see Figure 2.3.

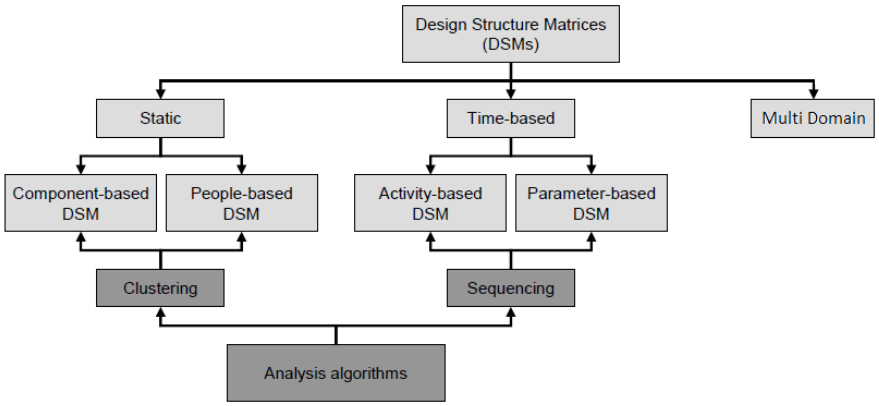


Figure 2.3: DSM classification including corresponding analysis techniques, adapted from Maurer (2007).

Time based DSMs are used to describe processes, i.e non simultaneous existing elements. The DSM elements can be activities that show interdependence (Activity DSM) or the design process of various system parameters (parameter DSM). The process of reordering these elements to find an optimal execution order is called sequencing.

Static DSMs are used to describe the static dependency structure of the components of a system, they can be used to investigate the underlying coupling structure. This is done by reordering the sequence in which the elements are represented in the DSM. This technique is called clustering, see Figure 2.2c for the clustered representation of the graph in Figure 2.2a. As can be seen in Figure 2.2c the structure can be separated in three distinct modules: an orange module, a green module and a purple module. The green module connects the orange module and the purple module. The orange module and purple module also show an extra module interaction between component 1 and component 2 that connects them. This structure was not visible in Figure 2.2b, the unclustered DSM.

In general, the underlying coupling structure exposed by clustering analysis can be categorized into three structural types.

- *A modular structure*: distinct modules can be formed with a high internal interaction and a low external interaction. See for example the "Front End Air Chunk", the "Refrigerant Chunk" and the "Interior Air Chunk" in Figure 2.4.
- *A hub- or bus-structure*: the system possesses bus components that connect a multitude of modules. See for example the "Air Control" and the "Refrigeration Controls"components.
- *An integral structure*: an integral coupling between the system's elements. No real distinct modules exist, and most components are connected to each other (Not displayed in the figure).

2.3 Development of the Design Structure Matrix

Eppinger and Browning (2012) distinguish two steps to obtain a DSM:

1. Decompose the system in its constituent parts, and

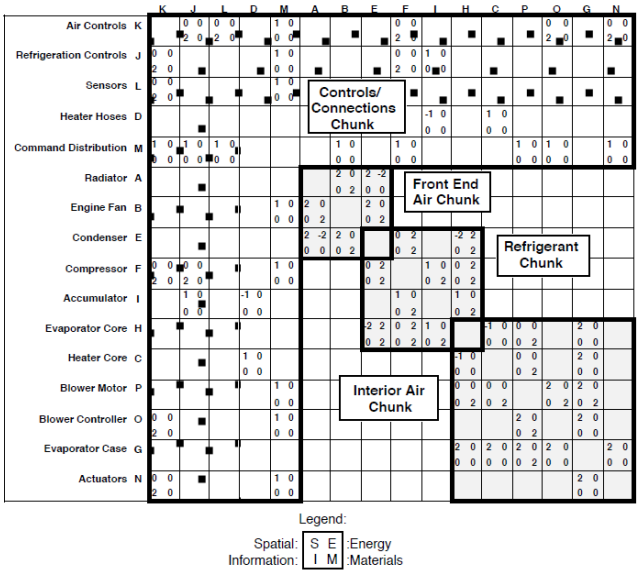


Figure 2.4: Resulting clustered DSM of Ford climate control system, adopted from Pimmler (1994).

2. identify and characterize the interactions between them.

In general, information about interactions is obtained by interviewing system's experts (Eppinger and Browning, 2012). Kusiak (2008) states that it is sometimes possible to obtain information about interactions from product documentations but that it can be a difficult process. Tilstra et al. (2009b) developed an interaction basis as an effort to assist in objective identification of the occurring interactions. Pimmler (1994) applied a rating scheme to facilitate in consistent rating of the strength of an interaction, see Figure 2.5

Spatial	
Required: (+2)	Physical adjacency is necessary for functionality.
Desired: (+1)	Physical adjacency is beneficial, but not absolutely necessary for functionality.
Indifferent: (0)	Physical adjacency does not affect functionality.
Undesired: (-1)	Physical adjacency causes negative effects but does not prevent functionality.
Detrimental: (-2)	Physical adjacency must be prevented to achieve functionality.

Figure 2.5: Rating scheme to enable an objective distinction between various interaction strengths, adopted from Pimmler (1994).

Tilstra et al. (2009a) furthermore recognized that knowledge about the existing dependency structure is often highly distributed over various system experts and documentation. They developed a method called distributed modeling as a means to both overcome the subjectiveness of experts and the distributed nature of interaction knowledge, see Figure 2.6.

Tilstra et al. (2009a,b) start with building a subsystem DSM; i.e. a DSM at the granularity level of subsystems. The depencies between the various subsystems are determined and depicted in the DSM, see Figure 2.6a. For every subsystem in this DSM a separate DSM on element level is built, see Figure 2.6b. In these separate DSMs, an external variable is included to represent the interactions the elements might have with other subsystems. The separate development of these element level DSMs allows to employ the specific knowledge on a particular subsystem a system's

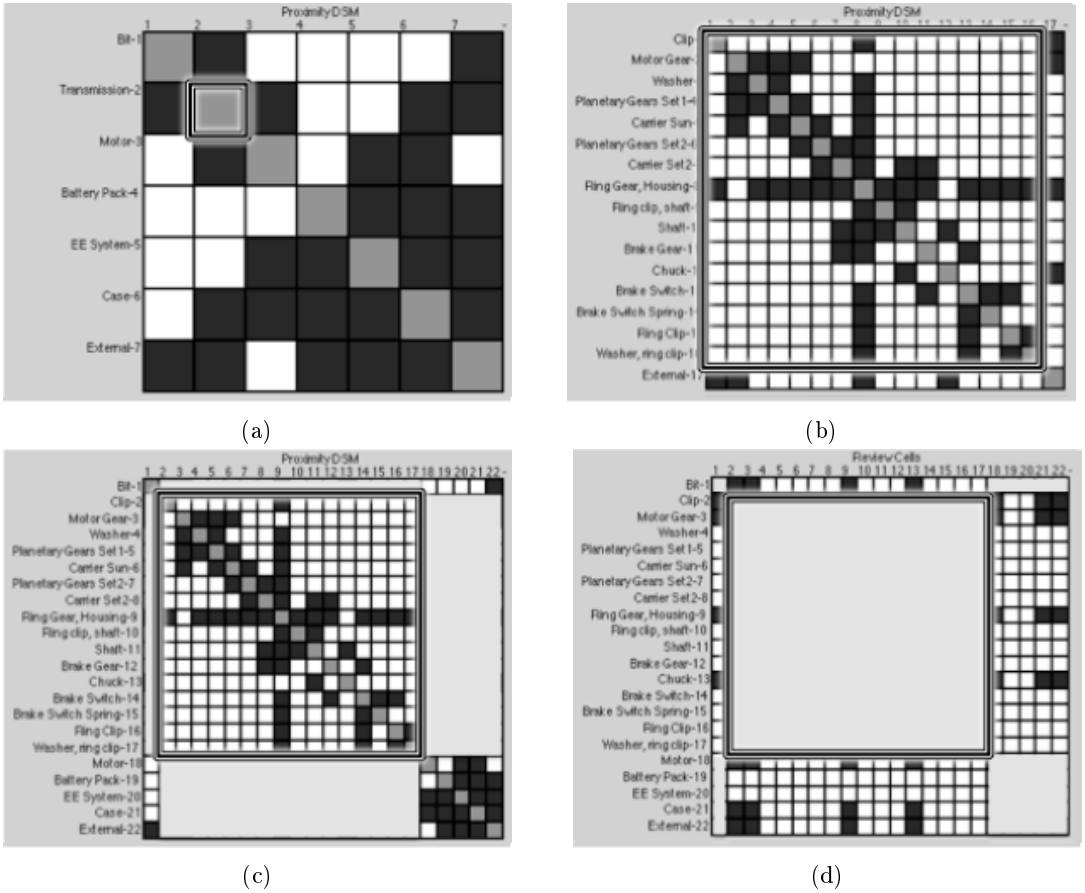


Figure 2.6: (a) DSM of subsystems (b) subsystem DSM (c) subsystem insertion (d) identify external (extra subsystem) interactions

expert might have. The element level DSMs are subsequently inserted in the original subsystem DSM, see Figure 2.6c. The subsystem DSM and the external interactions depicted in the element level DSMs can subsequently be used to identify possible interactions between the elements of the detailed DSM and the rest of the system, see Figure 2.6d.

An alternative way to obtain a DSM, is via the functional structure of a system (Dong and Whitney (2001)). This functional structure can be represented by a Design Matrix (DM). The DM depicts the dependency structure between the functions of a system and its components. Various conversion algorithms exists that can convert a DM to a DSM.

Since the DM obtained in practice is commonly incomplete, Tang et al. (2009) suggested that the DM-DSM conversion should only be used to enhance the existing DSM, i.e. improve the existing DSM by identifying missing interactions. Bagley (2005) used this technique to enhance the DSM of a Ford steering system that was developed by interviews.

Several techniques exist for this conversion. An intuitive method uses the notion that if two components contribute to fulfill the same function, these components must have a (indirect) interaction (Maurer (2007), Wilschut (2015)), see Figure 2.7 for an example.

The conversion is performed by going through the row of functions and by investigating which components are required for a particular function, e.g. Function 1 requires Component 1, Component 2 and Component 5. This means Component 1 has an interaction with Component 2 and Component 5 and hence, these interactions receive a score of "1". Sometimes the same pair of

	Component 1	Component 2	Component 3	Component 4	Component 5
Function 1	1	1			1
Function 2		1	1	1	
Function 3	1	1	1		

(a)

		1	2	3	4	5
Component 1	1	1	2			1
Component 2	2	2	2	2	1	1
Component 3	3		2	3	1	
Component 4	4		1	1	4	
Component 5	5	1	1			5

(b)

Figure 2.7: (a) A DM depicting the coupling structure between functions and components of a system (b) The DSM obtained by converting the DM.

components is used in another function. In this case the scores are just added, e.g. the interaction between Component 1 and Component 2 also exists for Function 3, so it receives score "2". Since no distinction is made in the direction of the interaction, the resulting DSM is symmetrical.

2.4 Case study: The NASA Pathfinder

Brady (2002) investigated the effect of technology readiness and risk in system components in NASA's Mars Pathfinder. To this end a technology risk DSM (TR-DSM) was developed. This case study also focuses on the dependency structure between the system's components as a means to improve a certain system characteristic. It recognizes the importance of the dependency structure between the components instead of the only considering the components itself. It therefore seems highly relevant with respect to the objectives stated in Section 1.2.

The technology risks that exist within the dependency structure of the Pathfinder are determined in three distinct steps:

First a component DSM was constructed. The interaction strengths between the components were rated according to a rating scheme introduced by Pimmler and Eppinger (1994). This scheme assists in the objective rating of interaction strengths and consists of descriptions of distinct interaction strengths matched with their respective ratings. The ratings for the different types of interactions (e.g. energy, spatial and information) were subsequently summed to obtain a number depicting the representative interaction strength I.

Secondly, a technology risk factor (TRF) is determined for each of the system's components. This is done by comparing each of the components to a rating scheme. The TRF ranges from 1 (proven technology) to 5 (highest risk/novice technology).

Thirdly, the actual DSM entry for component i and component j is determined by multiplying the individual TRF values of two components and their representative interaction strength I:

$$R_{i,j} = TRF_i \times TRF_j \times I_{i,j}$$

This number then represents the development and operational risk of both the components and their interaction. By completing this operation for all entries in the DSM, the TRF DSM is obtained.

The DSM is clustered with respect to the representative interaction strength I, see Figure 2.8.

As can be seen in the figure, 9 modules are identified via the clustering algorithm: 8 clusters and a bus module. The final cluster, "Command and Control" exists within the bus module. This means that this cluster exhibits both modular and bus-like characteristics. Furthermore only 2 interactions exists outside the modules, the coupling structure of the Pathfinder is therefore highly modular.

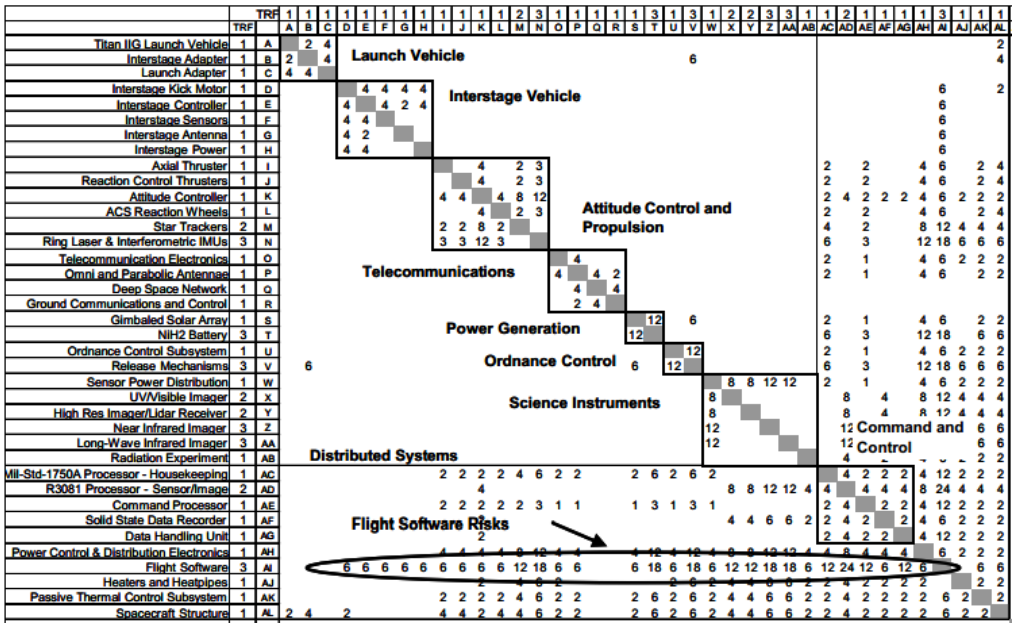


Figure 2.8: NASA technology risk DSM for Mars Pathfinder, adopted from Brady (2002).

After the coupling structure is determined, the risk values (R) are placed in the DSM. The higher the R value of a component pair, the higher their respective technology risk. Since the DSM has been clustered with respect to the physical coupling structure, the R values can now be used to identify high risk areas in the design. This identification is subsequently used to distribute the focus of design optimization.

2.5 Conclusion

The main system decomposition strategies found in literature are: assembly based decomposition, service based decomposition, functional decomposition and zigzagging. When investigating a particular decomposition, the decomposition viewpoint that was used needs to be taken into account.

The results of the decomposition: components and their functions, need to be defined on both a consistent granularity level and in a non-overlapping manner. This can be checked by investigating the component definitions.

The dependency structure of the system is described by the interactions between its constituent components, which can be established by interactions of various types and strengths. The two main representation methods of a system are: graph based and matrix based representations. Graph based representations are more intuitive, but become intractable with increasing system size. Matrix based representations are computationally beneficial.

The design structure matrix is a suitable medium to represent the systems coupling structure and offers computational advantages. The typical procedure to obtain a DSM is by interviewing system's experts on the interactions between components. To aid in this process, some guidelines have been provided to minimize subjectivity and overcome the problem of distributed knowledge.

A DSM can also be obtained via a Design Matrix to DSM conversion. This method uses the functional structure of a system and can be used in a complementary manner, i.e it can be used to verify or improve the DSM.

Reliability and availability (RA) analysis is characterized by the definition of failure. In this study, failure is defined as: failing to fulfill the required function. Limited work has been performed on the specific incorporation of RA in DSM context.

The NASA Pathfinder case proposes an elegant way to include technology risk analysis in the DSM methodology. A strong parallel can be drawn between the technology risk of the Pathfinder case and the RA analysis of lock system Eefde. The techniques developed in the case study are therefore used to include the RA analysis in the DSM methodology.

Chapter 3

Method

Examining the available data and referencing the results with the tools found in literature, points out a method to obtain a representative DSM of the system. Via a modification of the NASA Pathfinder case (Brady (2002)), this DSM is subsequently used to analyze the system's coupling structure with respect to its RA characteristics. See Figure 3.1 for a schematic of the method.

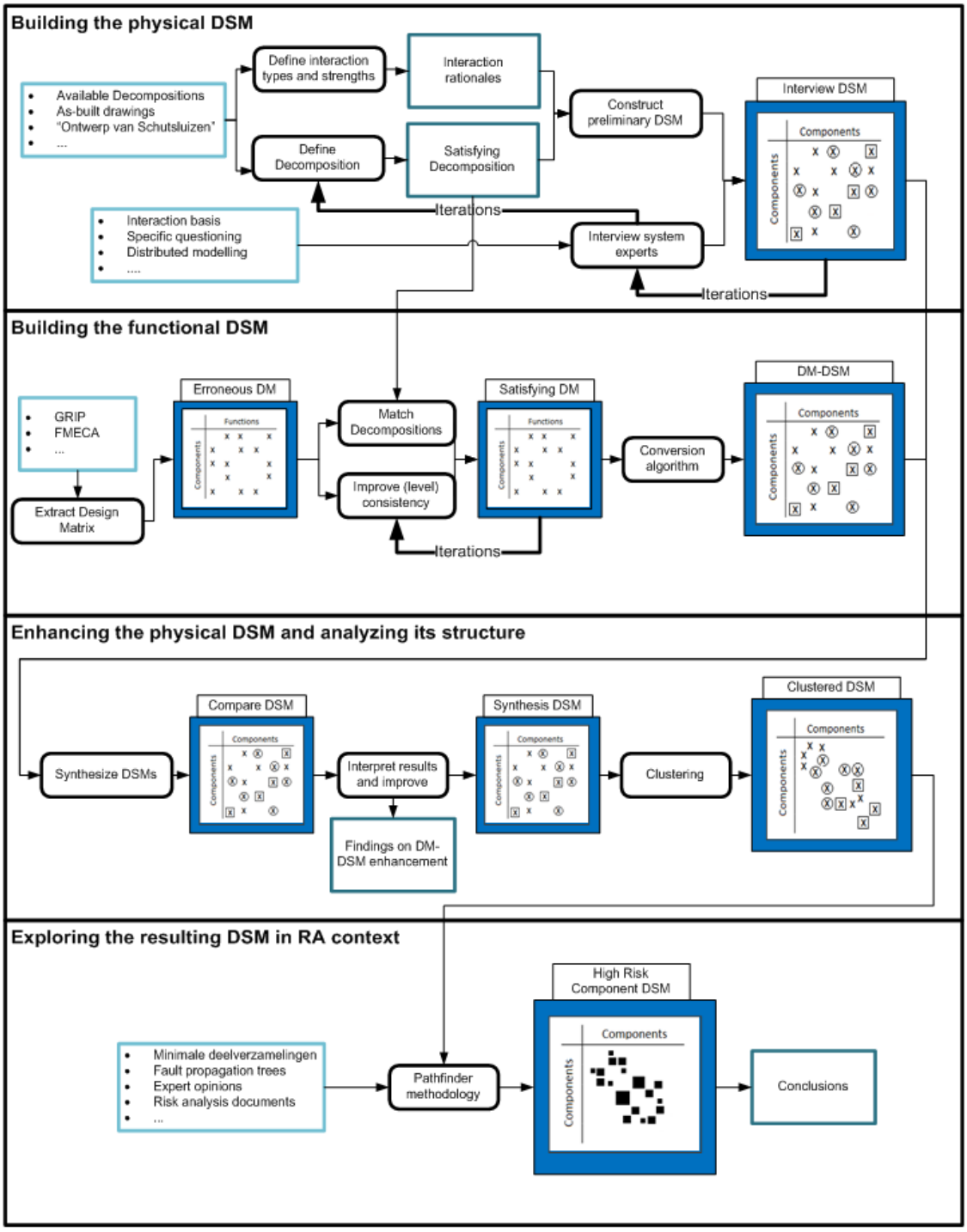


Figure 3.1: Schematic of proposed method.

The proposed method is divided into four main steps: building the physical DSM, building the functional DSM, enhancing the physical DSM and analyze its structure DSM, and exploring the resulting DSM in RA context. These steps are explained in more detail in the following sections.

3.1 Building the physical DSM

A physical DSM is built to collect and represent the physical interactions that occur within the lock system. This is done via the two steps from Section 2.3: decompose the systemt and identify the interactions between them.

Chiriac et al. (2011b) stated that service based decomposition is the most common decomposition method and that most companies already have such a decomposition in place. RWS is no exception and possesses 4 distinct lock decompositions. By investigating these available decompositions and applying the suggestions made by Chiriac et al. (2011a) and Tilstra et al. (2012) (i.e. ensuring a non overlapping definition of the components is used and by checking for a consistent granularity level), a decomposition of lock system Eefde is developed. This decomposition is subsequently reviewed by system's experts in an iterative manner until all important aspects of the lock are included.

The second step, identifying the interactions that exist between the components, is performed in three sub steps. First, the most important interaction types governing the system's coupling structure are determined by studying the working principles of the system. The most important types are: spatial, information, energy and location. For each of these interaction types, a rating scheme is developed to assist in the objective quantification of the strength of the interaction. The strengths either represent a weak interaction (rating 1) or a strong interaction (rating 2). The interaction identification and rating scheme is used to objectively identify and rate occurring interactions.

Secondly, a preliminary DSM is constructed by investigating design drawings and as-build drawings and referencing them with the obtained decomposition. Whenever a potential interaction is encountered, the interaction rating scheme is used to determine its type and strength.

The resulting preliminary DSM is improved via interviews with system's experts. As suggested by Park and Cutkosky (1999), a graph representation is used for the interviews since it is very intuitive for investigating interactions between components via interviews. A graph representation of every component in the system and its direct interactions with other components is constructed via the preliminary DSM. These graph representations in combination with the decomposition are used as a guideline to enable specific questioning during the interviews. These interviews are used to improve the existing coupling description and to suggest missing interactions.

3.2 Building the functional DSM

A functional DSM is built to enhance the physical DSM. This functional DSM represents the functional dependency structure that exists between the components of the lock system. The functional DSM is obtained by converting a design matrix (DM) into a DSM. A DM represents the dependency structure between the functions and components of a system.

RWS possesses two data sources that describe this dependency structure: GRIP Files and FMECA reports. These sources describe which components are required for a particular function. Since the components used in these sources do not directly match the components from the obtained decomposition, they are manually matched to each other. By subsequently including all of the depicted function-component relationships in the matrix, the DM is built for the lock system. The incompleteness of the data is party overcome by manually correcting obviously missing interactions.

The conversion of the DM into a functional DSM is performed by using the insight that if two components contribute to fulfill a particular function, an interaction (of any degree) between these components must exist (Wilschut (2015)). Subsequently, the limitations of this conversion are elaborated in order to enable a decent interpretation of this DSM. It is found that even if the dependency structure description between functions and components is incomplete, the functional DSM can still be useful for improving the physical DSM.

3.3 Enhancing the physical DSM and analyzing its structure

The functional DSM is used to enhance the physical DSM by suggesting missing interactions and verifying existing interactions.

This is done by constructing a comparison DSM in which both DSMs are depicted. This comparison DSM is constructed by comparing the physical DSM and the functional DSM. If an interaction solely exists in the functional DSM, the comparison DSM entry is "1". If an interaction exists only in the physical DSM the respective comparison DSM entry is "2". And if both the physical and functional DSM denote the same interaction, the respective comparison DSM entry is set to "3".

The type 1 interactions can depicts either a missing interaction or a higher order degree interaction (component A is connected to component D via B and C). All of these interactions are manually checked to distinct between these two possibilities.

The type 2 interactions suggest incompleteness of the functional DSM. By investigating these type 2 interactions, specific improvements for the DM can be suggested that will result in a better functional DSM.

The type 3 interactions are used to verify the interactions of the physical DSM. The reasoning is that if both DSMs identify the same interaction, it must exist. The comparison DSM can be used to suggest improvements for the DM, to verify the interactions obtained by constructing the physical DSM and to suggest new interactions.

The enhanced physical DSM is modularized by applying a clustering algorithm. Since the clustering algorithm requires a single representative interaction strength between a pair of components, the different interaction types are aggregated into a single number. The resultant modularized DSM is inspected and a post processing step as suggested by Helmer et al. (2010) is performed to identify overlapping clusters and a bus structure in the DSM.

The resultant structure, depicted by the modularized DSM, is reviewed. By critically inspecting the results of the modularization, some suggestions for improvement are identified and implemented. During this phase the clusters that naturally appear from the underlying coupling structure are identified and all remarkable interactions are discussed.

3.4 Exploring the resulting DSM in RA context

The improved and modularized DSM, which faithfully represents the coupling structure of lock system Eefde, is used as a base to identify components and modules with a high impact on the RA characteristics of the system.

In analogy to the NASA Pathfinder case study, the various interaction types and strengths are aggregated into a single representative interaction strength. In the NASA case study, this aggregation has been performed by simply adding the various interaction strengths to obtain the representative interaction strength. In this study a distinction is made between the effect of the various types.

Since the effect of the various interactions types on the reliability and the availability is different, an alternative aggregation procedure is used to obtain respectively the reliability interaction strength (RIS) and the availability impact strength (AIS). For reliability, a higher weight is assigned to interaction types with a high failure frequency (energy and information interaction types) and for availability, a higher weight is assigned to interaction types with a higher $MTTR$ (spatial interaction type).

Subsequently, a component impact value for both the reliability (CRI) and for availability (CAI) is determined for each of the components. For most components, these values are determined by inspecting data governing the failure frequencies and the $MTTR$ of the lock components. For some components the data is inadequate, and the impact values are estimated. The CRI and CAI values are characteristics of a component, in contrary to the RIS and AIS values which are a characteristics of the interaction between a component pair.

The reliability DSM is obtained by incorporating the reliability interaction aggregation to the modularized DSM. All interaction types that occur between each component pair in the modularized DSM are thereby aggregated into a single RIS. This RIS value is subsequently multiplied with the CRI values of both the components for each component pair and the reliability DSM is complete.

To obtain the availability DSM the RIS and CRI values are replaced by the AIS and CAI values respectively. The resulting DSMs represent the impact on respectively the reliability and availability of the lock's coupling structure.

Chapter 4

Decomposition of the system

As determined in the literature review, various methods for decomposing a system into its constituent parts exist. As stated by Chiriac et al. (2011b), not only the use of various methods result in a different decomposition, but also differing viewpoints of the practitioner can cause a change of focus in the decomposition of the system.

During the investigation of documentation of Rijkswaterstaat regarding the decomposition of lock systems, it was found that a great number of decomposition exists, all constructed with specific intentions. Some decompositions consider mainly the control aspects or on the civil engineering parts of the lock system. Other decompositions do not include certain components that are essential to the operation of the lock system.

In this chapter, effort is made to incorporate the different viewpoints of the various decompositions into a single decomposition that evenly distributes the focus over the various aspects governing the lock system. To ensure a manageable amount of components in the decomposition, the suggestion made by Eppinger and Browning (2012) to decompose the system into about 50 components, is followed.

First, the boundaries of the system are unambiguously defined. A balance needs to be found between incorporating all components that have an influence on the RA characteristics of the lock system and maintaining a manageable project.

Secondly, a selection of the existing decompositions is presented and their characteristics are compared. The idea is that by comparing the decompositions resulting from a variety of viewpoints, a more accurate and more complete decomposition of the system can be obtained.

Thirdly, a decomposition is developed by combining the best aspects of the existing decompositions. The resulting decomposition is reviewed by system experts. In this process, some components were added to the decomposition, some components were removed from the decomposition and some components were aggregated into a single component.

4.1 System boundary

The system boundaries are determined by investigating the components that have an influence on the RA of the function: allow ship passage. This is done by inspecting a fault tree analysis that has been performed for this function by Arcadis (2013a and 2013b). A fault tree analysis is a tool to determine the possible events that can lead to failure of a particular function. It traces these events down to its roots. The top level branches of this fault tree are depicted in Figure 4.1.

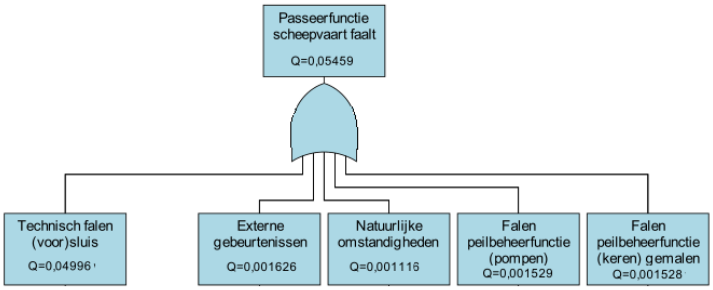


Figure 4.1: Top level branch of the fault tree for the function: allow ship passage, adapted from Arcadis (2013b).

In Figure 4.1, the Q depicts the impact on the non availability. Arcadis determined these values by multiplying the $MTTR$ and the frequency of failure. As can be seen in the figure, in total five events can cause failure of the ship passage function. Two of these events are external: external events (e.g. power cuts) and natural circumstances. The other three event are: failing to maintain the required water level by blocking water, failing to maintain the required water level by releasing water, and technical failure of the lock system.

By comparing the Q values of the various failure events, it can be concluded that technical failure of the lock system has a significantly higher contribution to the impact on availability than the other modes of failure. The other failure modes are therefore neglected in this thesis.

The subsequent analysis focuses on the lock system. The system boundaries of lock system Eefde are depicted in Figure 4.2.

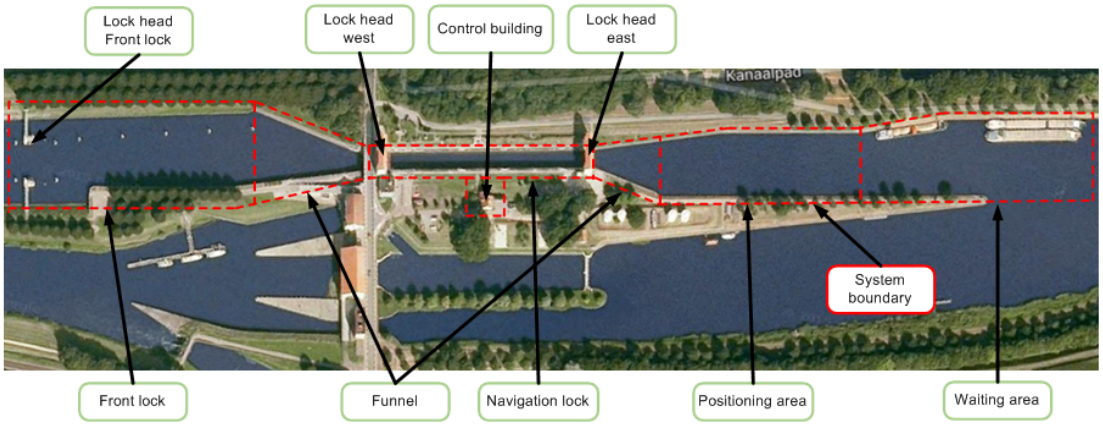


Figure 4.2: System boundary of lock system Eefde.

The different sections of the lock system are separated by dashed lines. The names of these sections are depicted below the figure. In total, six sections are distinguished. The Front lock is connected to the Navigation lock via the Funnel. The Funnel on the other side connects the Navigation lock to the Outport. Before ships are allowed to enter the , they have to wait in the Waiting area. The and Waiting area on the IJssel side of the lock system are located further downstream of the lock complex. The Run-out zone (not displayed in the figure) is the extension of the Waiting area on either side of the system and consists of a length of channel used by the ships to achieve their regular route trajectory.

The bridge is excluded from the analysis. As can be seen in the second level fault tree analysis (Arcadis (2013a)) , the bridge has no impact on the reliability and availability of the ship passage

function. The main subsystems of the system are depicted above the figure. It is important to note that the Control building is included in the lock system analysis, as it provides housing for the supporting systems.

4.2 Existing decompositions

At RWS the following four relevant decompositions are frequently used:

- the Basis specification (NL: Basisspecificatie) decomposition (Rijkswaterstaat, 2012b),
- the OTL (Object Type Library) decomposition (Rijkswaterstaat, 2014b),
- the GRIP decomposition (Rijkswaterstaat, 2014a), and
- the NEN 2767 decomposition (Rijkswaterstaat, 2013).

Only the decomposition made according to NEN 2767, describes the lock system Eefde. The other decompositions describe the decomposition of a "generic" lock system.

4.2.1 Basis specification decomposition

The Basis specification (NL: Basisspecificatie) decomposition is a reference for lock system specifications. It describes the most important components of a "generic" lock, i.e. the components that exist in the majority of lock systems, see Figure 4.3

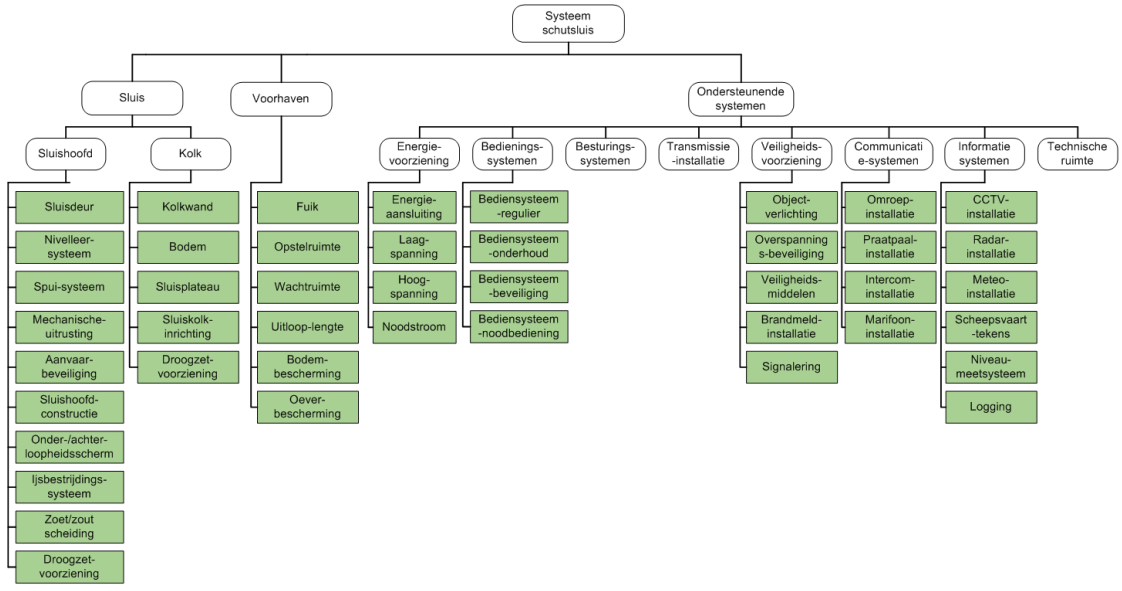


Figure 4.3: Basis specification decomposition of a generic lock (Rijkswaterstaat, 2012b).

This decomposition thoroughly describes the supporting systems. Since it describes a generic lock, it also contains some components that are not present in lock system Eefde. These are discharge system (NL: Spui systeem) and salt water/ fresh water separation (NL: Zoet/zout scheiding).

The dry chamber (NL: Droogzet voorziening) is solely used for maintenance on the Lock chamber. It is a separate object that is set in place when a particular area of the Lock chamber needs to be

accessed. Since it is only applicable to the Lock chamber wall, it can be seen as a part of it. It is hence not required explicitly include the dry chamber.

4.2.2 OTL decomposition

The OTL (Object Type Library) decomposition is part of a project by Rijkswaterstaat in which the focus is on ensuring all objects and their components are described in a non-overlapping manner. The parent child relationships are also linked in the OTL. Hence, it is denoted which components are used to form a subsystem, and which subsystems are part of a specific object, see Figure 4.4 for the OTL decomposition of a generic lock

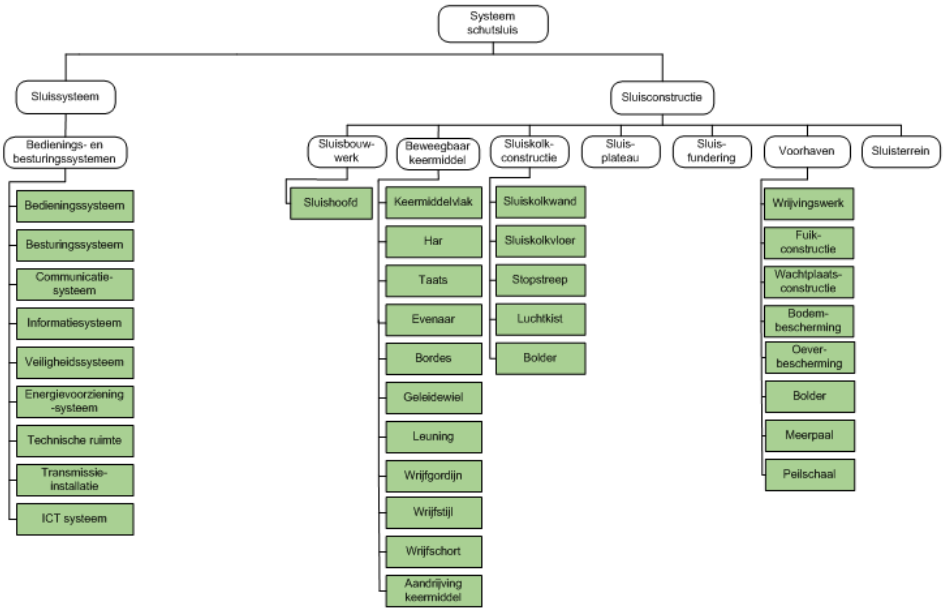


Figure 4.4: OTL decomposition of a generic lock (Rijkswaterstaat, 2014b).

It appears to be incomplete and to contain differences in decomposition detail between the components, i.e. there is an issue with the granularity level of the OTL decomposition. The decomposition does not contain the Vertical lift gates nor the Leveling system to control the water level in the Lock chamber. On the other hand, the components under the header Moveable water blocking system (NL: Beweegbaar keermiddel) are furthermore described in very high detail: five of these components make up the Actuators of the lock gates whereas the total number of components is much less than the Basis specification decomposition.

The granularity issue implies there is an increased focus on certain aspects of the decomposition. Since the objective is to obtain a single decomposition that evenly distributes the focus on the various aspects of the system, care must be taken when using decompositions with level issues for DSM based methods.

4.2.3 Grip decomposition

The Grip decomposition arises from a system control view of the lock system. It focuses more on the control and supervisory control than the other decompositions, see Figure 4.5.

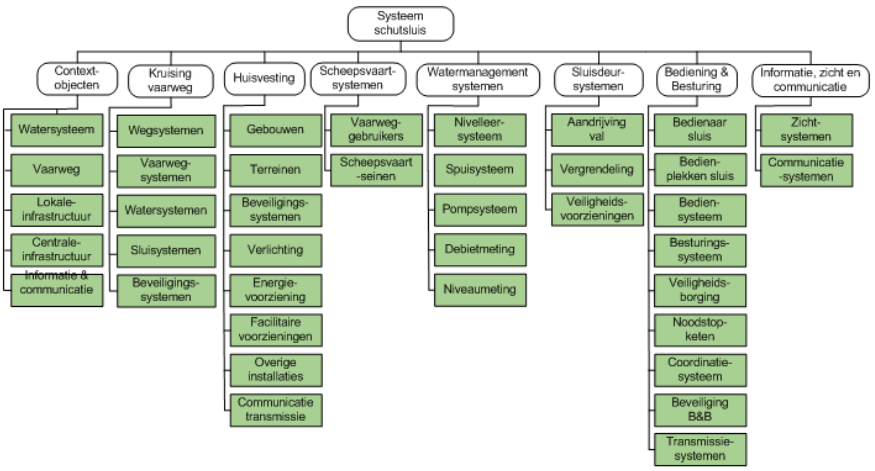


Figure 4.5: Grip decomposition of a generic lock (Rijkswaterstaat, 2014a).

The first two columns on the left side, context objects (NL: Contextobjecten) and objects related to the waterway (NL: Kruising vaarweg), describe the context of the lock system. They can be neglected during the investigation of the lock system itself.

This decomposition does not consider the physical components of the lock, i.e. the doors, the level slides, the swirls, the construction, etc. It does however provide the an elaborate decomposition of the control systems governing a lock system. About half of all the components are control components or sensors. The Grip decomposition therefore also contains a granularity level issue and cannot be used directly for DSM modeling.

4.2.4 NEN 2767 decomposition

The NEN 2767 decomposition is object specific, i.e it is developed for lock system Eefde. The focus of NEN 2767 is on the civil components. This is due to the fact that it has been developed for maintenance purposes.

The first two columns on the left hand side describe the decomposition of the Twentekanaal side lock head and the decomposition of the IJssel side lock head, respectively. As encountered in DSM literature, multiple instances of a certain component are included only once in the DSM unless the interaction between these components is clearly different (e.g. Ford climate control system, Pimmler (1994) and NASA Pathfinder risk assessment Brady (2002)), in the DSM methodology it is not common to incorporate the same components belonging to different subsystems. Since the DSM aims to represent the coupling structure of a system and its components, doing so can render the resulting DSM obscured (Eppinger and Browning (2012)).

4.3 Decomposition of lock system Eefde

The existing decompositions demonstrated how varying viewpoints on the system, yield distinct decompositions. These decompositions are however not suitable for direct use in the DSM analysis. They contain granularity level issues and components that are not required for the ship passage function. By integrating the existing decompositions into a single decomposition, the granularity level issues are reduced. The resulting decomposition is subsequently reviewed by system experts to reduce inconsistencies and to ensure all aspects of the lock system are included.

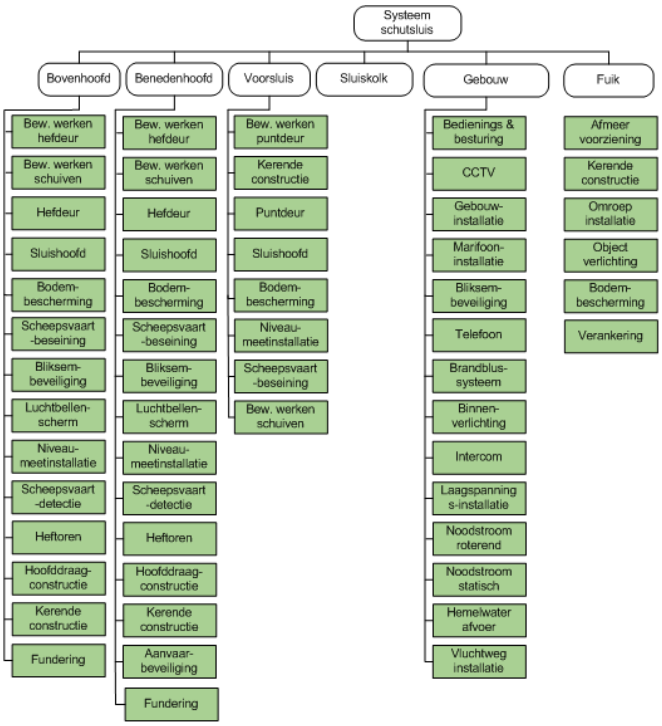


Figure 4.6: NEN 2767 decomposition of lock system Eefde (Rijkswaterstaat, 2013).

4.3.1 Integration of the decompositions

Since the NEN 2767 was specifically made for lock system Eefde, this decomposition has been taken as a starting point. The upstream lock head and downstream lock head for respectively the Twentekanaal side and the IJssel side contain the same dependency structures, they were aggregated to Lock head.

The control and supervisory control NL: (Bediening en besturing) of lock system Eefde are made up of many different subsystems with their own characteristics. In order to incorporate these characteristics in the DSM, its decomposition should include enough components to express these characteristics while maintaining an evenly distributed focus over the various aspects of the lock system. The control and supervisory control as decomposed by the GRIP decomposition consists of 9 components. Since the total of components should be around 50, using the GRIP decomposition for the control systems would consequently lead to excessive focus on the control and supervisory control subsystem. The decomposition of the control systems as defined by the basis specification decomposition consists of 5 components (NL: Bedieningssystemen + Besturingssystemen) and is therefore more suited for an evenly distributed decomposition.

A similar approach was taken for the energy supply of lock system Eefde. In the basis specification decomposition, the energy supply is decomposed with an increased level of detail: Grid connection, Low voltage supply, and Emergency power supply. The function of these different energy supplies is of interest for the RA analysis of the system. Hence, allowing more detail in the decomposition of the energy supply yields increased insight in its effects on reliability and availability.

The contrary is true for the emergency power supply. In the NEN 2767 decomposition, it is made up of two components, a static (battery) supply and a rotating supply (generator). Since their functions are essentially (at this level of abstraction) the same, they have been aggregated to Emergency power supply.

The Outport decomposition of the basis specification decomposition was incorporated to connect the lock system with the waterways.

Finally, the foundation of the Lock heads and the supporting construction (NL: Hoofddraagconstructie) have been aggregated to Lock head construction. This was done since the foundation solely has an interaction with the Lock heads and the Lock chamber, hence it would not yield extra insights in the resulting DSM.

4.3.2 Decomposition review

The final step in obtaining a suitable decomposition is reviewing the adapted NEN 2767 decomposition with RWS system experts. In this section, a summary of the results is presented.

The Lock swirl components (NL: Sluiskolk inrichting) are renamed to Shipping facilities and the Collision protection (NL: Aanvaarbeveiliging) of both the lock and the Front lock are included in the Shipping facilities.

The Security control system (NL: Bediensysteem beveiliging) is removed from the decomposition since it does not directly affect the ship passage function. Furthermore, an Operator/maintenance personnel and an Emergency shutdown have been added to the decomposition. Since the transmission installation (NL: Transmissie installatie) solely interacts with the supervisory control, it is merged into the supervisory control (NL: Besturingssysteem).

Since a Telephone is the primary means of communication for the operator (e.g. to contact maintenance personnel) it is included in the communication decomposition (NL: Communicatie systemen). Finally, a ship (NL: Schip) was added to the decomposition to investigate the occurring interactions with the rest of the system, see figure Figure 4.7.

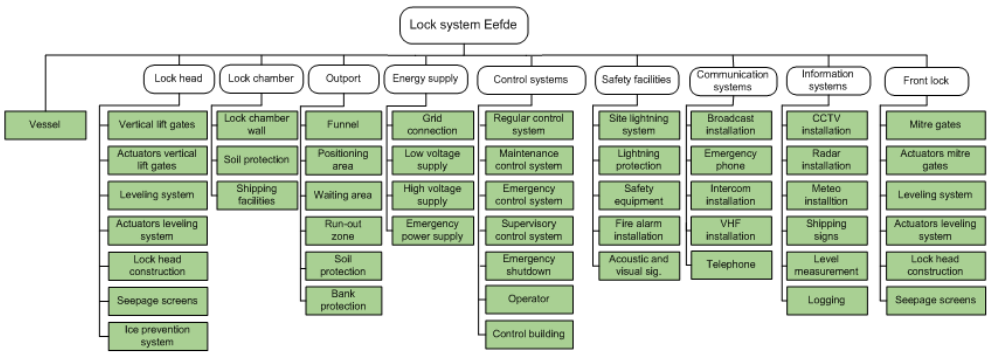


Figure 4.7: Reviewed decomposition of lock system Eefde.

This reviewed decomposition serves as a basis to build a DSM of lock system Eefde in the subsequent chapter.

4.4 Conclusion

The system boundaries have been defined by investigating which components have an influence on the RA of the ship passage function. The top level branch of the fault tree developed by Arcadis showed to be useful to objectively determine the system boundaries.

The decomposition of Energy supply and the Control systems provided by the Basis specification decomposition proved to be a useful balance between the number of components and the granularity level detail.

The OTL decomposition is incomplete in its description of the physical aspects of the lock. It does however describe the actuators of the lock doors in great detail. The Grip decomposition also does not represent the physical aspects of the lock system; it mostly focuses on the control aspects. The result of this skewed focus is that the control components are decomposed to an excessive high granularity level. The OTL and Grip decompositions can therefore not be used directly for DSM analysis.

The NEN 2767 decomposition has been selected as a basis to develop a decomposition of lock system Eefde. However, it lacks a description of the Energy supply and the Control systems. For the missing parts, the subsystem decomposition defined by the Basis specification decomposition is used.

The interviews that were held to check the obtained decomposition suggested new components and merged some components. They therefore showed that the knowledge of system's experts is required to capture all aspects of the system and to improve the granularity level consistency.

The employed method, consisting of: investigating existing decompositions, merging these decompositions into a single decomposition and finally reviewing the result, proved to be a practical way to obtain a decomposition that is useful for DSM analysis.

Chapter 5

Building the physical DSM

The physical DSM of lock system Eefde is developed in this chapter. This DSM represents the physical coupling structure between the components of the system. To develop the physical DSM, first a preliminary DSM of the lock system is constructed from documentation about lock system Eefde. Kusiak (2008), Tilstra et al. (2009b) and others, showed that documentation can be a valuable source for identifying interactions. In many DSM studies, expert interviews are used as a main source for DSM modeling (Eppinger and Browning, 2012). In this study both methods are used in a complementarily manner, i.e. the preliminary DSM obtained from data is improved via expert interviews.

The set of components depicted in the reviewed decomposition of Figure 4.7 is used to construct the DSM. The process of building the DSM consists of identifying the interactions that exist between these components.

First the type of physical interactions that occur in the system are determined by investigating the working principles of the lock system. Once the most important interaction types are identified, an interaction rating scheme is developed to enable an objective identification and rating of interactions and their strengths.

The physical interactions between the components are identified by investigating documentation on the lock system. Each time a possible interaction is encountered between a pair of components, the rating scheme is used to identify its type and rating. These characteristics are subsequently captured in the interaction score and placed in the DSM entry of the respective component pair.

The resulting preliminary DSM is iteratively improved by reviewing it with RWS system experts of various disciplines. Each suggestion made by the system experts is rated via the rating scheme and the DSM is updated. This is repeated until the system experts are satisfied with the DSM

5.1 Interaction rating scheme

The physical interactions that determine the coupling structure of the system, occur in various types and strengths. The interaction types that couple the components of the system are found by examining its working principles. The strength by which this coupling is characterized also varies. In order to objectively determine the type and strength of the interaction between a component pair, an interaction rationale is developed. This rationale provides a clear distinction between the various interaction types and strengths.

5.1.1 Occurring interaction types

The most common interaction types were summarized by Tilstra et al. (2009b) in an interaction basis. This interaction basis consists of 5 main interaction categories:

- Spatial: a pair of components is spatially connected.
- Material: a flow of material exists from one component to the other.
- Information: information exchange exist between a pair of components.
- Energy: a pair of components exchange energy.
- Movement: one component is connected via movement to another component, e.g. the gears in a gearbox.

Tilstra et al. (2009b) suggested to use this basis as a reference when identifying interaction types. They furthermore noted that specific systems require specific interaction types and that the provided interaction basis is not exhaustive. During the identification procedure, interaction types that are not mentioned in the basis may consequently arise.

By studying the principles of operation of the lock system, the connection that exists between its comprising components becomes more apparent. The identified connections are referenced with the interaction basis to determine the occurring interaction types.

In lock system Eefde, a significant part of the components is connected spatially, e.g. the Vertical lift gates with the Actuators vertical lift gates and the Actuators vertical lift gates with the Lock head construction, see Figure 5.1.

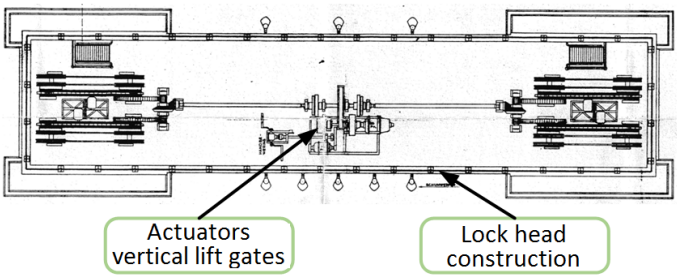


Figure 5.1: Section of Lock end construction depicting a (a part of) the Driving mechanism of the Lock doors, depicting a Spatial interaction between them (dienst infrastructuur, 2014).

Other component pairs are also connected in a spatial sense, but in a different way, i.e. the interaction basis description that fits most closely is spatial, but the nature of the interaction is different. An example is the interaction between the Vessel and the Shipping signs. The Shipping signs have to be placed in line of sight of the Vessel but they will never physically connect. Since the previously defined spatial interactions do physically connect, a distinction has to be made.

This distinction is made by introducing the location interaction type. This interaction type falls under the category of spatial interactions but solely includes non physically connected component pairs. A component pair is said to be physically connected when a small change of the dimensions of either one of them, has an effect on the dimensions of the other.

Hence, if a component pair is connected in a spatial sense, and the components are physically connected, the interaction is denoted as a spatial interaction. If the component pair is connected in a spatial sense, but the components are not physically connected, the interaction is denoted as a location interaction.

Information exchange is also abundantly present in the lock system. Both signal information and control information exchange occur between the various components of the lock, e.g. the control information send by the various control systems via the Supervisory control system to the various actuators.

The actuators are driven by electrical energy, hence energy exchange also occurs. A distinction can be made between two forms of energy exchange: mechanical energy exchange and electrical energy exchange. Examples can respectively be found in the mechanical energy exchange between the Vertical lift gates and the Actuators vertical lift gates and the interactions between the Low voltage supply, the Lock head construction and the Control building, see Figure 5.2.

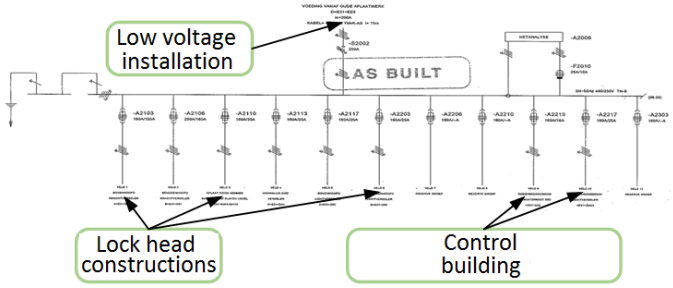


Figure 5.2: Section of as-built drawing of the low voltage network, depicting energy interactions(dienst infrastructuur, 2014).

Different interaction types were also encountered, but did not seem relevant with respect to the RA of the ship passage function. Examples of these types are:

- Structural interactions: The Vertical lift gates for example are structurally supported by the Lock head construction. They are however also connected spatially. This type of interaction can consequently be described by a form of spatial interaction. Thus, by denoting this as a spatial interaction, this interaction can still be incorporated.
- Material exchange (water) is evidently occurring within a lock system. In contrast to some of the material exchange interactions encountered in literature (e.g. the Ford climate control system, Pimmler (1994)), the exchange of water between a pair of lock components is not so evident. The flow of water is an intrinsically apparent feature of a lock system but is not easily used to describe the coupling between a component pair. An interaction that has been identified is between the Leveling system and a Vessel; the flow of water that is controlled by the Leveling system is used to level the water in the Lock chamber. Since the Vessel is located in the Lock chamber, this flow needs to be restricted to prevent excessive movement of the Vessel. Not many of these water type interactions have been encountered, hence the other types were given priority.

In total, four types of relevant interactions have been identified: spatial, location, information and energy. A flow chart is developed to clearly distinguish between the various types, see Figure 5.3.

When a pair A, B of components is encountered that potentially exhibits an interaction, it is checked if this pair confirms one or more of the three statements:

- There exists a spatial interaction between A and B: the interaction is either a spatial or a location interaction.
- There exists information exchange between A and B: an information interaction exists.
- There exists energy exchange between A and B: an energy interaction exists.

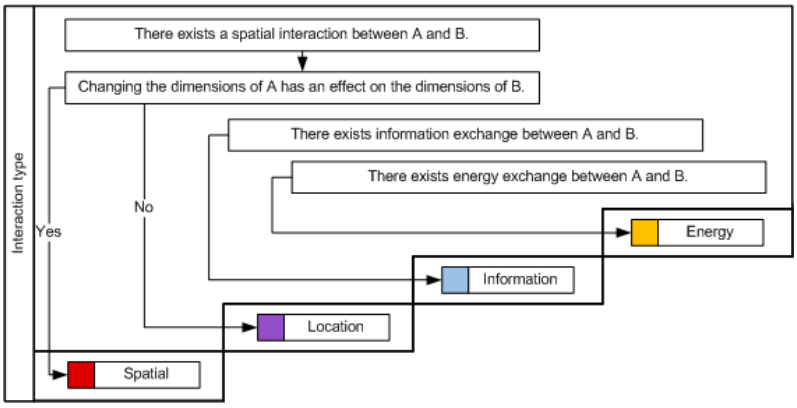


Figure 5.3: Rationale to assist in interaction type determination.

Since multiple statements can be true simultaneously, a pair of components may contain more than one type of interactions.

5.1.2 Interaction rating

Assigning different strengths to the interactions between components, assists in the coupling structure analysis. It enables a distinction between stronger and weaker interactions, thereby stressing (or reducing) the importance of a pair of components to be grouped in the same cluster. This can be used to ensure that components are grouped in the same cluster if this is required for functionality.

Literature often distinguishes between positive and negative interactions. This allows a pair of components to be actively separated during the structure analysis and to be placed in different clusters. However, in the context of a lock system this feature is irrelevant; no component pairs were identified that had to actively be prevented from occurring in the same cluster. Hence, the interaction strength analysis in this thesis, only differentiates between a weak (1) and a strong (2) interaction.

To distinguish between weak and strong interactions, a characteristic is determined for each of the interaction types:

- For **spatial** interactions force transmittance is used to enable a distinction between weak and strong interactions. If a pair of components are spatially connected and considerable force transmittance occurs between them, the interaction is considered stronger than if they were 'only' in contact.
- For **location** interactions it is checked whether or not the orientation between the components is required for functionality. For example, the Operator/maintenance personnel has a location interaction with the Control building. Since the orientation between these two is irrelevant for functionality, this interaction is receives rating 1. The interaction between the Operator/maintenance personnel and the control systems however, is important (the Operator/maintenance personnel cannot operate the control systems backwards). Hence this interaction receives rating 2.
- For **information** interactions a distinction is made between direct and indirect information links. The Operator/maintenance personnel indirectly provides input to the Supervisory control system via the control systems. Hence the interaction between the Operator/maintenance personnel and the Supervisory control system (indirect) receives rating 1, and the

interaction between control systems' and Supervisory control (direct), rating 2. As these indirect information interactions are commonly incorporated in analysis performed by RWS, they are also included in this study.

- For **energy** interactions it is checked if the system contains a back-up for the interaction. Between the High voltage supply and the Actuators vertical lift gates for example, a backup exists; the Actuators vertical lift gates are also connected to the Emergency power supply hence it receives rating 1.

These rating characteristics are incorporated in the interaction type rationale to enable the objective distinction between a weak and a strong interaction, see Figure 5.4.

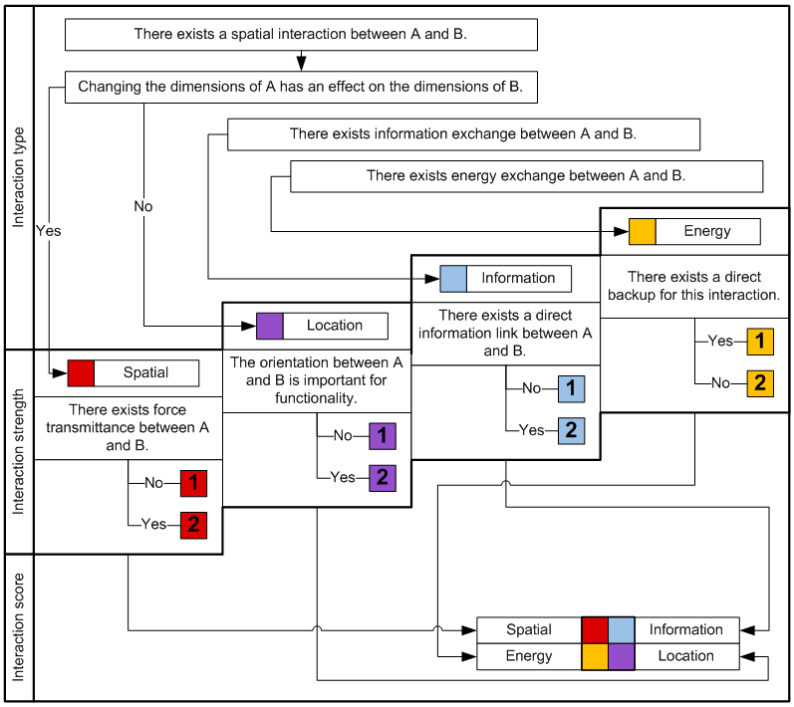


Figure 5.4: Rating scheme to assist in interaction type and strength determination.

The resulting rationale is divided into three sections that each represent a phase of DSM completion: interaction type, interaction strength and the interaction score. The latter summarizes the various interaction scores and is used as the DSM entry for the respective component pair. The colors assigned to each of the interaction types in the rating scheme, are unique. Throughout this study spatial interactions are marked **red**, location interaction are marked **purple**, information interactions are marked **blue** and energy interactions are marked **yellow**.

5.2 Building the preliminary DSM

By investigating as-built drawings, system manuals and other product documentation (see appendix), a part of the occurring interactions between components is identified. This set of interactions may be incomplete and could contain errors due to misinterpretation of the documentation. The interaction score of each pair of elements is placed in their respective DSM entry and the preliminary DSM is completed. This DSM is subsequently improved in an iterative manner via expert interviews.

First, the components of the reviewed decomposition (Figure 4.7) are used to construct the empty DSM of lock system Eefde, see Figure 5.5. Since this decomposition consists of 50 components, the resulting DSM will be of dimensionality 50×50, see Figure 5.5 for a sectional view.

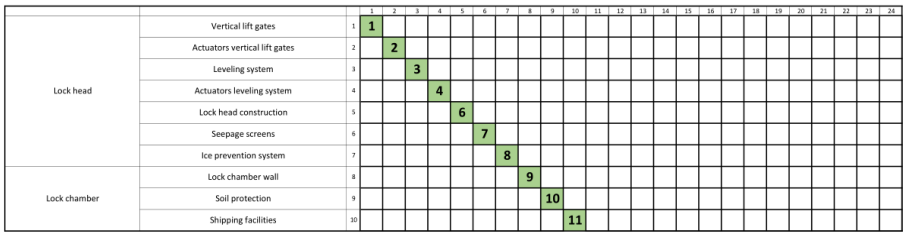


Figure 5.5: Section of empty DSM

In Figure 5.5, the first column denotes the subsystems and the second column the components. The third column and the first row denote the component numbering. The numbers assigned to the components are determined by sequentily numbering components of the subsystems in the decomposition of Figure 4.7. These numbers are unique and are used as a identifier for the components throughout this thesis. To increase the readability, the component numbering is repeated on the diagonal of DSM.

By studying documentation, it is checked, for each pair of components, whether or not an interaction exists. For the majority of component pairs the result is evidently negative and the corresponding DSM entry is left blank. For some component pairs an interaction is to be expected. If so, the following procedure is followed:

- The component pair of interest is denoted.
- The relationship that exists between them is described, if this is not evident, documentation is consulted.
- The rating scheme in Figure 5.4 is used to determine the occurring interaction types.
- Finally the interaction rating is determined via the rating scheme and the justification is provided.

For example the component pair: Leveling system and Actuators leveling system for example, the elaboration of this procedure is as follows.

Documentation regarding one or both of the components is examined, until the relationship between them can be established. In this case an overview of the Lock head east was found, which unambiguously displays the relationship that exists between the two components, see Figure 5.6.

The relationship between the components can be expressed by: The Actuators leveling system drive the movement of the Leveling system. After the relationship is described, the rating scheme is followed to determine the occurring interaction types and their strengths.

If the dimensions of one component are changed, the dimensions of the other are affected. Consequently, a spatial interaction exists between the components. In order to determine the strength of this interaction,it is checked if force transmittance occurs. Since one components drives the movement of the other, force transmittance exists between them. Hence, the components share a Spatial interaction with strength 2.

The force exerted by one component drives the movement of the other. Since a force exerted over a distance also equals energy, an Energy type of interaction is present. The rating of this interaction is determined by checking the redundancy of the interaction. Because no back-up system exists for this interaction, the strength is 2.

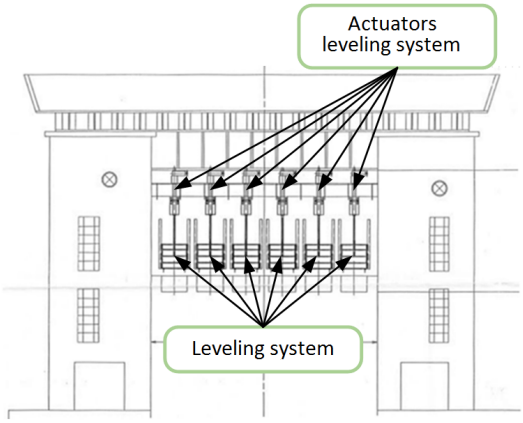


Figure 5.6: Layout of the Lock head east depicting the relationship between the Actuators leveling system and Leveling system (dienst infrastructuur, 2014).

Browning (2001) suggests to summarize the results of such an analysis in an interaction rationale. See Figure 5.7 for the interaction rationale between the Actuators leveling system and Leveling system. For some component pairs, the type of interaction and its strength is immediately apparent by using the rating scheme. In this case no rationale is developed.

Whenever a pair of components is encountered for which the available data does not sufficiently describe whether an interaction exists or not, the respective DSM entry is completed as if the interaction occurs and a note is made of this ambiguous interaction. These interactions receive extra attention during the interviews.

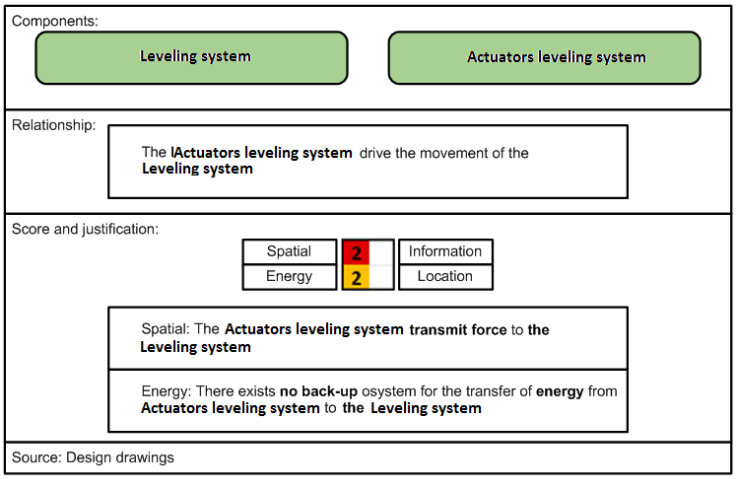


Figure 5.7: Rationale for the interactions between Leveling system and Actuators leveling system, following Browning (2001).

Thirdly, all the interactions scores that were identified for the element pairs, are stored in their respective DSM entry. Each entry in the DSM contains four slots that directly correspond to the interaction score as depicted in the rating scheme. In total, 194 interactions are identified, see Figure 5.8 for a sectional view of the resulting preliminary DSM.

As can be seen in the sectional view, already some clusters are forming. This phenomenon is caused by the component sequence dictated by the reviewed decomposition. Since this decomposition

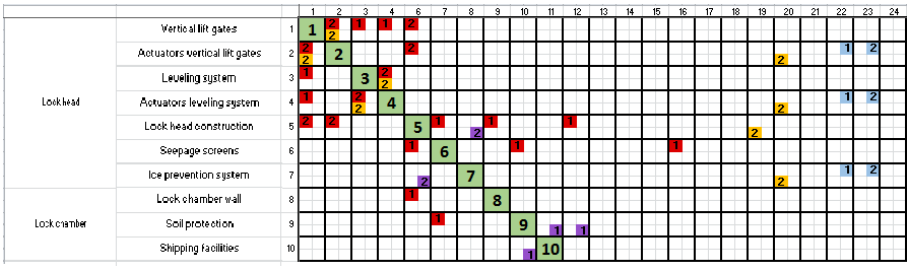


Figure 5.8: Section of the preliminary DSM.

already grouped components into subsystems, some of the more tightly coupled subsystems will appear as clusters in the DSM.

5.3 Reviewing the DSM via interviews

The preliminary DSM is subsequently reviewed by system experts. By using the list of ambiguous interactions encountered during the development of the preliminary DSM as a guideline in these interviews, more specific questioning is possible, i.e. these ambiguous interactions can be assessed by system's experts.

A meeting was held with the technical manager of lock complex Eefde. In this meeting the principles of the DSM approach were explained and the preliminary DSM was presented. After the manager became familiar with the DSM representation, immediately some suggestions were made. One of the more influential remarks was that the Emergency power supply provides an emergency power supply to all components required for the lock's functionality, and not just the primary ones.

Subsequently, the technical manager was asked to provide contact details of system experts of the various disciplines encountered in the DSM representation, i.e: control engineering, electrical engineering, mechanical engineering and civil engineering.

The system experts reviewed the preliminary DSM and complemented it by suggesting unidentified interactions. During these interviews, the statement by Park and Cutkosky (1999) that graph representations are more intuitive, was utilized: it was found that by using graph representations of the DSM, one for each row in the DSM, the required time can be significantly reduced. A graph representation releases the system expert of the need to completely understand the DSM.

5.3.1 Interview preparation

Tilstra et al. (2009a) suggested to be as specific as possible during the interviews. By eliminating the room for interpretation of the questions, the consistency of the results is increased. Hence, instead of reviewing all the interactions that were identified, only the interactions of a particular component were reviewed.

To assist in this process, the row in the preliminary DSM corresponding to the component of interest is represented by means of a graph, see Figure 5.9.

The graph is constructed by representing all interactions that are depicted in the row of the component of interest. The interactions are depicted by colored edges. The colors are consistent with the various interaction types and the strengths are depicted by a number on the center of the lines.

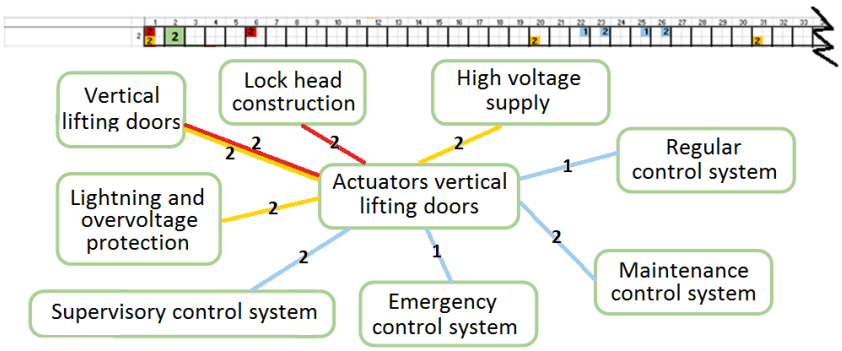


Figure 5.9: Graph representation of the Actuators vertical lifting doors elicited from the preliminary DSM.

During the interviews, the decomposition from depicted in Figure 4.7 was also provided. This was done to ensure that if a new interaction would be identified, the system expert would link existing components instead of extending the decomposition by introducing new components.

For example: If the system expert would suggest an interaction between a Bollard and a Vessel, the interaction would be represented by an interaction between the Lock chamber wall and a Vessel, since a Bollard is part of the Lock chamber wall.

5.3.2 Interview results

The interview sessions increased the total number of interactions to 216, even though a part of the interactions had been removed, an increase of 11 percent was achieved. The most influential changes are presented in this section.

A small amount of interactions is deleted during the interviews. Out of the 193 interactions that are identified on forehand, 5 are removed. The main reason for this is that the Emergency control system is solely used to return the system into a safe state. This means interactions with secondary systems, like the Ice prevention system are not present. Another interaction that is deleted, is the interaction between the Funnel and the Lock head construction front lock. This is due to a misinterpretation of the definition of a Funnel. The Funnel only connects to the lock system itself, and not to the Front lock; The Front lock is directly connected to the IJssel.

A total of 18 new interactions are identified during the interviews. A significant part is caused by the observation that the Maintenance control system has a more elaborate functionality than the Regular control system. Another major contribution is the insight that the Seepage screens, the Lock head construction and the Soil protection have to be physically connected in a watertight manner to be able to perform their function.

In addition, some of the interaction ratings are altered. The majority of these changes consist of the interaction strengths with the Logging. Since all (communication) systems are indirectly, via the Supervisory control system connected to the Logging, the strengths are decreased to 1.

By incorporating the improvements obtained by the interviews, the preliminary DSM more correctly represents the actual coupling structure of lock system Eefde. Since the DSM was completed manually, a check has been performed to ensure symmetry. The few errors that were found, were mostly due to an interaction being placed in the row or column adjacent to the true position. See Figure 5.10 for the resulting physical DSM.

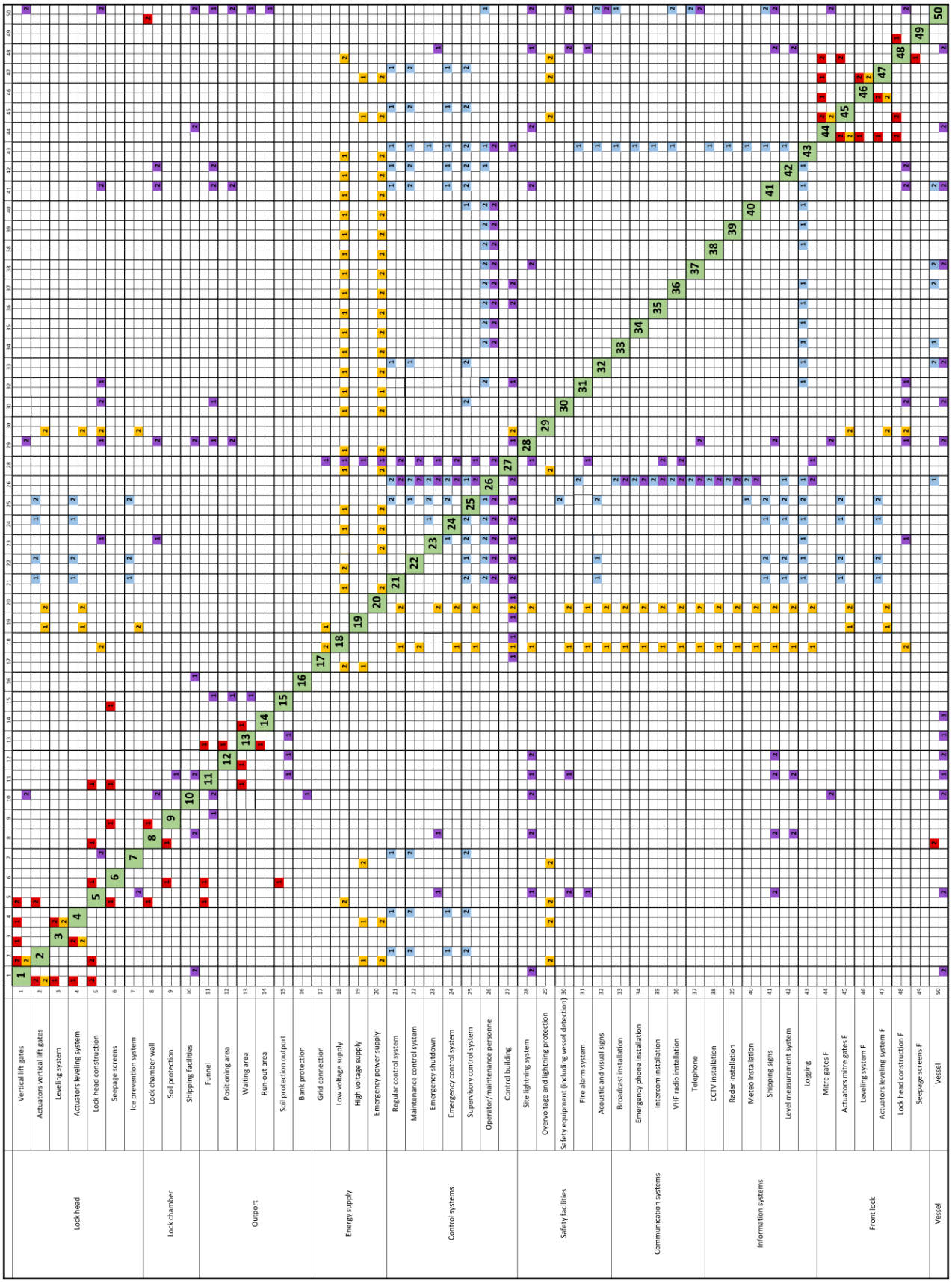


Figure 5.10: The physical DSM of lock system Eefde.

Since the interview review process was iteratively repeated until the system's experts were satisfied with the presented coupling structure, it can be assumed that the physical DSM describes the coupling structure of the system in a satisfying manner.

By investigating the physical DSM of lock system Eefde, some interesting characteristics can be observed. Some clusters are forming around the first three subsystems defined by the reviewed decomposition. These clusters do not directly correspond to the subsystems which suggests the lock system contains other, more naturally occurring subsystems. Some components show a very integrative character. The Low voltage supply for example has interactions with 23 other components over various subsystems. The structural review of the physical DSM is discussed more in dept in Chapter 8. For now it suffices to see that the physical coupling characteristics of the components are presented in a representative way by use of the DSM.

5.4 Conclusion

The relevant interaction types that govern the working principles of lock system Eefde are: spatial, location, information and energy interactions. Using a rating scheme to systematically identify these types enabling an objective distinction between weak and strong interactions proved helpful. A preliminary DSM is developed by studying documentation and rating potential interactions with the rating scheme. Reviewing this DSM with systems experts was greatly simplified by using a graph representation and the decomposition developed in Chapter 4. A 11 percent increase in interactions is obtained via the reviewing phase. The resultant physical DSM of lock system Eefde is able to depict the coupling characteristics of its components in a representative way.

Chapter 6

Building the functional DSM

The physical DSM developed in Chapter 8 represents the physical dependency structure that exist between the components of the lock system. In this chapter, another type of dependency structure is investigated: the functional dependency structure. The functional dependency between a pair of components is formed by a shared function. A functional DSM that represents these functional dependencies is determined and used to complement the physical DSM.

The functions of a system are fulfilled by its components (Suh (1990)). The functions and components of a system are thus coupled with each other. A Design Matrix (DM) can be used to represent the relation between the functions of a system and its components. According to Dong (2002), the DM of the system can be used to identify potential physical interactions. These potential interactions can be used to verify or enhance the physical DSM (Tang et al. (2009)).

In literature, various methods are found to convert a DM to a DSM (Suh (1998), Guenov and Barker (2004), Wilschut (2015), Tang et al. (2009) and Maurer (2007). Since the resulting DSM is obtained via the functional coupling of the system, it is named a functional DSM. Bagley (2005) used this technique to determine a DSM of a Ford steering system. Tang et al. (2009) suggested to use the DSM resulting from the DM to DSM conversion to enhance the DSM obtained by interviews.

In this study, the same conversion method as used in Wilschut (2015) is used: if two components contribute to the same function, these components may have a dependency between them. Given that the DM accurately describes the dependency structure between functions and components, this conversion method identifies more potential interactions than actually occur in the system. Hence, the actual occurring physical interactions are a subset of the interactions depicted by the functional DSM. The functional DSM can thus be used to identify interactions that were missed during the development of the physical DSM.

In order to obtain a functional DSM that can be used to identify potential physical interactions, the properties of the conversion method are investigated in Section 6.1. These properties are subsequently used to develop the DM and to interpret the resulting functional DSM.

In Section 6.2, a DM that describes the dependency structure between the functions and the components of the lock system is obtained via documentation that describes their relationship. The components used in the documentation are matched to the components that appear in the decomposition obtained in Chapter 4 (see Figure 4.7). Since the available documentation fails to completely describe the dependency structure between functions and components, the resulting DM is incomplete. Some of the missing dependencies are evident and are added manually to the DM.

Finally in Section 6.3, the DM is converted to a functional DSM. The characteristics of this functional DSM are analyzed to obtain insight in the functional dependency structure of the lock

system. Some of the results of this analysis pose implications for the DM, that can be used for improvement.

6.1 Properties of the conversion method

The basic principle governing the DM to DSM conversion has been described in Section 2.3. The properties of this conversion method and their implications for the resulting functional DSM are elaborated in more detail.

Consider the function: "Allow ships to enter the lock system". The components required to fulfill this function are: the Waiting area, the Positioning area and the Funnel. The description of which components are required to fulfill a particular function are defined as the relationship description. The ships wait for passage in the Waiting area. When enough ships have gathered in the Waiting area they enter the Positioning area. In the Positioning area, the ships are positioned in an efficient layout. When the lock system is ready to provide ship passage, the ships travel through the Funnel into the lock system. The layout of these three components can be schematically presented as follows. See Figure 6.1.

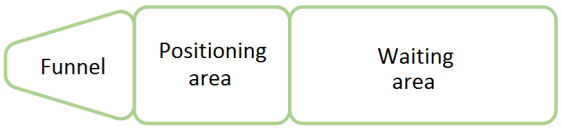


Figure 6.1: Schematic of the Outport.

The functional relationship between the Funnel, Positioning area and Waiting area formed by the function: "Allow ships to enter the lock system" can be used to construct a DM, see Figure 6.2a. The function is placed in the first row of the DM, and the components are placed in the columns. The DM is subsequently be converted to a functional DSM by the conversion method, see Figure 6.2b.

	Funnel	Positioning area	Waiting area
Function	1	1	1

(a)

		1	2	3
Funnel	1	**1**	1	1
Positioning area	2	1	**2**	1
Waiting area	3	1	1	**3**

(b)

		1	2	3
Funnel	1	**1**	1	
Positioning area	2	1	**2**	1
Waiting area	3		1	**3**

(c)

Figure 6.2: (a) DM of the (simplified) Outport (b) The DSM obtained by conversion (functional DSM) (c) The physical DSM.

Since all components are required for the function, the functional DSM that follows from converting this DM is completely filled. This suggests all components have an interaction with each other. By investigating the schematic depicted in Figure 6.1, this can be invalidated; The Funnel is spatially connected to the Positioning area and the Positioning area is spatially connected to the Waiting area, no interaction exists between the Funnel and the Waiting area. The actual coupling structure of the Outport can be represented by the physical DSM, depicted in Figure 6.2c.

By comparing the functional DSM with the physical DSM, it can be observed that the physical DSM is a subset of the functional DSM, i.e. the functional DSM contains more interactions than the physical DSM. This characteristic will always arise if three or more components are required for a single function.

The excess interactions can however be used to identify indirect interactions between components. Since information type interaction with score 1 are formed by indirect interactions between components, investigating the excess interactions may depict information interactions that were missed

in the physical DSM. The control and supervisory control often deal with indirect information interactions. If more than three components are required for a single function, the occurring interactions in the resulting functional DSM, may also depict second degree or higher indirect interactions, e.g. component 1 has an interaction with component 4 via component 2 and component 3.

A granularity level issue in the DM, may also give rise to similar problems. Consider again the function: "Allow ships to enter the lock system" and its corresponding DM, see Figure 6.2a. If the main function is split into two subfunctions: Function 1: "Allow ships to enter the Positioning area" and Function 2: "Allows ships to enter the lock", a alternative DM arises, see Figure 6.3.

	Funnel	Positioning area	Waiting area
Subfunction 1		1	1
Subfunction 2	1	1	

Figure 6.3: DM of Outport with subfunctions.

Applying the conversion method to this DM, yields a functional DSM that equals the physical DSM depicted in Figure 6.2c.

A final property concerns the incomplete representation of the dependency structure in the DM. If a component is not mentioned in combination with another component in the DM, the resulting functional DSM will not show an interaction between these components. If the subfunction: "Allow ships to enter the Positioning area" could be completed by the Waiting area alone, the resulting DM would only show three connections, see Figure 6.4a.

	Funnel	Positioning area	Waiting area
Subfunction 1			1
Subfunction 2	1	1	

(a)

		1	2	3
Funnel	1	1	1	
Positioning area	2	1	2	
Waiting area	3			3

(b)

Figure 6.4: (a) DM of the (simplified) Outport (b) The functional DSM obtained by conversion.

Subsequently converting this DM to a functional DSM, yields a DSM that only shows an interaction between the Funnel and the Positioning area. The connection between the Positioning area and the Waiting area is missed since the relationship description is incomplete. Hence, an incomplete relationship description in the DM results in missing interactions.

6.2 Building the DM from data

By studying data that describes the couping structure between functions and components, a DM can be elicited. Two data sources are found that contain data about the coupling structure between functions and components: the GRIP database and Failure Mode and Criticality Analysis (FMECA) reports.

The GRIP database describes the coupling structure of functions and components for a generic lock. The components in this database strongly resemble the components depicted in the NEN 2767 decomposition. but do not always directly correspond to the components of the decomposition used in this study. Sometimes the mapping is evident, e.g. the Lightning to the Site lighting system. In other cases, the granularity levels of the decompositions do not match, e.g. the

Technical emergency control (NL: Noodbediening technisch) and the Manual emergency control (NL: Noodbediening hand) are merged together to form the Emergence control.

Since the GRIP database is developed for a generic lock, it contains a significant amount of functions that are not applicable to lock system Eefde, e.g. functions governing a lock in contact with the sea. Hence, all non applicable functions from the GRIP database are removed from the function set. These functions were manually selected by referencing their description with the functionality of the lock system.

An example of a function that is excluded from the DM is: "Allow roadtraffic to pass" (NL: "Begeleiden wegverkeer"). Although lock system Eefde contains a bridge for traffic, the system boundary defined in Section 4.1 excludes this bridge; it has no influence on the RA for ship passage. After selection, in total 22 functions form the function set used in the DM, see Figure 6.5.

As can be seen in Figure 6.5, about 40 percent of the components is not allocated to any of the depicted functions. Hence, the functional DSM will not indicate any interactions amongst them. Three different causes exist for these missing dependencies:

1. The set of functions is incomplete. For example: the Ice prevention system is used to break the layer of ice during winter and increase the locks availability. This function is not included in GRIP.

2. Not all components that are required for a function are listed, i.e. the relationship description is incomplete. The function: Control lock system, for example, also requires the Operator/maintenance personnel and not just the control systems.

3. A granularity level issue. For instance, the function: "Allow ship passage" is defined on the same granularity level as the function: "Provide audio communication". Whereas the latter function is actually is subfunction of the function: "Allow ship passage".

Item 1, concerning the incomplete function set, can partly be overcome by extending the function set via the incorporation of functions from Failure Mode and Criticality Analysis (FMECA) reports. These reports analyze the functional structure of a lock to define critical lock functions. Subsequently, these functions are mapped to their physical counterparts; the components. Since the FMECA reports are made specifically for lock system Eefde, all functions and components are applicable. Only the granularity level of some components needs to be matched to the decomposition used in this study. Although still incomplete, by incorporating these functions, the DM is improved.

The DM complemented by FMECA functions, still misses dependencies, i.e. not all components required for the functions are listed. These dependencies can be partly complemented by investigating the working principles of the lock system, and manually adding them to the DM. See Figure 6.6 for the resulting DM.

The granularity level issue is a more difficult problem to solve. To obtain a function set of a consistent level, a functional hierarchy has to be constructed, which requires a profound insight in the break down structure of the locks functionality. There exist methods that support this analysis, e.g. zigzagging, Suh (1990). In this study, the property that: the more detailed the granularity level of the functions used in the DM, the fewer potential interactions will be depicted in the functional DSM is simply used. High level functions will generate a larger number of potential interactions. The actual occurring physical interactions in the physical DSM qill be a subset of the interactions in the functional DSM. Hence, a pragmatic approach for dealing with level issues in the function set is to remain cautious during the interpretation of the functional DSM and inspect unexpected potential interactions.

6.3 Conversion of the DM

The DM depicted in Figure 6.6 is converted to a functional DSM via the conversion method described in Section 2.3 and Section 6.1. For each component, it is checked if another component is also required for the same function. If so it is checked how many functions are shared by this pair of components. This number is depicted in the functional DSM entry, see Figure 6.7.

			Allow ship passage	Facilitate lock control	Handling and control	Provide control facilities	Provide control information	Manage admission control area	Control lock system	Emergency control	Safeguard safety	Maintenance control	Manage control mode lock system	Safeguard continuity	Monitor malfunctioning	Process control commands	Illuminate lock system	Provide audiocommunication	Supply energy	Provide visual on lock system	Provide radar images	Provide visual on meteo	Facilitate shipping industrie	Log information of navigation lock proces
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Lock head	Vertical lift gates	1	1																					
	Actuators vertical lift gates	2																						
	Leveling system	3																						
	Actuators leveling system	4																						
	Lock head construction	5																						
	Seepage screens	6																						
	Ice prevention system	7																						
Lock chamber	Lock chamber wall	8	1																					
	Soil protection	9																						
	Shipping facilities	10	1								1												1	
Outport	Funnel	11	1																					
	Positioning area	12	1																					
	Waiting area	13	1																					
	Run-out area	14	1																					
	Soil protection outport	15																						
	Bank protection	16																						
Energy supply	Grid connection	17																	1					
	Low voltage supply	18																						
	High voltage supply	19																						
	Emergency power supply	20																	1					
Control systems	Regular control system	21	1	1	1	1	1	1	1		1		1	1	1	1							1	
	Maintenance control system	22							1			1			1									
	Emergency shutdown	23							1		1													
	Emergency control system	24							1	1	1													
	Supervisory control system	25	1		1				1		1			1	1									
	Operator/maintenance personnel	26																						
	Control building	27		1	1			1			1									1				
Safety facilities	Site lightning system	28															1							
	Overvoltage and lightning protection	29									1													
	Safety equipment (including vessel detection)	30																						
	Fire alarm system	31									1													
	Acoustic and visual signs	32									1												1	
Communication systems	Broadcast installation	33																1						
	Emergency phone installation	34					1											1						
	Intercom installation	35									1							1						
	VHF radio installation	36																1						
	Telephone	37																1						
Information systems	CCTV installation	38					1													1				
	Radar installation	39																			1			
	Meteo installation	40					1															1		
	Shipping signs	41					1																1	
	Level measurement system	42					1																	
	Logging	43					1				1													1
Front lock	Mitre gates F	44	1																					
	Actuators mitre gates F	45																						
	Leveling system F	46																						
	Actuators leveling system F	47																						
	Lock head construction F	48																						
	Seepage screens F	49																						
Vessel	Vessel	50																						

Figure 6.5: DM of lock system Eefde, elicited from data

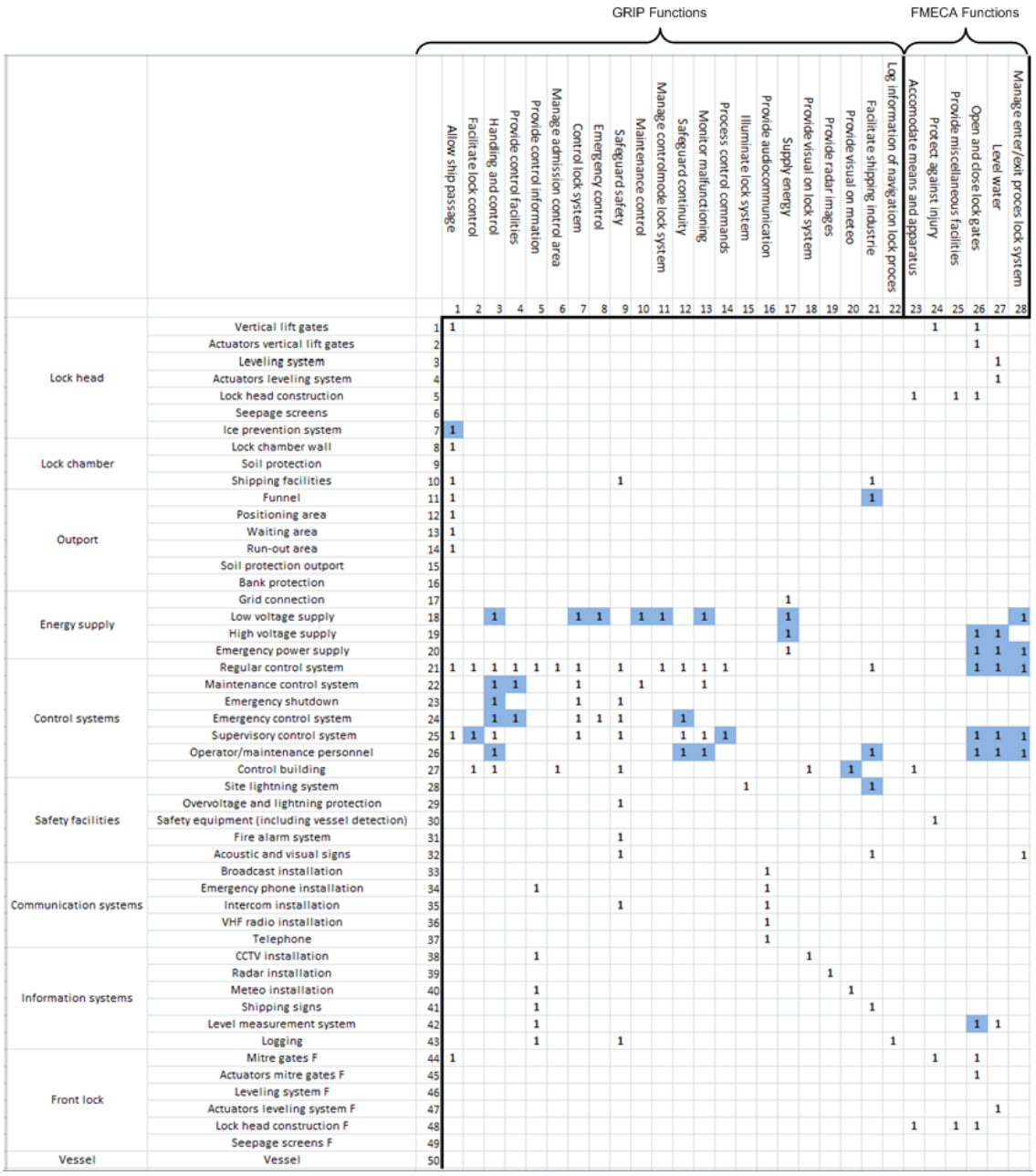


Figure 6.6: DM of lock system Eefde complemented by additional functions (FMECA) and manually added dependencies (depicted in blue).

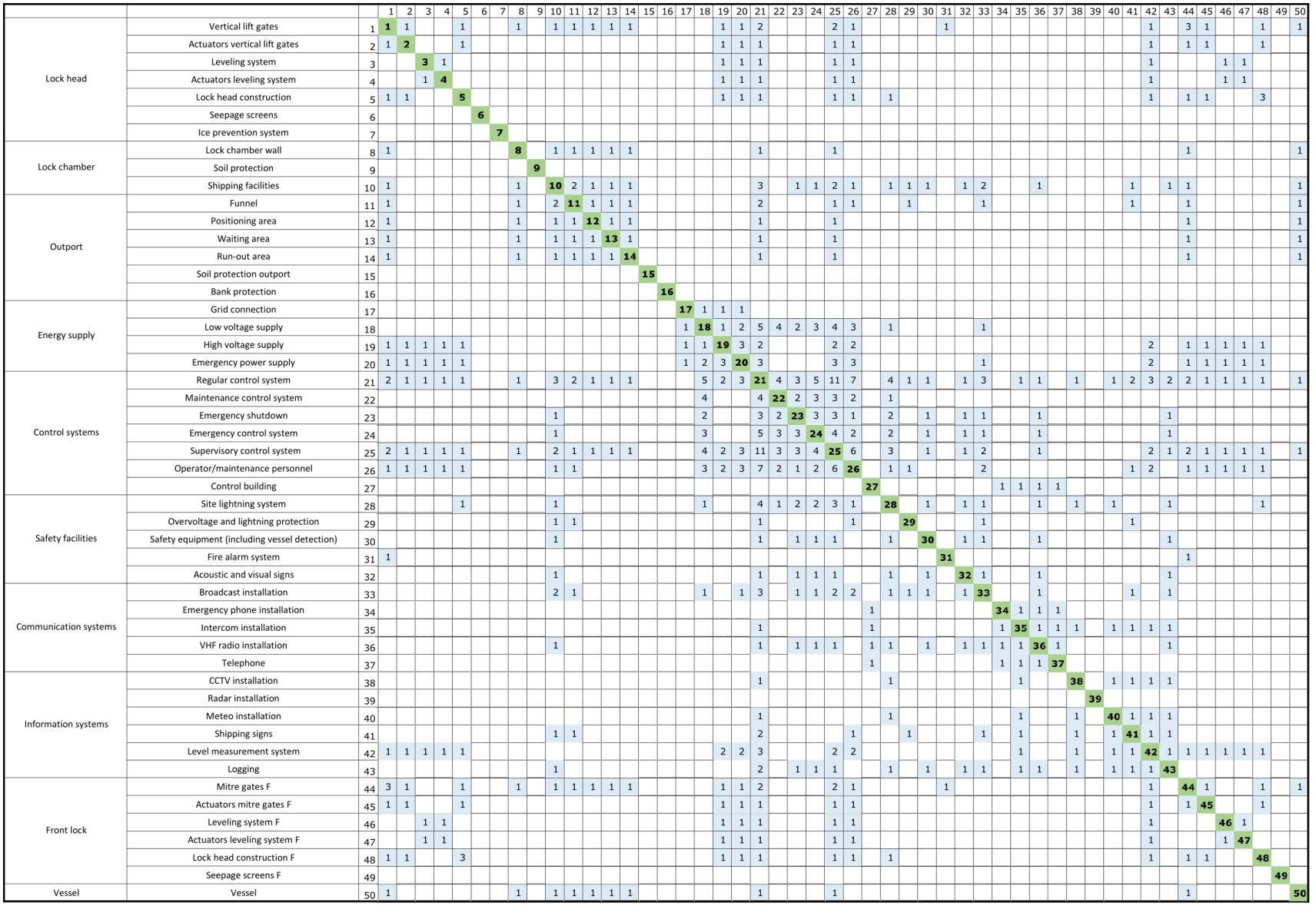


Figure 6.7: Functional DSM obtained by DM to DSM conversion.

The amount of functions a component pair has to satisfy can be used as a measure for the strength of their dependence. If a component pair shares a function, the components have to collaborate to fulfill this function, and thereby exert an influence on each other. If more than one function has to be realized, the degree of collaboration between the component pair is increased, and by that, their interdependence.

For the majority of the interactions in the functional DSM, the respective component pair shares only one function. A small portion of the interactions is however due to two or more shared functions. The Regular control system and the Supervisory control system have the highest interdependence with a total of eleven shared functions.

A total of six components show no interaction in the functional DSM. These are: the Seepage screens for both the Navigation lock (6) and the Front lock (49), the Soil protection for both the Outport (15) and the Lock chamber (9), the Bank protection (16) and the Radar installation (39). The function of the Seepage screens is to prevent water flow around the foundation of the lock. Since this function is not explicitly mentioned in GRIP and the FMECA reports, the related components are not depicted in the functional DSM.

The Soil protection is in place to protect soil and to ensure a watertight seal. This function is also not mentioned in the data. The Soil protection has however very little interaction with other components, hence the lack of interactions in the functional DSM is not an issue.

The Radar installation provides the Operator/maintenance personnel with additional information regarding the location of ships. In the function set, two functions are mentioned that relate to the Radar installation: "Provide radar images" (19) and "Provide visual on lock system" (18). Since the first function already explicitly mentions the Radar installation, the GRIP database did not incorporate it in the description of the second function. The function: "Provide radar images" is too specifically formulated, and will therefore fail to provide information about the coupling structure of the Radar installation. Aggregating "Provide radar images" into "Provide visual on lock system" would be a logical step in improving the level consistency of the set of functions. Incorporating this improvement in the function set would yield interactions in the functional DSM with the CCTV installation and the Control building.

At first glance, the dependency structure depicted by the functional DSM strongly resembles the dependency structure depicted by the physical DSM in Figure 5.10. As determined by investigating the principles of the conversion method, the similarities and differences between the two can be used to suggest missing interactions for the physical DSM, missing dependencies in the DM and missing functions in the function set. The comparison of the two DSMs and the implications thereof are discussed in the subsequent chapter.

6.4 Conclusion

By investigating the properties governing the conversion method that is used to transform a DM into a DSM, some important implications for the resulting functional DSM are found. If the DM is a complete description of the dependency structure between the functions and components of a system, the functional DSM resulting from conversion will be over complete, i.e. the actual occurring physical interactions are a subset of the potential interactions depicted in the functional DSM.

Components that do not appear together with another component in the relationship description of a function, will yield no interactions in the functional DSM. The identification of these components in the DM can be used to suggest missing functions for the function set.

The DM of Eefde that is used to obtain the functional DSM contains issues. The function set that has been used is incomplete, i.e. the lock system has more functions than contained in the function

set. This gives rise to components without interactions in the functional DSM, e.g. component 6, 49, 15, 16 and 9. These non interacting components can be used to identify missing functions.

The function set, provided by the GRIP database and the FMECA reports, contains some granularity level issues, i.e. not all functions are defined on the same level of detail. This causes an over-complete description of the dependency structure between the components in the functional DSM. To address this issue, a level consistent decomposition of the functionality of lock system Eefde needs to be developed. The consequence of this issue is that an excess of potential interactions is present in the functional DSM. The physical DSM should anyways always be a subset of the functional DSM, hence developing this functional decomposition is considered less effective than remaining cautious during the interpretation of the potential interactions suggested by the functional DSM.

Developing the functional decomposition becomes more important when the functional dependency structure of the lock system is to be analyzed. The zigzag decomposition technique mentioned in Section 2.1 developed by Suh (1990) can be used to obtain a level consistent decomposition. Once this level consistent function set is determined, the DM can be used to obtain a DSM that depicts the dependency structure between functions. This is done by applying the same conversion algorithm as used in this study but instead of determining components that contribute to the same function, the functions that require the same components are marked to have a potential dependency.

The final issue with the Eefde DM elicited from data is that the relationship descriptions of the functions are not completely described. Although this has been partly solved by manually complementing these relationship descriptions, some are incomplete. Hence, if the resulting functional DSM does not depict all interactions that exist between the components of the lock system, this can be caused by either an incomplete function set, or by incomplete relationship descriptions.

However, since the interactions of the physical DSM should be a subset of the potential interactions in the functional DSM, the incomplete functional DSM can still be used to enhance the physical DSM.

Chapter 7

DSM comparison and enhancement

The physical DSM obtained in Chapter 5 is compared to the functional DSM obtained in Chapter 6 by constructing a comparison DSM. This comparison DSM is used to classify the interactions into three groups: interactions that solely exist in the functional DSM, interactions that solely exist in the physical DSM and interactions that exist in both the physical and the functional DSM.

The second group of interactions is used to deduce improvements for the DM. These improvements consist of missing dependencies and missing functions for the function set. The first group of interactions is of main interest for this study as they suggest missing interactions that can be used to enhance the physical DSM and thereby improve its representation of the physical dependency structure of the lock system.

7.1 The comparison DSM

A comparison DSM is developed in which the differences and similarities of the physical and functional DSM are depicted. Via element wise comparison of the physical DSM and the functional DSM, it can be determined whether the respective interactions match or not. The element wise comparison yields three different results:

- the interaction exists solely in the functional DSM, depicted by a "1" (light blue),
- the interaction exists solely in the component DSM, depicted by a "2" (blue) in the compare DSM, or
- the interaction exists in both the physical and the functional DSM, depicted by a "3" (dark blue) in the comparison DSM.

By adding different color values to the various results, their distinction is stressed, see Figure 7.1 for the resultant comparison DSM.

			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
Lock head	Vertical lift gates	1	1	3	2	2	3			1		3	1	1	1	1					1	1	1				1	1			2		3										1		1	1			1		3
	Actuators vertical lift gates	2	3	2			3														3	3	3	2		2	3	1				2											1		1	1			1		
	Leveling system	3	2		3	3															1	1	1				1	1															1				1	1			
	Actuators leveling system	4	2		3	4															3	3	3	2		2	3	1				2											1				1	1			
	Lock head construction	5	3	3			5	2	2	2			2							2	1	1	1		2		1	1		1	2	2	2	2								2	1		1	1			1		2
	Seepage screens	6					2	6			2		2				2																																		
	Ice prevention system	7					2		7												2		2	2			2				2																				
Lock chamber	Lock chamber wall	8	1				2			8	2	3	1	1	1	1							1		2		1				2											2	2		1					3
	Soil protection	9						2		2	9		2																																						
	Shipping facilities	10	3							3		10	3	3	3	1		2					1		1	1	1	1		1	3	1		1	1			1				1		1	3					3
Outport	Funnel	11	1				2	2		1	2	3	11	1	3	1	2						1				1	1			3		2		1							3	2		1					3
	Positioning area	12	1							1		3	1	12	3	1	2						1				1				2											2			1					3
	Waiting area	13	1							1		3	3	3	13	3	2						1				1																		1					3
	Run-out area	14	1							1		1	1	1	3	14							1				1																		1					3
	Soil protection outport	15						2					2	2	2		15																																		
	Bank protection	16										2						16																																		
Energy supply	Grid connection	17																	17	3	3	1								2																					
	Low voltage supply	18					2												3	18	1	1	3	3	3	3	3	1	2	3	2		2	2	3	2	2	2	2	2	2	2	2	2	2				2		
	High voltage supply	19	1	3	1	3	1		2										3	1	19	1	1				1	1		2													1		1	3	1	3	1		
	Emergency power supply	20	1	3	1	3	1												1	1	1	20	3		2	2	3	1	2	2	2		2	2	3	2	2	2	2	2	2	2	2	3	2	1	3	1	3	1	
Control systems	Regular control system	21	1	3	1	3	1		2	1		1	1	1	1	1				3	1	3	21	3	3	1	3	3		3	1	1		3	3		1	1		1		1	3	3	3	1	3	1	3	1		1
	Maintenance control system	22		2		2			2											3			3	22	3	1	3	3		3					2							2	2	2		2		2			
	Emergency shutdown	23					2			2		1								3		2	3	3	23	3	3	3		3		1		1	1			1						3					2		
	Emergency control system	24		2		2						1								3		2	1	1	3	24	3	3		3		1		3	3			1				2	2	3		2		2		
	Supervisory control system	25	1	3	1	3	1		2	1		1	1	1	1	1				3	1	3	3	3	3	3	25	3		3		1	2	3	3			1				2	2	3	3	1	3	1	3	1		1
	Operator/maintenance personnel	26	1	1	1	1	1					1	1							1	1	1	3	3	3	3	3	26	2	3	1			2	1	2	2	2	2	2	2	1	3	2	1	1	1	1	1		2
	Control building	27																		2		2						2	27	2						1	1	1	1											2
Safety facilities	Site lightning system	28					1					1							2	3	2	2	3	3	3	3	3	3	2	28	2	3		3	1			3	2	1		1			3				1		
	Overvoltage and lightning protection	29	2				2			2		3	3	2						2		2	1					1		2	29				1							3			2				2		2
	Safety equipment (including vessel detection)	30		2		2	2		2			1											1		1	1	1			3		30		1	1			1					1		2		2	2		
	Fire alarm system	31	3				2						2							2		2					2					31												1				2		2
	Acoustic and visual signs	32					2					1								2		2	3		3	1	3	2		3		1		32	1			1						3					2		
Communication systems	Broadcast installation	33										1	1							3		3	3	2	3	1	3	1		1	1	1		1	33			1				1		3						2
	Emergency phone installation	34																		2		2						2	1							34	1	1	1						2						2
	Intercom installation	35																		2		2	1					2	1							1	35	1	1	1		1	1	1	3						
	VHF radio installation	36										1								2		2	1		1	1	1	2	1	3		1		1	1	1	1	36	1					3							
	Telephone	37																		2		2						2	1	2						1	1	1	37					2							2
Information systems	CCTV installation	38																		2		2	1					2		1						1			38		1	1	1	3							
	Radar installation	39																		2		2						2												39				2							
	Meteo installation	40																		2		2	1				2	2		1						1					1		40	1	1	3					
	Shipping signs	41					2			2		1	3	2						2		2	3	2		2	2	1			3				1		1			1		1	41	1	3				2		2
	Level measurement system	42	1	1	1	1	1			2			2							2	1	3	3	2		2	3	3								1			1		1	1	42	3	1	1	1	1	3		
	Logging	43										1								2		2	3	2	3	3	3	2		3		1		3	3	2	3	3	2	3	2	3	3	3	43						
Front lock	Mitre gates F	44	1	1			1			1		3	1	1	1	1					1	1	1				1	1			2		1										1		44	3	2	2	3		3
	Actuators mitre gates F	45	1	1			1														3	3	3	2		2	3	1				2											1		3	45			3		
	Leveling system F	46			1	1															1	1	1				1	1															1		2		46	3				
	Actuators leveling system F	47			1	1															3	3	3	2		2	3	1				2											1		2		3	47			
	Lock head construction F	48	1	1			1													2	1	1	1		2		1	1		1	2	2	2	2									2	3		3	3			48	2	2
	Seepage screens F	49																																															2	49	
Vessel	Vessel	50	3				2			3		3	3	3	3	3						1				1	2	2		2		2		2	2			2				2			3				2		50

Figure 7.1: Comparison DSM of the physical and functional DSM. A "1" (light blue) interaction exists only in the functional DSM, a "2" (blue) interaction exists only in the physical DSM and a "3" (dark blue) interaction exists in both.

By combining the interaction of both the physical and the functional DSM in the comparison DSM, the total amount of interactions is increased. A total 394 interactions are depicted in the comparison DSM. 216 of them were already identified via the physical DSM and 178 additional interactions have been suggested by the functional DSM.

A total of 91 type 3 interactions were identified. The type 3 interactions occur in both the physical and the functional DSM. They can therefore be interpreted as a confirmation of their respective existence.

An interaction that exists in the physical DSM without a corresponding interaction in the functional DSM (type 2), indicates an inconsistency. A total of 125 of these interactions are identified in the comparison DSM. It has been shown that the physical DSM should be a subset of the functional DSM if the functional DSM is obtained via a complete DM. Hence, if type 2 interactions occur, the DM is incomplete. An incomplete DM can be caused by two distinct issues:

- the function set is incomplete, i.e. not all (toplevel) functions are incorporated, (and) or
- the relationship description, which describes which components collaborate to fulfill a particular function, is incomplete.

If an interaction exists solely in the functional DSM (type 1), this interaction may suggest an interaction in the physical DSM. A total of 178 of these interactions have been identified via the DM conversion. However, the majority of these type 1 interactions are caused by indirect interactions (see the Outport example in Section 6.1). Since only information type interactions in the physical DSM allow indirect interactions, all other indirect interactions in the functional DSM are to be neglected. More details are provided in Section 7.3.

7.2 Feedback on the DM

A total of 216 physical interactions were identified. In the comparison DSM it is found that 125 of them are not confirmed by the functional DSM. As reasoned before, this suggests issues with either the function set or the relationship description. By investigating the type 2 interactions and referencing them with the DM, some of these issues can fairly specifically be identified and improvements can be stated.

The physical information type interaction between the Actuators vertical lift gates and the Maintenance control system does not appear in the functional DSM, hence it is a type 2 interaction. By investigating the DM, it can be found that the Actuators vertical lift gates only appear in the relationship description for the function: Open and close lock gates and not in the relationship description of the function: Maintenance control. Hence via the comparison DSM, it is concluded that the relationship description of Maintenance control in the DM is incomplete. In the DM it can also be seen that if the Actuators vertical lift gates are added to the relationship description of the function: Maintenance control, a lot of other components also have to be added to its relationship description to remain consistent. This suggests the function is defined on an excessively high granularity level. Hence the Maintenance control functions contains two issues: an incomplete relationship description and a granularity level issue.

This issue consequently involves two steps to be solved. First, the function needs to be broken down into several, more specific subfunctions to prevent its relationship description from coupling too many components, e.g. the function: Maintenance control lock head, Maintenance control lock chamber etc. Secondly, the relationship description of these various subfunctions needs to be completed and the improved DM needs to be converted to a functional DSM. This functional DSM can now be used, via the construction of a comparison DSM, to check if the type 2 interactions

disappeared. This procedure results in a improved description of the coupling structure of functions and components.

In some cases, type 2 interactions are solely caused by an incomplete relationship description. All communication systems for example are required for the function: Provide audio communication. Hence the functional DSM shows a coupling between all these components. However, the comparison DSM shows a high amount of type 2 interactions between the communication systems and the Low voltage supply. Hence, the comparison DSM suggests that the Low voltage supply is missing from the relationship description in the DM. By complementing the relationship description of the function with the Low voltage supply, the majority of the type 2 interactions regarding the Low voltage supply disappear.

If the DM and its corresponding function set is to be improved, this process should be repeated until all type 2 interactions disappear. If the sole objective of the functional DSM is to enhance the physical DSM, this is not required. Although improving the level consistency via the mentioned procedure will yield a lower number of type 1 interactions, and by that a smaller quantity of suggested interactions to be investigated, the effort is considered to be greater than simply investigating a larger amount of suggested interactions.

7.3 Suggested interactions

If a set of components is included in the relationship description of a function, the functional DSM will show an interaction between all these components. This means that even indirect interactions of the xth degree will be depicted in the functional DSM. In the physical DSM, only the information type interactions are allowed to express indirect interactions, and only of the first degree. Hence, the type 1 interactions, caused by indirect interactions of any other interaction type, have to be neglected.

Since the majority of the relationship descriptions contains more than 3 components, the degree of a type 1 interaction needs to be determined manually. This is done by investigating each particular interaction and determining if a component pair is connected directly, or via other components.

Information type interactions in the physical DSM are allowed to be first degree indirect. Constructing an "information only" comparison DSM, may therefore yield interesting insights. A significant amount of the components of the reviewed decomposition contain no information interactions at all, hence these components are excluded from this analysis, see Figure 7.2.

A total of 141 interactions remain in the reduced information type comparison DSM, of which 73 are suggested by the functional DSM. 34 of them are type 3 interactions, hence 50 percent of the information interactions in the physical DSM is confirmed by the functional DSM. Which is an increase with respect to the 40 percent confirmation for the DSM containing all interaction types.

The information type interactions that were missed during the construction of the physical DSM can be categorized into two groups: direct type 1 interactions and first degree indirect type 1 interactions. The classification is performed manually by inspecting the working principles governing the lock system.

For example, the Operator/maintenance personnel and the Actuators vertical lift gates depict a type 1 interaction. Studying the functionality of the lock system shows their control circuit, see Figure 7.3.

Since the components are connected via the Regular control system and via the Supervisory control system, they have a second degree indirect information interaction and the interaction suggested by the functional DSM is neglected.

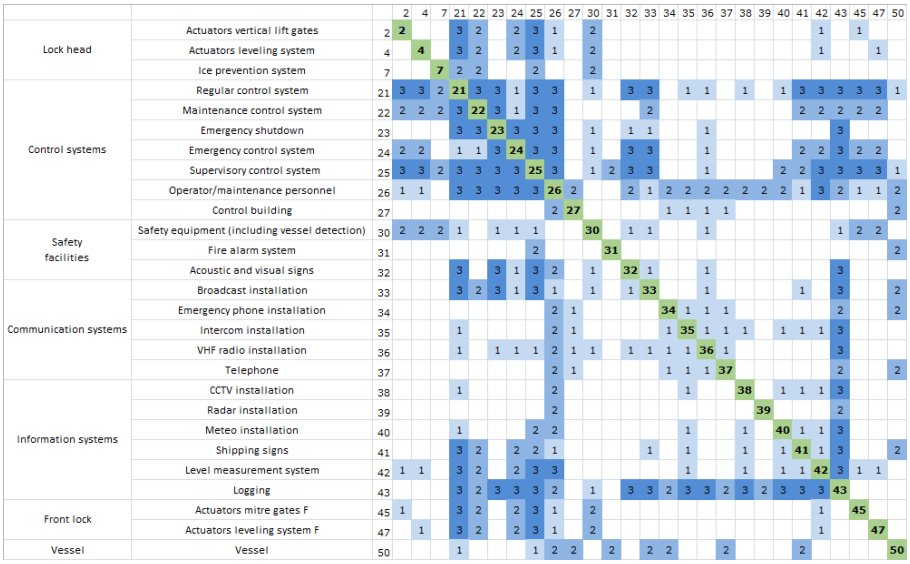


Figure 7.2: A compressed comparison DSM of the physical information interactions and functional DSM. A "1" (light blue) interaction exists only in the functional DSM, a "2" (blue) interaction exists only in the physical DSM and a "3" (dark blue) interaction exists in both.



Figure 7.3: Control circuit of the Operator/maintenance personnel and the Actuators vertical lift gates.

Another component pair with a type 1 interaction does yield a suggestion that can be used to complement the physical DSM. The Regular control system and the Maintenance control system depict a type 1 interaction, hence their coupling structure is investigated, see Figure 7.4.

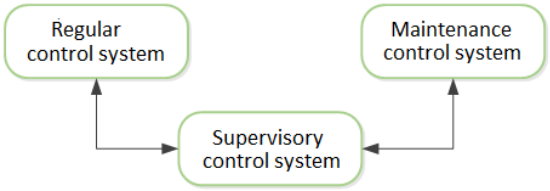


Figure 7.4: Coupling structure between the Regular control system and the Maintenance control system.

As can be seen in the figure, the Regular control system and the Maintenance control system have an indirect interaction between them. Since this interaction is of the information type, this indirect interaction should be in the physical DSM. Hence, the functional DSM can successfully be used to identify missed interactions in the physical DSM. By repeating this procedure for all type 1 interactions in the information comparison DSM, a total of 10 new information interactions were identified. Of which 1 interaction depicts a direct interaction.

All the other interaction types, i.e. Spatial, Location and energy require a direct relation to constitute an interaction. To analyze the suggested interactions for these the full comparison DSM is analyzed with exemption of the information interactions.

In total, 4 new interactions are identified by investigating the remaining type 1 interactions. This number is much lower than the 10 new information interactions that have been identified. This is due to the fact that indirect Spatial, Location and Energy interactions of the first degree and higher are neglected.

All the newly identified interactions are rated through the rating scheme developed in Section 5.1 and placed in the physical DSM, see Figure 7.5.

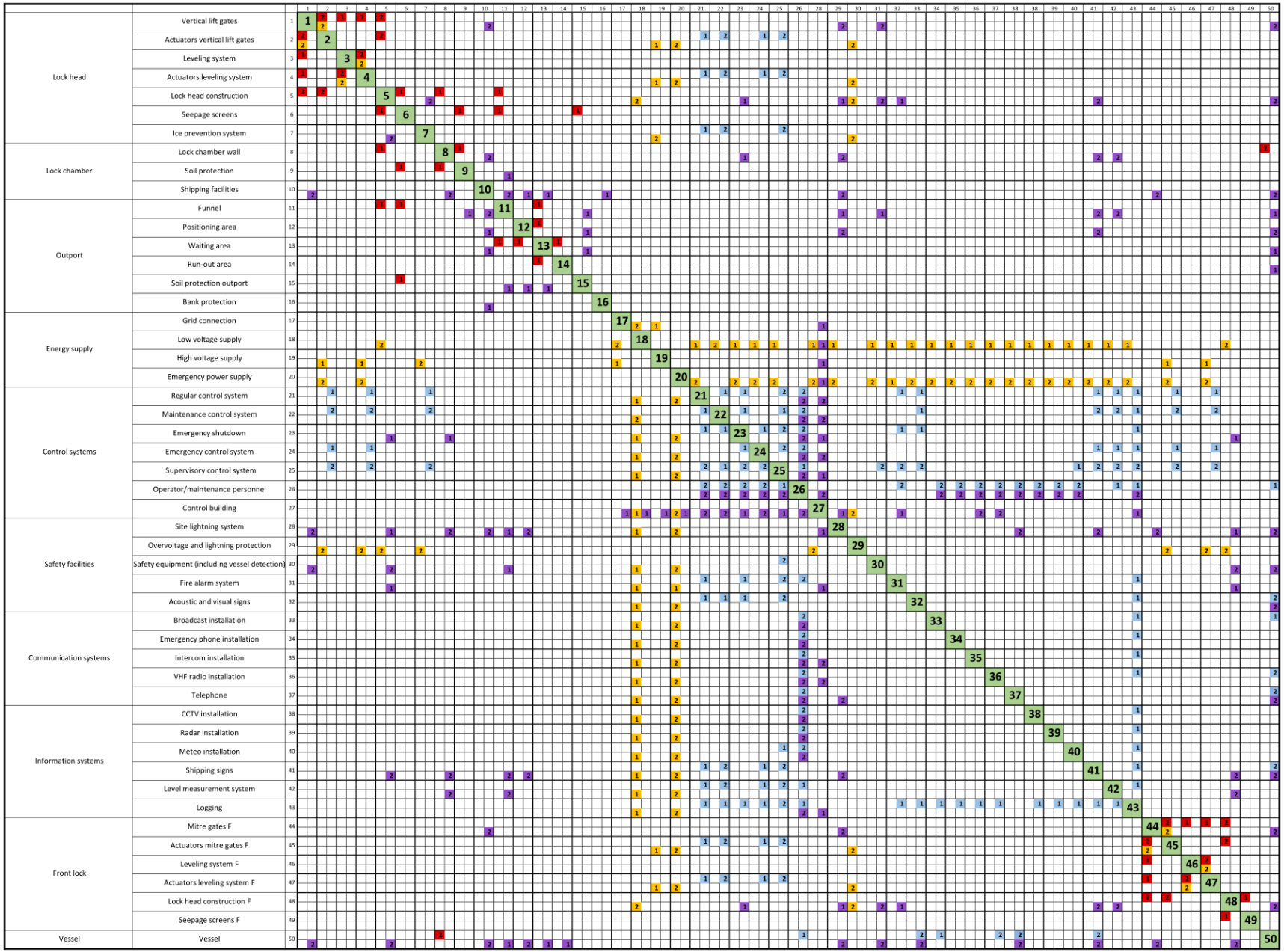


Figure 7.5: Physical DSM, enhanced by suggested functional interactions.

7.4 Conclusion

With the aid of a comparison DSM to examine the differences between the functional DSM and the physical DSM, the functional structure of the system is successfully used to enhance the physical DSM. Even if the DM that is used for the conversion method is incomplete, a functional DSM can be obtained that is useful to enhance the physical DSM.

By investigating the individual type 2 interactions, specific suggestions for improvement of the DM are made. If a type 2 interaction is caused by a function that is defined on a suitable granularity level, its relationship description is incomplete. If the function that caused a type 2 interaction is not defined on a suitable granularity level, the function needs to be decomposed into subfunctions. The physical DSM, the functional DSM and the DM can consequently be used in an iterative manner to complement each other.

Since solely the information interaction type allows indirect interactions, the enhancement procedure is more effective for this interaction type. For other interaction types only the more obvious direct interactions are allowed to appear in the physical DSM. Still a total of 4 interactions, other than information type, are identified via the DM to DSM enhancement.

Chapter 8

Coupling structure analysis

The enhanced physical DSM of Chapter 7 was obtained by complementing the physical DSM via suggested interactions by the functional DSM. This enhanced physical DSM is a representative model of the dependency structure of lock system Eefde. In this chapter this DSM is clustered to reveal the underlying coupling structure of the system.

The first step in the clustering analysis is the application of a clustering algorithm. In order to apply this clustering algorithm, the interaction strengths are aggregated, i.e. the various interaction types and strengths that couple a component pair are aggregated into a single number. This aggregation procedure is applied to obtain an aggregated DSM that can be used as an input for the clustering algorithm.

The clustering algorithm developed by Van Dongen (2008) and later adapted for use in DSMs by Wilschut et al. (2014), is applied to the aggregated DSM in order to identify modules of strongly coupled components. After the clustering algorithm is applied, a manual post processing step is carried out to identify components that appear in two clusters simultaneously (overlapping components) and a bus module that provides the integral coupling in the system. The overlapping components are determined via the definition of overlapping clusters. The bus components of the lock are determined by investigating how integrative the various components are.

The obtained modularized DSM is subsequently reviewed. The resultant clustering gives rise to an improvement of the decomposition determined in Section 4.3.2 by suggesting new and naturally emerging subsystems. The characteristics of the components in these subsystems are studied to assign a suitable name for the emerging subsystems. The overlapping components defined in the post processing phase are investigated and the legitimacy of all interactions existing outside of modules (i.e. inter module interactions) is verified.

8.1 Structural aggregation of the interaction types and strengths

In this study, four different physical interaction types are considered, namely: spatial, information, energy and location. Each of these interaction types, or a combination thereof, each with their own interaction strength, may exist between a component pair. The clustering algorithm requires a single number to represent the interaction strength. Hence, the four interaction types have to be aggregated into a single representative interaction strength. In the NASA Pathfinder case study, Brady (2002) simply added the interaction strengths of four interaction types to obtain a number for the representative interaction strength, see Figure 8.1.

Some interaction types are more important than others with respect to the coupling structure analysis. By allowing a distinction between the various interaction types, the structural coupling

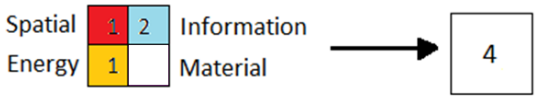


Figure 8.1: Aggregation of interaction strengths as used by Brady (2002).

can be stressed, i.e. the various interaction types have a different influence on the representative structural interaction strength (RSIS)

This distinction is made by rating the relative importance of the interaction type to occur in the same cluster. Since the coupling structure is of interest, it is considered important for the location and spatial interactions to appear within a cluster. The information and energy interactions to do not necessarily need to appear within a cluster; the power cable or information transfer cable, which enables the interaction, can easily be extended. Energy interactions that are formed by mechanical energy, always occur in combination with a spatial interaction, hence they will be forced to appear in a cluster.

Since location interaction types often have a preference for proximity, their importance weight is factorized with a 2. Spatial interactions represent the most important coupling with respect to the physical structure, hence their importance weight is rated with a 3. See Figure 8.2 for an aggregation example.

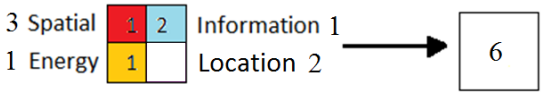
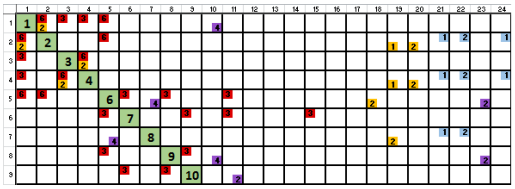


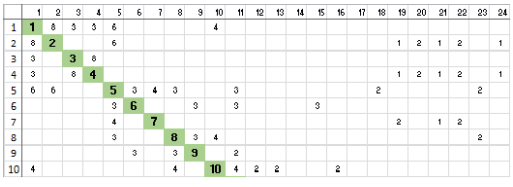
Figure 8.2: Structural aggregation of interaction strengths by including interaction type importance.

The spatial interaction has a rating of 1 and its importance weight is 3, hence its contribution to the representative interaction strength is 3. For information, energy and location the same procedure is followed and the total representative interaction strength is given by 6.

This aggregation is performed for the enhanced physical DSM of Chapter 7. First a weighted DSM is developed to incorporate the importance weights of all the interactions. The interaction strengths is this DSM are obtained by multiplying the original interaction strengths with their respective weighing factor, see Figure 8.3a. Subsequently, these weighted interaction are summed to obtain the representative interaction strength, and the aggregated DSM is developed, see Figure 8.3b.



(a)



(b)

Figure 8.3: (a) Section of weighted DSM, incorporating the importance weights for the various interaction types. (b) Section of aggregated DSM, depicting the representative interaction strengths.

As can be seen in the figure, a component pair with more than one interaction type between them, shows a stronger representative interaction strength. Furthermore, since the importance weight

of spatial interactions is high, these interactions are more apparent in the aggregated DSM by the higher representative interaction strength assigned to them.

The aggregation procedure used in this section is focused on the physical structure of the system. By manipulating the weights of the various interaction strengths, different structures can be investigated, e.g. information flow structures and electrical plans.

8.2 Clustering the physical DSM

To reveal the underlying coupling structure of lock system Eefde, the clustering algorithm is applied to the aggregated DSM. This algorithm permutes the rows and columns in such a fashion that clusters of tightly coupled components appear.

The clustering algorithm organizes the aggregated DSM in a modular manner. Some of the components however have a more integral character, i.e. they have an interaction with a high amount of other components and should therefore be treated as so called bus components. These components are identified manually and placed in a bus module.

8.2.1 Modularization of the aggregated DSM

The modularization of the aggregated DSM is performed by a clustering algorithm. The settings of this algorithm have been optimized via Latin Hypercube Sampling (McKay et al. (1979)), see Appendix A for details.

By employing these settings, a first approximation of the modularization of lock system Eefde is determined, see Figure 8.4.

This computational result is subsequently used as a starting point for post processing. Since the algorithm does not distinguish overlapping clusters and bus components, these are manually introduced via a post processing step.

8.2.2 Post processing of the proposed solution

As suggested by Eppinger and Browning (2012), the solutions proposed by clustering algorithms can be manually improved. Helmer et al. (2010) even explicitly incorporate a separate manual post processing step in their clustering procedure. These procedures are used for the structure analysis of lock system Eefde.

The clustering algorithm defines 7 distinct clusters. By close inspection of these clusters, some suggestions for improvement can be found. Cluster 1 shows a strong connection with Cluster 2 via three spatial interactions of the Lock head construction. This connection can be represented by extending Cluster 1 and thereby allow Cluster 1 and Cluster 2 to overlap. For the remaining clusters, a similar procedure is followed. Whenever a strong connection is found between a pair of clusters, it is investigated whether allowing these clusters to overlap would improve the visualization of the coupling structure.

Some components have a more integral coupling structure, i.e. they are connected to a great number of other components (Sosa et al., 2003). The coupling structure of these high connectivity components can not be depicted, in a representative manner, in a fully clustered DSM. Another type of module has to be incorporated that represents an integral coupling structure, this module is called a bus module. Since the current clustering algorithm is not able to distinguish bus components, the bus module, a strategy is developed to identify them.

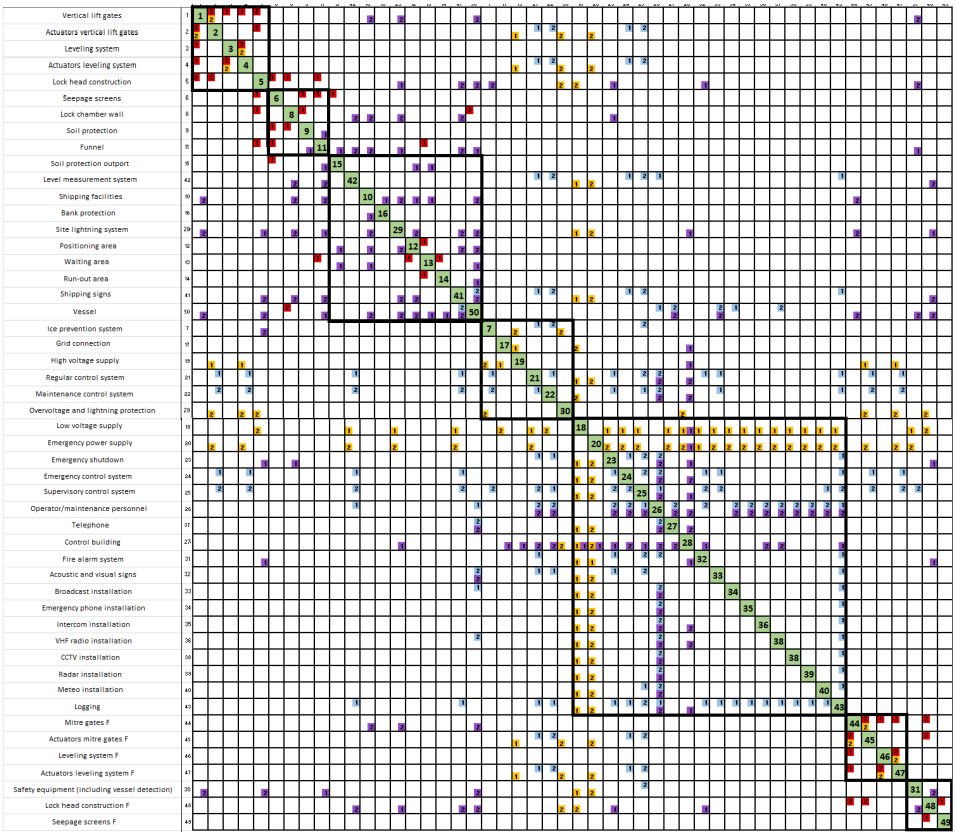


Figure 8.4: Modularization as suggested by clustering algorithm.

Sosa et al. (2003) suggested a way to capture these components via a systematical approach: By determining the amount of cross cluster interactions a subsystem has, its connectivity can be determined. The connectivity values are subsequently be used to identify the subsystems with the most integrative character.

By visually inspecting the manually adapted modularization, it can be seen that within the same cluster the connectivity of each component can vary greatly. This variation suggests that using the connectivity values on subsystem level for bus analysis is less appropriate; the whole subsystem will be deemed an integrative subsystem whilst a large portion of its components may have a low connectivity. Hence, the principle of the connectivity values is applied on component level in order to determine integrative components as opposed to integrative subsystems.

For each of the components, the connectivity is determined by summing all the interaction strengths. By sorting the components based on their connectivity value, the most integrative components appear on the left hand side, see Figure 8.5.

Now that the connectivity values of all components in the DSM are known, some threshold needs to be determined to enable distinction between integrative components and modular components. Sosa et al. (2003) compared the connectivity values of various subsystems to distinct between modular and integrative subsystems. Since the objective is to identify integrative components instead of subsystems, an alternative criterion on component level has to be determined. As a starting point, the top 10 highest connectivity components are set to be bus components.

Some of these components behave more like overlapping components than bus components. They have a high connectivity value, but their interactions are not evenly distributed. The Control building for example is strongly connected only to the bus module and two distinct clusters, it is

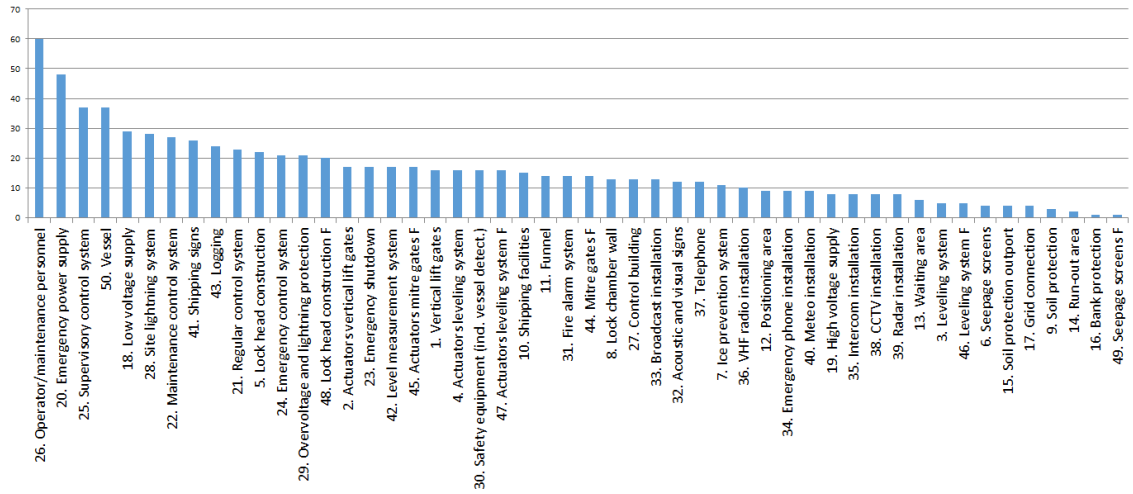


Figure 8.5: Components sorted by their connectivity value.

therefore removed from the bus module and placed back as an overlapping component between the two clusters. This procedure is repeated until all components that behave like overlapping components are removed from the bus module.

Subsequently, an opposite procedure is carried out. By investigating the characteristics of all components, it becomes clear that some of them posses an integrative character while this is not suggested by their connectivity value. The majority of these components does not really fit in any of the proposed clusters. The Safety equipment (incl. Vessel detection) for example does not have a high connectivity value, but its interactions are distributed over various clusters. The only legitimate position of this component is consequently in the bus module.

Manually incorporating these results in the adapted modularization, extends the representation with overlapping components and a bus module as shown in Figure 8.6.

8.3 Coupling structure review

The clusters determined in the previous section contain distinct characteristics. These characteristics are used to determine a representative name for the resultant clusters. The characteristics of overlapping components that connect a pair of clusters are inspected. Furthermore, interactions that appear beyond the borders of the defined modules require close inspection; they either represent an inter cluster coupling or an erroneous interaction.

8.3.1 Cluster designation

The clusters of components can be thought of as naturally appearing subsystems. The name of these subsystems is determined by investigating its comprising components. In some cases, the clusters closely match the subsystems defined in the decomposition of Section 4.3.2, and the name can be adopted. For instance, the subsystem Outport in this decomposition, shows strong similarities with the third cluster of the modularization; it is extended by the Level measurement system and the Shipping facilities. Hence, the name ‘Outport’ of this subsystem is adopted to denote the third cluster.

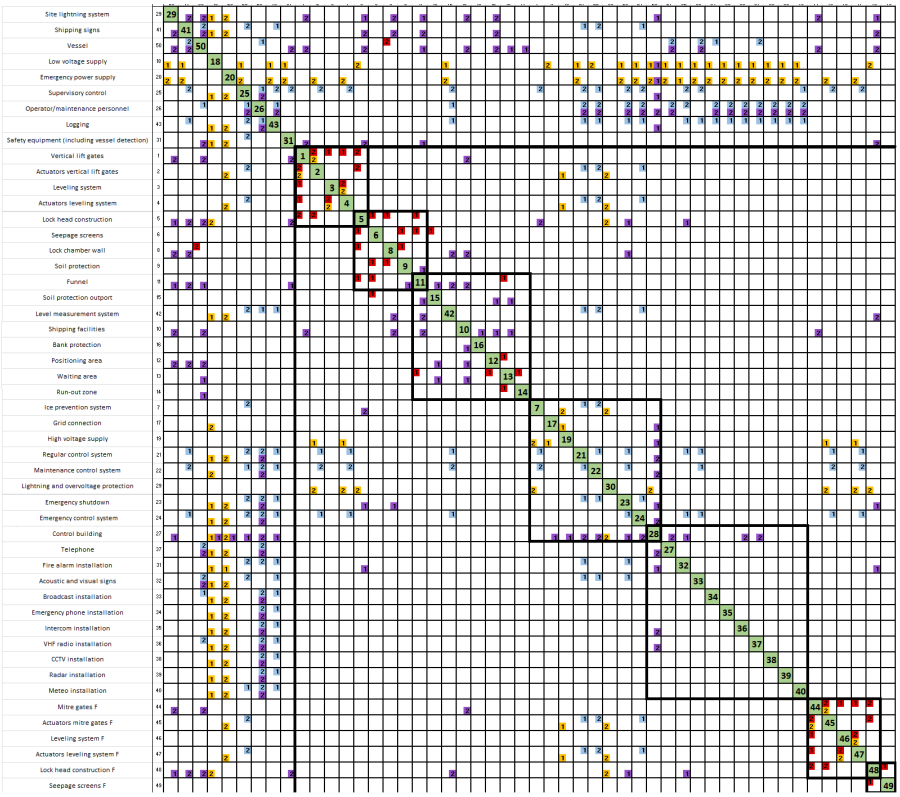


Figure 8.6: Modularization of lock system Eefde including a bus module and overlapping components.

For the other clusters, the characteristics of the components in a cluster have to be investigated to determine a representative name. Cluster 1 denotes a subset of the subsystem Lock head of Figure 4.7, see Figure 8.7.

The Lock head construction appears in Cluster 1 and Cluster 2, it is therefore an overlapping component that couples these two clusters. The other components in Cluster 1: Vertical lift gates, Actuators vertical lift gates, Leveling system and Actuators leveling system, refer to the moving parts of the Lock head. A suitable name of Cluster 1 is therefore: Navigation lock mechanical.

Cluster 2 consists of, besides the Lock head construction, the Seepage screens, the Lock chamber wall, the Soil protection and the Funnel. The latter is an overlapping component and connects Cluster 2 to Cluster 3.

Consequently, Cluster 1 and Cluster 2 defined by the clustering algorithm are more intuitive subsystems than the original Lock head and Lock chamber grouping of the decomposition depicted in Figure 4.7of Section 4.3.2. The three non overlapping components of Cluster 2 are static construction components. Cluster 2 will hence be named: Navigation lock civil.

A similar procedure is followed for the remaining clusters. In some cases however, a component is encountered that seems unrelated to the other components in the cluster. In these cases, a satisfying explanation needs to be found. An example occurs in the Outport subsystem.

The clustering algorithm suggested to extend the Outport by the Level measurement system, albeit this component shows very little similarities with the rest. The function of Level measurement system is to measure the water levels of the various sections of the lock system. Although this suggests a integrative coupling structure, its connectivity is relatively low and can therefore not be included in the bus module. Since its function is to support the control of the lock system,

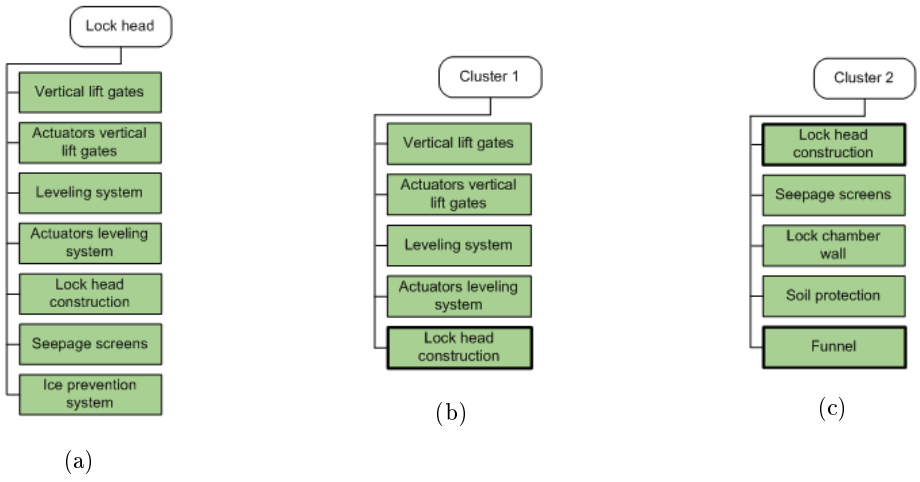


Figure 8.7: (a) Subsystem Lock head adopted from the reviewed decomposition (b) Decomposition of Cluster 1 (c) Decomposition of Cluster 2. The overlapping components are depicted by a thick edge.

the Level measurement system is manually re-placed from Cluster 3 into Cluster 4: Control and facilitating systems.

Another difficulty is encountered during the analysis of Cluster 5; the cluster consisting of eleven components is sparse, see Figure 8.8.

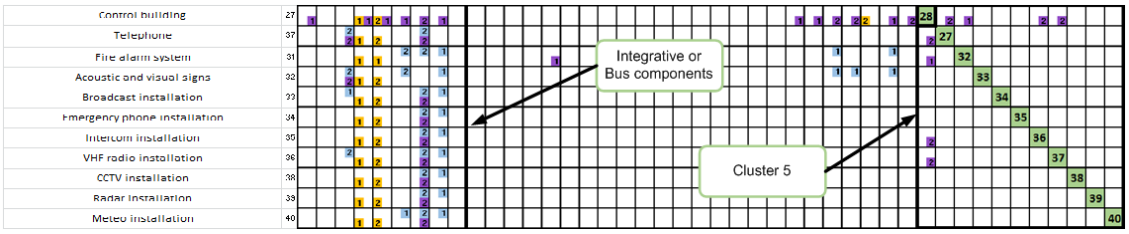


Figure 8.8: Section of the clustered DSM, depicting the coupling structure of Cluster 5.

As can be seen in the figure, Cluster 5 shows very little intra cluster interactions. Only the overlapping component Control building links some of its components. Considering the components within this cluster, this sparse nature can be expected, i.e. these components do not require interactions between them. By investigating the bus components, depicted on the left hand side, it can be seen that the coupling between these components is formed by strongly connected common bus components. All the components in Cluster 5 are indirectly coupled via the Low voltage supply and the Emergency power supply. They are furthermore connected via information links with the Operator/maintenance personnel and the Logging. The function of all these components is either to support communication or to provide necessary information for the control of the lock system. Cluster 5 is consequently named: Information and communication systems.

For Cluster 6 and Cluster 7, a similar consideration is made as is done for Cluster 1 and Cluster 2. These clusters are respectively named Front lock mechanical and Front lock civil. The resultant cluster designation of all clusters is depicted in Figure 8.10.

By summing the individual connectivity values (see Section 8.2.2) of the components within a module, the connectivity value of the modules can be obtained. Overlapping components belong to two clusters simultaneously and hence their contribution is incorporated in both modules, see Figure 8.9.

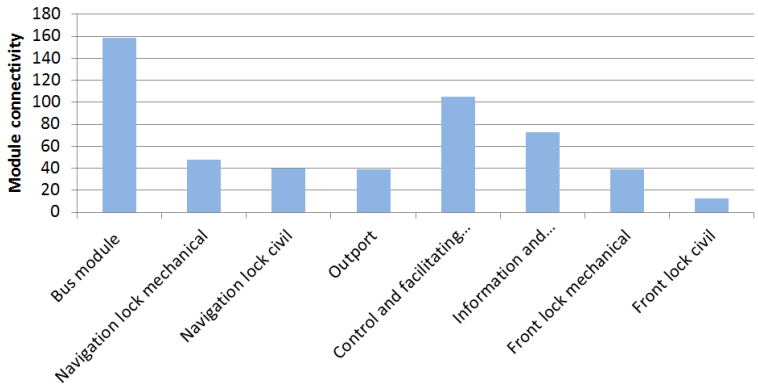


Figure 8.9: Connectivity values of modules.

As expected, the bus module yields the highest connectivity value. Cluster 4 and Cluster 5 also contain high values. The designation of these clusters yielded respectively: Control and facilitating systems and Information and communication systems. Their integrative character can consequently be expected.

8.3.2 Overlapping components

The next step of the structure review is the inspection of overlapping components. In Section 8.2.2, the overlapping components were removed from the bus module by manually inspecting their characteristics. In this section, these components are inspected more closely.

Several perspectives exist on how to handle overlapping clusters and the components that cause the overlapping. Hölttä-Otto et al. (2005) viewed overlapping components as if they obscure true cluster definition and proposed the following techniques to overcome these issues:

- Merging of clusters. By merging a pair of clusters into a single cluster, the overlapping component is incorporated in the aggregated cluster.
- Assignment of a component to one of the two clusters. This option maintains the inter connective nature of the cluster pair.
- Define a new cluster; the overlapping component forms a new cluster. This option causes an increase of inter cluster interactions.
- Cloning the component. This option duplicates the overlapping component and assigns each of them to one of the two clusters.
- Splitting of the component. This option splits the overlapping component into two distinct components.

Helmer et al. (2010) share this view on overlapping components but extended the approach to include all components with a "bus like character", i.e. components that have a high connectivity or show interactions with multiple clusters in a similar fashion.

Browning (2001) suggested a different view on overlapping components. The overlapping components are not treated as an issue, but merely viewed as a system characteristic. By investigating the overlapping components of lock system Eefde, it can be seen that this view more closely represents the characteristics of these components. Consider for instance component 11, the Funnel. The function of this component is to guide ships from the Outport subsystem into the Navigation

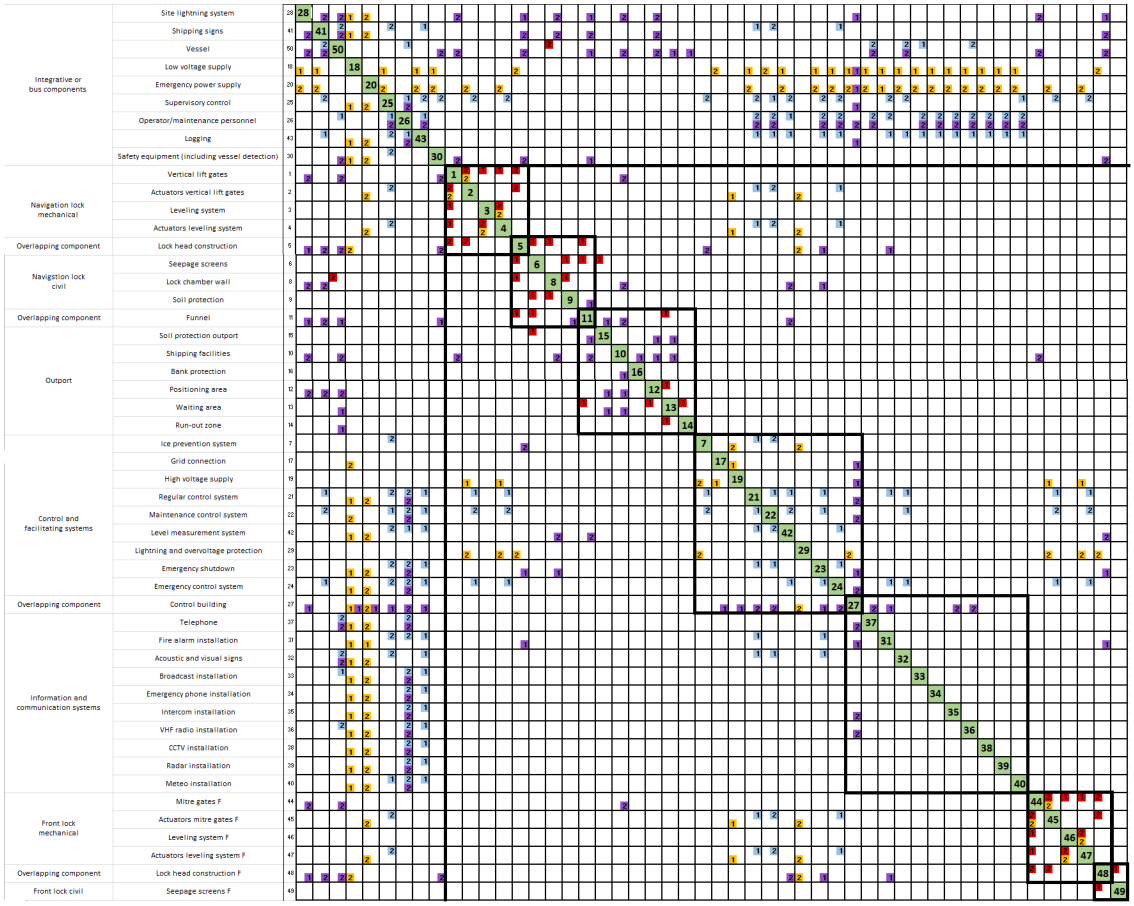


Figure 8.10: DSM after cluster designation.

lock. It thereby connects these two subsystems. This connection is most faithfully represented by maintaining the overlapping nature of the component.

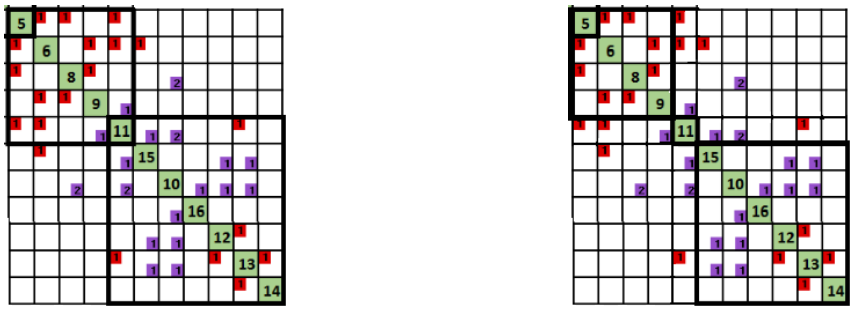
The other overlapping components are: the Lock head, the Control building and the Lock head front lock. All these components have a connective character, i.e. their function is to connect the various subsystems. Maintaining their overlapping nature consequently most accurately represents the system coupling structure.

8.3.3 Inter module interactions

Inter module interactions, i.e. interactions that exist between the clusters and the bus module, depict points of attention. These interactions can represent:

- Inter module connections that describe the relationship that exists between two clusters. Hence, during the design of the lock system, these connections are the 'channels' about which the design teams of the different modules need to communicate.
- Erroneous interactions that appear in an unexpected location, might depict an erroneous coupling.

Hence, careful investigation of these interactions is required to increase the understanding of the system's coupling structure and to verify the legitimacy of its DSM representation.



(a) (b)

Figure 8.11: (a) Cluster 2 and Cluster 3 as overlapping clusters, with component 11 as overlapping component. (b) The result of manually introducing a new cluster.

Since the various interaction types posses different characteristics with respect to inter module connections, a distinction between them has to be made during the analysis. In total 39 inter module interactions are depicted in Figure 8.10. The distribution of these interactions for each of the interaction types is depicted in Figure 8.12.

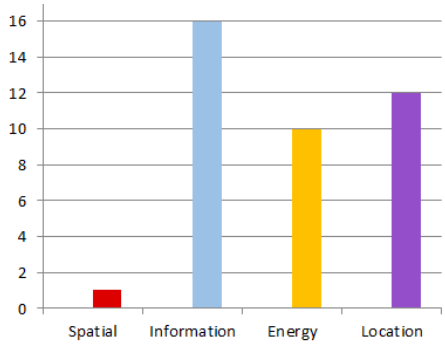


Figure 8.12: Distribution of inter module interactions.

This distribution closely matches ones intuition. The spatial interactions that physically connect a component pair, only appear once outside of a cluster. The other interaction types constitute a more remote type of coupling and are therefore more likely to appear beyond a module. Hence, the structural aggregation defined in Section 8.1 successfully assisted in obtaining a representative structural coupling structure.

Inter module interactions of the information type describe the information flow between clusters. By close inspection of Figure 8.10, it can be seen that all these information flows connect to the Control and facilitating systems subsystem. More precisely, these inter module information type interactions can be categorized into three groups:

1. The connection between the Control and facilitating systems subsystem and the Navigation lock mechanical subsystem (via indirect information flows and a direct coupling with the Maintenance control system).

2. The connection between the Control and facilitating systems subsystem and the Information and communication systems subsystem.

3. The connection between the Control and facilitating systems subsystem and the Front lock mechanical subsystem.

Interaction	Component 1	Component 2
1	1. Vertical lift gates	10. Shipping facilities
2	5. Lock head construction	7. Ice prevention system
3	5. Lock head construction	23. Emergency shutdown
4	5. Lock head construction	32. Fire alarm installation
5	8. Lock chamber wall	10. Shipping facilities
6	8. Lock chamber wall	42. Level measurement system
7	8. Lock chamber wall	23. Emergency shutdown
8	11. Funnel	42. Level measurement system
9	10. Shipping facilities	44. Mitre gates front lock
10	42. Level measurement system	48. Lock head construction front lock
11	23. Emergency shutdown	48. Lock head construction front lock
12	32. Fire alarm installation	48. Lock head construction front lock

Table 8.1: Inter module location interactions.

The components within the Control and facilitating systems subsystem that provide the inter module connections are: the Regular control system, Maintenance control system and Emergency control system. Since the function of these components is to sent control information to components throughout the system, these interactions are verified and the three information flow groups are depicted in the Figure 8.13.

For the energy interaction, a similar procedure is followed. The inter module interactions of the energy type all originate from the same cluster: the Control and facilitating systems. The components that provide the inter module interactions are: the High voltage supply and the Lightning and over-voltage protection. The integrative character of these components sufficiently explains the inter module interactions and the two energy flow groups are depicted in Figure 8.13.

12 inter module location interactions are identified. They are evenly distributed across the DSM, hence these interactions can not be attributed to a single cluster nor can they be grouped. Consequently, they have to be investigated individually. The individual inter module location interactions are depicted in Table 8.1.

The Shipping facilities are an aggregation of, amongst others, the Collision protection. This component is used to protect the Vertical lift gates and the Mitre gates front lock from a collision with a ship. This component will subsequently maintain its integrative character and yield inter module interactions.

The Emergency shutdown, the Fire alarm system and the Level measurement system posses similar characteristics. A multitude of these components is placed in the lock system.

Interaction 2 of Table 8.1, between the Lock head construction and the Ice prevention system, poses a difficulty. The only location interaction between Ice prevention system and the rest of the system, is with a component in Cluster 1, yet the clustering algorithm placed it in Cluster 4. The reason can be found by investigating the representative interaction strengths. Even when the interaction weight of $\times$ 2 for location interactions is incorporated, the information and energy interactions still outnumber the location interaction. Consequently, the Ice prevention system was placed in the cluster containing the highest representative interaction strength: Cluster 4.

Since the objective of the clustered DSM is to faithfully represent the coupling structure of lock system Eefde, any manual alternation to the DSM that improves this representation is legitimate. By moving the Ice prevention system to the Navigation lock mechanical subsystem, the connection of this subsystem to the Control and facilitating systems subsystem is stressed by increasing the amount of energy and information interactions between them.

Finally, one inter module spatial interaction exists. This interaction couples the Navigation lock civil subsystem with the Outport subsystem via the component pair Seepage screens and Soil protection outport.

Since the weight of spatial interactions for the determination of the representative interaction strength was set to $\times$ 3, the clustering algorithm focused mostly on these interactions, yet the interaction is still depicted beyond the module borders. The function of the Seepage screens is to prevent groundwater currents and the resulting damage to the foundation. This is done by creating a watertight connection with the various sections of the lock system, both above and below ground level. The Seepage screens are therefore placed on the interfaces of subsystems and consequently possess natural inter cluster characteristics.

By employing all the improvements suggested by the structure review, a more accurate description of the coupling structure of lock system Eefde is obtained, see Figure 8.13.

Furthermore, a subsystem representation of the DSM is obtained by connecting the naturally emerging subsystems via the inter module interactions determined in Section 8.3.3, see Figure 8.14. This subsystem DSM represents the dependency structure of the lock system on subsystem level. It can be used as a simplified representation of the lock's dependency structure or to map the communication that must exist between the design teams of the various subsystems.

Combining the overlapping components with the cluster designation from Section 8.3.1 yields a new, more naturally emerging decomposition of the lock system, see Figure 8.15. This decomposition contains the same components as the decomposition of Figure 4.7 in Section 4.3.2, but copies overlapping components to stress the fact that an overlapping component appears in two clusters simultaneously.

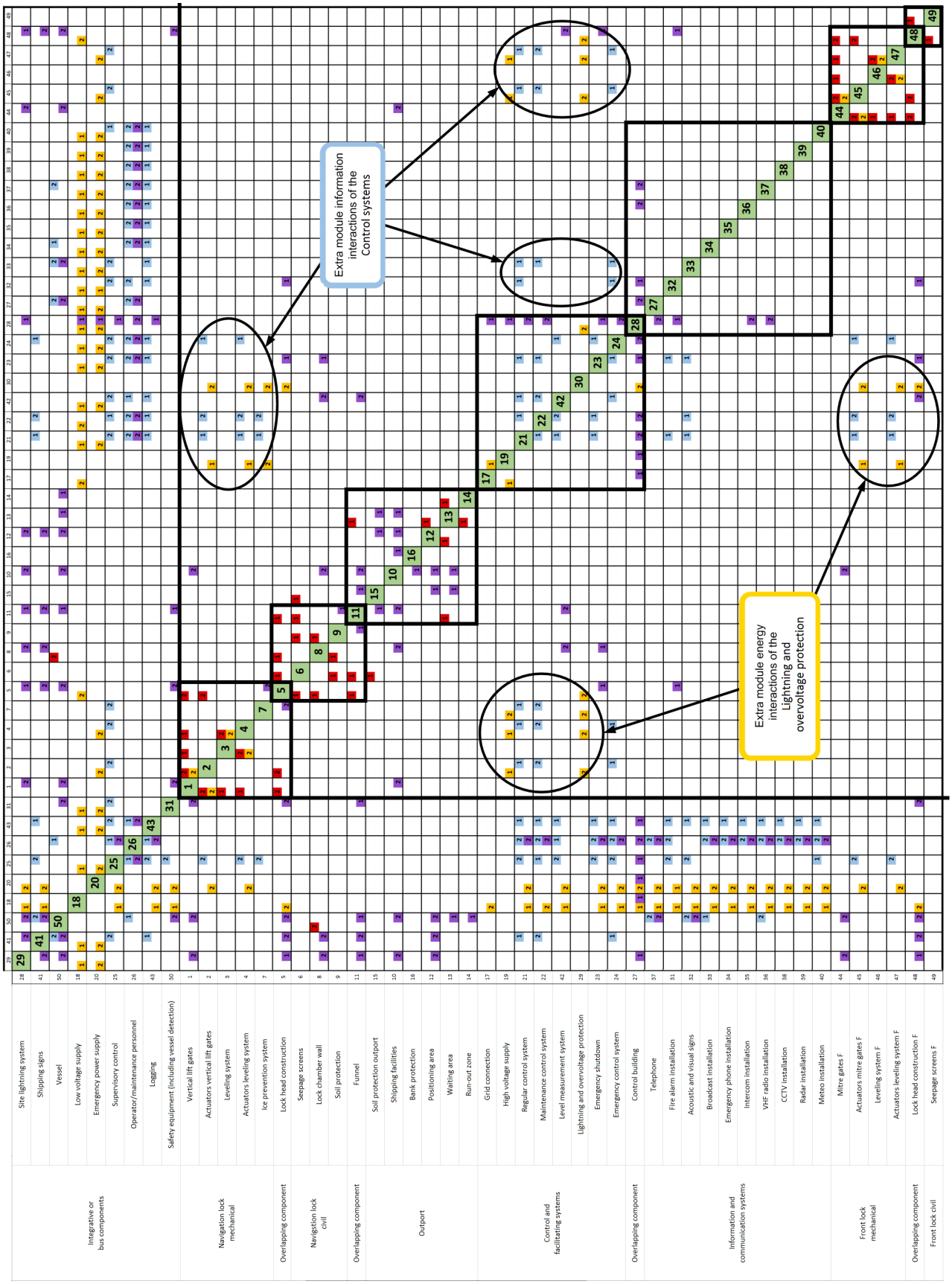


Figure 8.13: Modularized design structure matrix of lock system Eefde.



Figure 8.14: Subsystem design structure matrix of lock system Eefde. The diagonal entries depict the subsystems and the off-diagonal entries depict the interaction groups that exist between these subsystems.

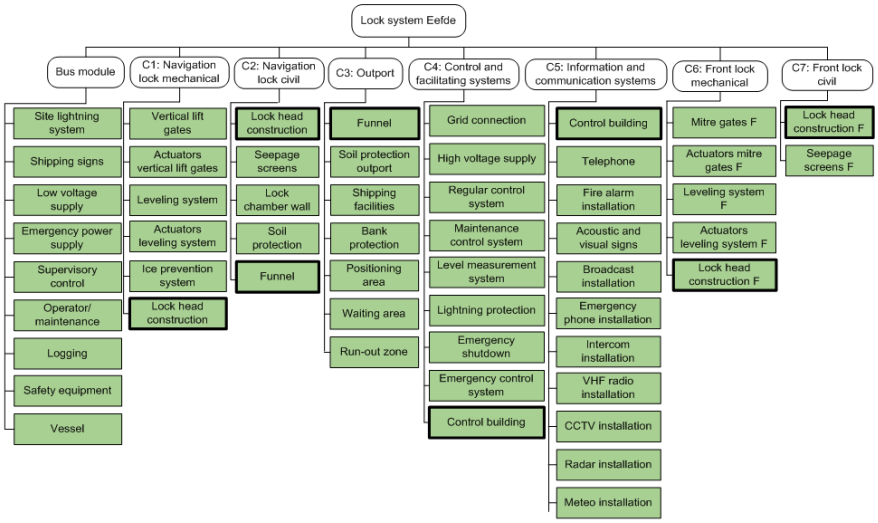


Figure 8.15: Decomposition of lock system Eefde with naturally emerging subsystems, overlapping components (thick edge) and bus module (first column)

8.4 Conclusion

The coupling structure of lock system Eefde is fairly modular, i.e. the modules determined in this chapter can be treated relatively disjoint. The interactions between these modules are provided by the bus module, overlapping components, 3 information interaction groups and 2 energy interaction groups.

The underlying coupling structure of lock system Eefde has been revealed by clustering the enhanced physical DSM obtained in Chapter 7. To do so, an aggregation method for the various interaction types and strengths is determined that focuses on the physical coupling structure of the system. By applying the clustering algorithm a proposed grouping of components (modularization) is obtained. This solution is subsequently improved by a post processing step in which overlapping components and a bus module are introduced. The resultant modularization shows clusters of components that have a strong interaction with each other. These clusters can be viewed as an improvement of the decomposition obtained in Section 4.3.2. This decomposition, consisting of naturally emerging subsystems is presented in Figure 8.15.

Effort is taken to define a suitable name for these subsystems. The overlapping components defined during the post processing phase are reviewed and each of the inter module interactions is inspected. This results in two DSMs: A modularized DSM, see Figure 8.13, that represents the coupling structure of components in the system and a subsystem DSM, see Figure 8.14, that represents the coupling structure of the various subsystems in the system. Note that the components of the various subsystems are listed in Figure 8.15.

In the subsequent chapter the coupling structure obtained in this chapter is used to investigate reliability and availability risks in the context of the dependency structure of the lock system. Furthermore, since the coupling structure has been obtained without incorporating RA, it can be used for other purposes, e.g. allocating design teams and interactions between them, analyzing other characteristics than RA, etc.

Chapter 9

Reliability and availability coupling structure analysis

The modularized DSM of lock system Eefde, depicted in Figure 8.13, is used as a basis for the identification of areas in the design of the lock system with high reliability and availability risks. This is done by adapting the principles governing the NASA Pathfinder DSM case study (Brady (2002)). The method used to analyze these RA risks is split into four parts:

- First, the interactions of the modularized DSM are aggregated into two representative interaction strengths: the reliability interaction strength (RIS) and the availability interaction strength (AIS). These interaction strengths represent the importance of the interaction between a component pair with respect to respectively reliability and availability. The weights used for this aggregation consequently differ from the weights used for the structural aggregation used for the clustering of the DSM as described in Section 8.1.

- Secondly, component reliability impact (CRI) values and component availability impact (CAI) values are assigned to each of the 50 components. These impact values represent the qualitative impact of a component on the RA performance of the lock relative to the other components. The available data on reliability and availability of lock components is used to objectively elicit these CRI and CAI values. For some components insufficient data is available and the CRI and CAI are estimated.

- Thirdly, the reliability DSM is built. This is done by filling the modularized DSM of Chapter 8 with the RIS values and multiplying them with the CRI value of both respective components. The reliability DSM entries are referred to as reliability risk (RR) values. By highlighting the areas of high RR values, the reliability DSM can be used to determine component pairs with a high reliability risk for the ship passage function. The reliability DSM is also used to investigate the contribution of components, respectively modules to reliability from the viewpoint of the lock system architecture.

- Finally, the availability DSM is built. To this end, the availability risk (AR) values are determined. The RIS values are replaced by the AIS values and the CRI values by the CAI values. The procedure to obtain the availability DSM is the same as for the reliability DSM. It is also analyzed in a similar fashion.

9.1 Reliability and availability interaction strengths

In Section 8.1, the four interaction types and their respective strengths are aggregated for structure analysis into the representative structural interaction strength (RSIS). The designation of the various weights for this aggregation was performed from a structural viewpoint. In this section the aggregation is determined from a reliability and availability viewpoint of the system to obtain the representative interaction strengths for reliability (RIS) and availability (AIS).

The contribution of the various interaction types to the RA characteristics of the lock system differs. It can be reasoned that the supply of energy to the Supervisory control system via an energy interaction is more important for the RA of the lock passage function than the location interaction between the Vessel and the CCTV.

In most cases the failure of a spatial, information or energy interaction will result in failure of the main system function: providing ship passage. The location interaction types are in this context less important, location interactions consequently receive weight 1 for both the RIS and AIS aggregation. For the spatial, information and energy interactions the weights differ for reliability and availability.

Reliability interaction strength (RIS)

The assumption in this thesis is that failures related to information and energy interactions have a higher failure frequency than failures related to spatial interactions. So a component pair connected by an energy or information interaction is assigned a higher increased reliability risk value due to the interaction than a component pair connected by a spatial interaction. This difference in reliability behavior must be represented by the RIS value determined by aggregation. To do so, the weights of energy and information interactions are set to 3, and the weight of spatial interactions is set to 2. An example of the aggregation of the interaction between the Operator/maintenance personnel component and the Regular control system component is depicted in Figure 9.1. The result of this weight distribution is that the focus is on interactions between components with a relative high failure frequency.

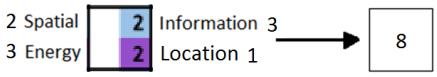


Figure 9.1: Aggregation of interaction strengths for the determination of the RIS.

Availability interaction strength (AIS)

The availability interaction strength (AIS) represents the increased availability risk of the ship passage function of a component pair due to the type and strength of the interaction between the components. The effect of a failure on the non availability from the multiplication of the respective failure frequency with the mean time to repair ($MTTR$). Although the failure frequencies of energy and information interactions will generally be higher than spatial interactions, the $MTTR$ of spatial interaction is typically much higher; it typically requires a longer time span to repair spatial interactions. Consequently, the weight distribution of the RIS aggregation is adapted to obtain the AIS aggregation distribution, see Figure 9.2. The interactions that, upon failure, cause the highest non availability of the ship passage function receive increased attention via the AIS aggregation.

The aggregations are subsequently applied to the modularized DSM obtained in Chapter 8. By aggregating the interaction types to represent their increased risk for respectively reliability and

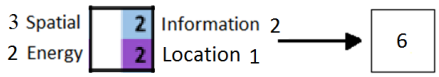


Figure 9.2: Aggregation of interaction strengths for the determination of the AIS.

availability, the contribution of interactions is included in the DSM based RA analysis. In the subsequent section, the impact of components on reliability and availability is included.

9.2 Determination of component R and A impact values

In this section the reliability and availability impact of components is included in the analysis by introducing the component reliability impact (CRI) and component availability impact (CAI) on the ship passage function for each of the 50 components. Brady (2002) determined so-called technology risk factors for each of NASA pathfinder components. For this study, the equivalent of these technology risk factors are the CRI and the CAI.

The CRI is determined by the failure frequency of a component. The CAI is a combination of the failure frequency and its $MTTR$. They are fundamentally different from the RIS and AIS values of the previous section: the CRI and CAI express respectively the reliability and availability impact of components, whereas the RIS and AIS express respectively the increased risk for reliability and availability due to the interaction type and strength between a component pair. The CRI and the CAI value of a component is rated between 1 and 5. A score of 1 represents no increased RA impact due to the component, and a score of 5 represents a high contribution of the component to the system's reliability and availability. The method used to determine the CRI and the CAI values is very similar, hence only the determination of the CAI values is elaborated in this section.

Minimal cut sets

To assist in the objective determination of these impacts, minimal cut sets regarding the RA of the lock system are studied. As mentioned before, Arcadis performed a fault tree analysis for the lock system. One of the results of this analysis are minimal cut sets, Arcadis (2013c). These minimal cut sets represent the smallest sequence of sets that cause failure of the ship passage function. These sets are determined by investigating the course of sets, through various AND and OR gates, leading to failure. As this analysis is performed on the current state of the lock system, the resulting CRI and CAI values may not necessarily be representative for other lock systems. As an example, the top 15 of these cut sets are denoted in Figure 9.3.

Most of the cut sets depicted in Figure 9.3 consist of a single event. As can be seen in the figure, the top 5 of the cut sets is responsible for 80 percent of the non-availability of the lock system. This is mostly due to a high $MTTR$ for the civil components. The reliability contribution of the various components differ significantly from their availability contributions. The Vessel detection, part of the Safety equipment for example has a negligible small contribution to the non availability of the ship passage function (0,06 percent), while its contribution to the failure frequency is the highest of all components (27,2 percent).

By investigating the description of each cut set, they are assigned to the components of the lock system. Subsequently, these cut sets are used to objectively deduce CRI and the CAI values for the components.

Nr	Cut set id verzameling	Cut set event beschrijving verzameling	Gemaal (aangeleverd door RWS)	Aantal Cut sets [-]	Fre-quentie [#/u]	MTTR [u]	Niet-beschik-baarheid [u/jaar]	Niet-beschik-baarheid over functietijd [% / functietijd]	Bijdrage niet-beschik-baarheid [%/ totale NB]	Bijdrage faalfre-quentie [% / totale FF]
1	199-NVT-5	Instabiel bovenhoofd door falen bodem bescherming		1	4,73E-06	2190	90,7	1,04%	22,1%	0,4%
2	157-1133-2	Damwand fuik benedenhoofd faalt constructief		1	9,48E-06	730	60,6	0,69%	14,8%	0,9%
3	213-1368-2	Verankering damwand bovenhoofd faalt constructief		1	9,48E-06	730	60,6	0,69%	14,8%	0,9%
4	213-1368-3	Verankering damwand benedenhoofd faalt constructief		1	9,48E-06	730	60,6	0,69%	14,8%	0,9%
5	157-1133-1	Damwand fuik bovenhoofd faalt constructief		1	9,48E-06	730	60,6	0,69%	14,8%	0,9%
6	FRACTIE-1.199-NVT-4	Voorsluis in gebruik en Instabiel sluishoofd voorsluis door falen bodem bescherming		1	3,71E-07	2190	7,1	0,08%	1,7%	0,0%
7	FRACTIE-1.101-1003	Voorsluis in gebruik en Aandrijving (hydromotor) puntdeur faalt		2	1,50E-06	534	7,0	0,08%	1,7%	0,1%
8	NAT-1	Hoogwater		1	0,00E+00		6,7	0,08%	1,6%	0,0%
9	N - FUNDERING	1.17.1 Fundering faalt	X	1	3,43E-08	17521	5,3	0,06%	1,3%	0,0%
10	O - FUNDERING	2.16 Fundering faalt	X	1	3,43E-08	17521	5,3	0,06%	1,3%	0,0%
11	194-1145	Scheepvaart scanner faalt		4	2,98E-04	2	5,2	0,06%	1,3%	27,2%
12	EXT-8	Brand oude gemaal (NSA+verdeelinrichting)		1	6,53E-07	730	4,2	0,05%	1,0%	0,1%
13	EXT-13	Obstakel (schutsluis en voorsluis)		1	1,14E-04	4	4,0	0,05%	1,0%	10,4%
14	122-1111-2	Camera C9 bovenhoofd faalt		1	6,45E-05	4	2,3	0,03%	0,6%	5,9%
15	FRACTIE-1.101-1006-2	Voorsluis in gebruik en Eindschakelaar nivelleerschuif voorsluis faalt		4	6,22E-07	367	2,0	0,02%	0,5%	0,1%

Figure 9.3: Top 15 cut sets leading to failure of the ship passage function.

Assigning the cut sets

The most direct indicator for the CRI value of a component is the relative contribution to the failure frequency (last column in Figure 9.3). And for the CAI, the relative contribution to the non availability (next to last column in Figure 9.3) determines the availability impact of a component.

To determine the CAI values, the minimal cut sets are ordered by their contribution to non-availability. Hence, cut sets with a higher index number have a significantly smaller contribution. By investigating these contributions the decision was made to solely include the top 100 cut sets. These sets are subsequently assigned to the components of the lock system by linking the description of each cut event to the components, see Table 9.1.

By summing the contributions to non-availability for each of the cut sets, the contribution per component can be determined, see last column in Table 9.1. If the description of a cut event fits two or more components, its contribution is evenly distributed over these components. The resulting contributions vary greatly. The reason for this can be found in the large differences in $MTTR$ between the components. The Supervisory control fails relatively frequently, but its $MTTR$ is only 4 hours. The walls of the Funnel and Lock chamber fail relatively rarely, but their $MTTR$ is 730 hours.

Determining the CAI values

A linear scale is subsequently used to convert the contribution values to CAI values. Two boundary conditions are in place for this scale:

- if the contribution to the non availability of a component is zero, the corresponding CAI value is set to 1 (Setting it to 0 would result in zero risk for the component pair), and
- the highest CAI value needs to be 5.

Component												Contribution to non availability
1. Vertical lift gates	43	46	-	-	-	-	-	-	-	-	-	0,002
2. Act. vert. lift gates	16	22	44	45	65	67	72	75	76	78	79	0,01
3. Leveling system	43	-	-	-	-	-	-	-	-	-	-	0,001
4. Act. leveling system	19	40	-	-	-	-	-	-	-	-	-	0,004
5. Lock head construction	1	8	9	30	31	94	95	100	-	-	-	0,14
6. Seepage screens	-	-	-	-	-	-	-	-	-	-	-	-
7. Ice prevention system	43	-	-	-	-	-	-	-	-	-	-	0,001
8. Lock chamber wall	3	4	9	10	93	97	98	99	-	-	-	0,32
9. Soil protection	1	-	-	-	-	-	-	-	-	-	-	0,11
10. Shipping facilities	9	10	-	-	-	-	-	-	-	-	-	0,03
11. Funnel	2	5	-	-	-	-	-	-	-	-	-	0,26
12. Positioning area	-	-	-	-	-	-	-	-	-	-	-	-
13. Waiting area	-	-	-	-	-	-	-	-	-	-	-	
14. Run-out zone	-	-	-	-	-	-	-	-	-	-	-	-
15. Soil protection outport	-	-	-	-	-	-	-	-	-	-	-	-

Table 9.1: Section of the distribution of the top 100 cut sets over the components. The numbers in the middle denote the indexes of the cut sets.

To distinguish between zero contribution and a small contribution, any non zero contribution receives a score of 1 plus the value suggested by the linear scale. Hence, no increased risk (zero contribution) results in a CAI value of 1, a small contribution yields a CAI value of 2 and the maximum CAI value is 5. See Figure 9.4 for the resultant scale.

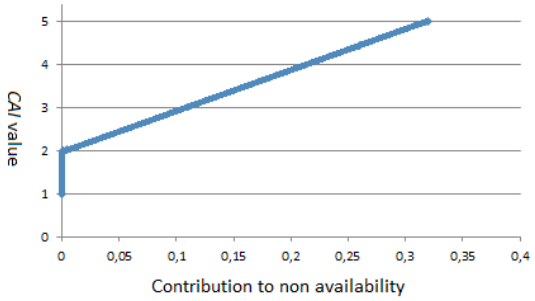


Figure 9.4: Linear scale for the determination of CAI values.

As can be seen in Table 9.1, a large portion of the components has no cut sets assigned to it. Two possible explanations exist:

- the relative contribution to the non-availability is so insignificant that it is not listed in the top 100 cut sets, or
- the components used in the DSM are not incorporated in the fault tree analysis. (e.g. the Operator/maintenance personnel).

The contributions for these components have to be determined manually. For some of the components, manually assigning a non-availability contribution is straightforward. The Run-out zone of the lock system is the section of the canal that is connected to the lock system. Since the chance that the canal itself fails is negligible, the Outport is assigned a CAI score of 1.

For other components, the CAI values are determined by comparing their characteristics to similar components. The CAI is subsequently determined by estimating if the respective component has a higher, equal or lower impact on the availability of the ship passage function. The 8 components with the highest CAI values are depicted in the first column of Table 9.2.

The CRI values are determined in a similar fashion. Instead of using the contribution to non availability, the contribution to the failure frequency (last column in Figure 9.3) is taken to deduce a suitable scale. The top 8 components with the highest CRI values are depicted in the third column of Table 9.2.

High CAI value component	CAI value	High CRI value component	CRI value
8. Lock chamber wall	5	30. Safety equip. (incl. detection)	5
11. Funnel	4	4. Act. leveling system	4
30. Safety equip. (incl. detection)	4	2. Act. vertical lift gates	3
2. Act. vertical lift gates	3	25. Supervisory control	3
5. Lock head construction	3	26. Operator/maintenance pers.	3
9. Soil protection	3	38. CCTV installation	3
26. Operator/maintenance pers.	3	44. Mitre gates F	3
28. Site lighting system	3	1. Vertical lift gates	2

Table 9.2: The 8 components with respectively the highest CAI and CRI values.

Now that both the increased risks associated with the interactions (via the RIS and the AIS values) and the impact of components (via the CRI and the CAI values) is determined, the reliability DSM and availability DSM can be determined.

9.3 The reliability DSM

By using the reliability interaction strength (RIS) values determined in Section 9.1 and the component reliability impact values (CRI) determined in Section 9.2 the reliability DSM is constructed. The process of constructing the availability DSM is very similar. Its details and subsequent analysis are provided in Section 9.4.

Similar to the risk calculation in Brady (2002), the reliability DSM entries are determined by multiplying the impact of two components with the interaction strength between them. The value of the DSM entry thus increases when the interaction strength increases. In analogy with the definition of risk: "Risk is the potential of losing something of value", the reliability DSM entries are named Reliability Risk (RR) values. These RR values represent the reliability risk of a component pair. For component pair A and B, the RR is determined by:

$$RR_{A,B} = CRI_A \times CRI_B \times RIS_{A,B}$$

See Figure 9.5 for the reliability DSM of lock system Eefde. To facilitate the readability of the reliability DSM, an additional row and column are included to also depict the respective CRI values.



Figure 9.5: Reliability DSM of lock system Eefde.

Since the RR values are determined by scaled impact values and derived interaction strengths, the reliability DSM depicts the reliability risks within the dependency structure in a qualitative manner. The RR values in the DSM are color coded to stress the differences in value. Three different sources for reliability risk are studied via the DSM:

- the reliability risk of component pairs,
- the reliability risk of components, and
- the reliability risk of modules.

Reliability risk of component pairs

The RR values in the reliability DSM depict the reliability risk of component pairs. They represent the risk formed by the combined effect of the impact on reliability of each of the components and the increased risk due to the type and strength of the interaction between them. The RR values thereby include the dependency structure of the lock components in the analysis of reliability risks. Investigating high impact component pairs leads to an increased understanding of the sources of reliability loss. The five component pairs that yield the highest reliability risk in the reliability DSM are depicted in Table 9.3

RR value	Component 1	Component 2
90	25. Supervisory control	30. Safety equipment (incl. Vessel detection)
80	3. Leveling system	4. Actuators leveling system
72	25. Supervisory control	4. Actuators leveling system
72	26. Operator/maintenance personnel	38. CCTV
60	1. Vertical lifting gates	2. Actuators vertical lifting gates

Table 9.3: Five component pairs with the highest reliability risk, indicated by the reliability DSM.

A high RR value can have three different causes: the representative reliability interaction strength (RIS) between a component pair is high, the reliability impact (IAI) of component A is high or the IAI of component B is high or a combination hereof.

The reliability DSM suggests that the Supervisory control and the Safety equipment (incl. Vessel detection) form the highest reliability risk component pair. This is mostly due to the high CRI rating of the Safety equipment (incl. Vessel detection); according to the minimal cut sets, the Safety equipment (incl. Vessel detection) is responsible for 27,1 percent of the total failure frequency.

The second and third highest risk component pairs are formed with the Actuators leveling system. These component pairs have a similar origin. In this case, also the high CRI value of a component is the main cause. The Actuators leveling system has a CRI value of 4.

The high reliability risk of the Operator/maintenance personnel and the CCTV component pair is caused by the RIS that couples these components. Their CRI values are both 3, which is a moderate value. The RIS between them however, is 8. This is caused by the fact that two different interaction types couple these components, namely information and location.

Reliability risk of components

The contribution of components to the reliability risk is determined from the viewpoint of the system's architecture. This is done by determining the amount of the reliability risk depicted in

the reliability DSM that can be attributed to a component. Two approaches are used in this study. The first metric, reliability risk Metric 1 (RRM1) is formed by summing all RR values depicted in the row corresponding to the component of interest. This metric thereby assigns a higher reliability risk to components with a high connectivity and to components that have interactions with high impact components. See Figure 9.6 for the summed reliability risk values (blue). The CRI values of the components (orange) are also plotted to allow comparison between the two.

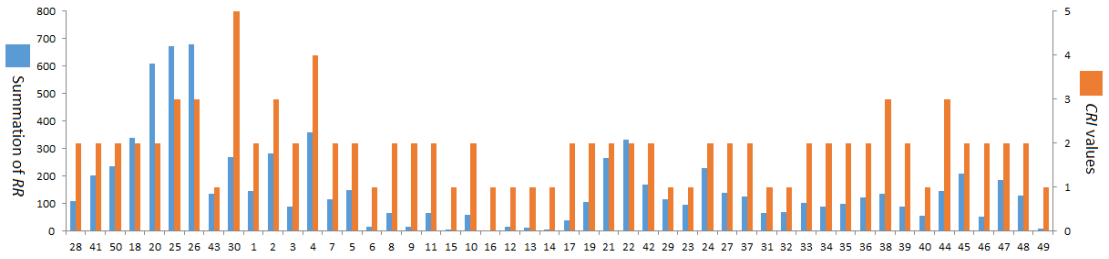


Figure 9.6: RRM1 values (blue) and the CRI values (orange)

Some components have a moderate CRI value assigned to them while the RRM1 value is high. This difference is caused by including the dependency structure of a component in the determination of its reliability risk, whereas the CRI value is solely determined by the impact on reliability of the component.

The component sequence depicted in the figure corresponds to the sequence that was obtained via the structural analysis in Chapter 8. It can be seen that the reliability risk is not evenly distributed amongst the components. The majority is located on the left hand side of the distribution, i.e. within the bus module and Cluster 1: Navigation lock mechanical.

The cause of a RRM1 value of a component can differ. Two distinct causes can explain a high risk:

- the component has a high CRI and the high impact is mostly caused by the high failure frequency of the component itself, or
- the component is tightly coupled (via high reliability risk interactions) to the rest of the system. This can be determined by summing all RIS values the component has with other components.

If both the CRI and the summation of RIS values are high, the effects re-enforce each other and the impact of a component and its interactions reach very high values, e.g. the Operator/maintenance personnel and the Supervisory control. The RRM1 values for the 8 components with the highest CRI values are depicted in the fourth column of Table 9.5.

Component	CRI	Summation of RIS	RRM1
26. Operator/maintenance personnel	3	120	678
25. Supervisory control	3	105	672
20. Emergency power supply	2	142	610
4. Act. leveling system	4	45	360
18. Low voltage supply	2	85	340

Table 9.4: High reliability risk components due to high CRI values and tight coupling.

The Emergency power supply demonstrates the effect of highly integrative characteristics. Its CRI value is reasonably low, but the combination with a high summation of RIS still yields a high RRM1 value.

Reliability risk metric 2 (RRM2) is used as an alternative way to assess the reliability risk of a component. It is derived from RRM1 by dividing it by the amount of interactions a component has. This cancels out the effect of interaction quantity, and solely focuses on the reliability risk caused by the impact values and the RIS values. A component receives a high RRM2 value if it has a high CRI value or if it contains strong interactions with components with a high CRI value. The top 5 components with the highest reliability risk due to a high CRI value and strong interactions with high CRI components is depicted in Table 9.5

Component	CRI value	Nr. of interactions	RRM1	RRM2
30. Safety equipment (incl. vessel detect.)	5	8	720	33,75
4. Act. leveling system	4	9	360	40
2. Act. vertical lift gates	3	9	282	31,33
25. Supervisory control	3	20	672	33,60
26. Operator/maintenance personnel	3	18	678	37,67
38. CCTV installation	3	4	135	33,75
44. Mitre gates F	3	6	144	20,57
1. Vertical lift gates	2	8	144	18

Table 9.5: High reliability risk components due to high CRI values and strong interactions with high CRI value components.

As can be seen in Table 9.5, a high CRI value does not directly translate to high values for the metrics. The Safety equimpent (incl. vessel detection) has the highest CRI value assigned to it and also yields the highest RRM1 value. Three components are suggested by both RRM1 and RRM2 to have a high reliability risk. These components are: Operator/maintenance personnel, Supervisory control and Actuators leveling system. The detailed interpretation of these results is provided in the Chapter 10.

Reliability risk of modules

The third perspective of reliability risk that is studied via the reliability DSM is the reliability risk of modules defined in Chapter 8. The subsystem DSM developed in Chapter 8, see Figure 8.14, defines which components belong to each module. These modules are analyzed via three different metrics:

- Reliability Risk Module Metric 1 (RRMM1): by summing the RRM1 values of each component in the module. For the module: Cluster 1, this yields 1138. Since the RRM1 assigns a high value to components with a high connectivity, the RRMM1 metric thus also assigns higher reliability risks to modules that are tightly coupled to the rest of the system,
- Reliability Risk Module Metric 2 (RRMM2): by summing the RR values within the boundaries of a module in the reliability DSM. For Cluster 1 this yields 424. This approach focuses more on high reliability risk component pairs existing within the module, and
- Reliability Module Risk Metric 3 (RRMM3): by dividing RRMM1 by the connectivity of each module (see Figure 8.9). The connectivity of Cluster 1 is 48, hence RRMM3 yields 23,71. This metric cancels out the effect of an integrative character. It assigns high reliability risks based on high CRI values and strong interactions with high CRI components.

Module	RRMM1	RRMM2	RRMM3
Bus module	3248	1060	20,43
Cluster 1: Navigation lock mechanical	1138	424	23,71
Cluster 2: Navigation lock civil	308	80	7,70
Cluster 3: Outport	164	52	4,21
Cluster 4: Control and facilitating systems	1491	272	14,20
Cluster 5: Information and communication systems	1091	52	14,95
Cluster 6: Front lock mechanical	779	328	19,98
Cluster 7: Front lock civil	146	18	11,24

Table 9.6: Three different module metrics to assess the reliability risk of modules.

The varying values for the metrics show that the reliability risk of a module varies with the viewpoint that is taken. The bus module yields, as can be expected, the highest reliability risk caused by a tight coupling to the rest of the system (RRMM1). It also yields the highest reliability risk caused by high risk component pairs within the module (RRMM2). Cluster 1: Navigation lock mechanical, yields the highest reliability risk of a module without taking into account the amount of interactions (RRMM3). The detailed interpretation of these results is provided in Chapter 10

9.4 The availability DSM

The availability DSM is developed in a similar fashion as the reliability DSM. The only differences are: the RIS values that represent the reliability interaction strengths of interactions are replaced by the AIS to represent the availability interaction strengths, and the CRI values of the components are replaced by the CAI values.

The availability DSM entries are named Availability Risk (AR) values. These AR values represent the availability risk of a component pair. They are determined by multiplying the AIS of a component pair by their CAI values. See Figure 9.7 for the availability DSM of lock system Eefde.

$$AR_{A,B} = CAI_A \times IAI_B \times CAI_{A,B}$$



Figure 9.7: Availability DSM of lock system Eefde.

The resulting availability DSM represents the qualitative risks within the coupling structure on the availability of the lock system. It is analyzed on the same fashion as is done for the reliability DSM.

Availability risk of component pairs

The AR values in the Availability DSM depict the relative availability impact of component pairs. The 5 components that yield the highest availability risk in the availability DSM are depicted in Table 9.7

AR value	Component 1	Component 2
60	50. Vessel	8. Lock chamber wall
60	1. Vertical lifting gates	2. Act. vertical lifting gates
54	2. Act vertical lifting gates	5. Lock head construction
45	5. Lock head construction	8. Lock chamber wall
45	8. Lock chamber wall	9. Soil protection

Table 9.7: Five component pairs with the highest availability risk as indicated by the availability DSM.

A high AR value can have three causes: the representative availability interaction strength (AIS) between a component pair is high, the availability impact (CAI) of component A is high or the CAI of component B is high.

Since force transmittance occurs between them, the Vessel has a strong (rating 2) spatial interaction with the Lock chamber wall. The AIS is consequently also relatively high. Furthermore, the impact of failure of the Lock chamber wall on the availability of the ship passage function is very high and received a CAI of 5. The combination of a strong interaction with a high impact component thus yields a high AR.

For the Actuators vertical lift gates, the main reason for a high AR score is found in the AIS value. The Actuators vertical lift gates have both a spatial and an energy interaction with the Vertical lift gates. This combination of interaction types yields a AIS score of 10 and is thereby the strongest AIS value of lock system.

Comparing these top 5 highest availability impact component pairs with the top 5 highest reliability impact components pairs, yields some interesting insights. The Supervisory control system that appeared two times in the reliability top 5, with respectively the Safety equipment (incl. Vessel detection) and the Actuators leveling system, is not depicted in the availability top 5. This means that its impact on the reliability is greater than its impact on the availability. The component pair Actuators vertical lift gates and Vertical lift gates has a high impact on both the reliability and the availability.

Availability risk of components

The availability risk of components is investigated via the same metrics as used in Section 9.3:

- Availability Risk Metric 1 (ARM1): is determined by summing the AR values of the row corresponding to the component of interest. This metric yields higher availability risk values if the component has a high CAI value or if it is tightly coupled to the rest of the system, and

- Availability Risk Metric 2 (ARM2): is determined by dividing ARM1 by the amount of interactions a component has. It hereby cancels out the quantity of components it is coupled to and yields higher values due to a high CAI value and strong interactions with high CAI value components.

The top 5 components with the highest availability risk due to their tightly coupled nature and high CAI value (ARM1) is depicted in Table 9.8.

Component	CAI	Summation of AIS	ARM1
26. Operator/maintenance personnel	3	90	408
5. Lock head construction	3	40	303
25. Supervisory control	2	71	280
50. Vessel	2	51	256
8. Lock chamber wall	5	21	245

Table 9.8: Top 5 components with the highest relative RA impact.

The lock chamber wall for example has a very high contribution to the non-availability according to the minimal cut sets. The CAI value has been consequently set to the highest possible rating: 5 (Section 9.1). Although the Lock chamber wall is not tightly coupled to a high number of components (low summation of AIS), this very high CAI score still yields a high availability impact.

Availability risk Metric 2 (ARM2) is used as an alternative way to assess the availability risk of a component. It is derived from RRM1 by dividing it by the amount of interactions a component has. This cancels out the effect of interaction quantity, and solely focuses on the availability risk caused by the impact values and the RIS values. The five components with the highest availability risk according to ARM2 are depicted in Table 9.9

Component	CAI	Number of interactions	ARM2
8. Lock chamber wall	5	8	30,63
2. Actuators vertical lift gates	3	9	26
3. Leveling system	2	2	26
46. Leveling system front lock	2	2	26
26. Operator/maintenance personnel	3	18	22,67

Table 9.9: High availability risk components due to high CAI values and strong interactions with high CAI value components.

Two components are suggested by both ARM1 and ARM2 to have a high availability risk. These components are: Operator/maintenance personnel and Lock chamber wall. The detailed interpretation of these results is provided in the Chapter 10.

Availability risk of modules

The availability impacts of modules is, similar to the reliability impact, investigated via three metrics:

- Availability Risk Module Metric 1 (AMM1) assigns higher availability risks to modules that are tightly coupled to the rest of the system,

- Availability Risk Module Metric 2 (AMM2) focuses more on high availability risk component pairs existing within the module, and
- Availability Module Risk Metric 3 (AMM3) assigns high availability risks based on high eCAI values and strong interactions with high CAI components and cancels out the effect of an integrative character.

Module	AMM1	AMM2	AMM3
Bus module	2080	584	13,08
Cluster 1: Navigation lock mechanical	969	452	20,19
Cluster 2: Navigation lock civil	807	336	20,18
Cluster 3: Outport	297	28	7,62
Cluster 4: Control and facilitating systems	1069	220	10,18
Cluster 5: Information and communication systems	612	44	8,38
Cluster 6: Front lock mechanical	672	352	17,24
Cluster 7: Front lock civil	213	18	16,38

Table 9.10: Three different module metrics to assess the availability risk of modules.

The highest availability risk module due to a tight coupling with the rest of the system is the bus module. The bus module also contains the highest availability risk component pairs. This is, as is the case with the RRMM2, caused by the high amount of component pairs that exists within this module. The highest availablity risk without taking into account the amount of interactions a module has, is denoted to Cluster 1: Navigation lock mechanical and Cluster 2: Navigation lock civil. Followed closely by Cluster 6: Front lock mechanical and Cluster 7: Front lock civil. A more detailed analysis is provided in Chapter 10.

9.5 Conclusion

The reliability and availability risk analysis that has been performed for component pairs, components and modules shows that different viewpoints on the risk analysis suggest different causes for high risk.

The reliability and availability DSM directly depict respectively the reliability and availability risk of component pairs. Hence, investigating their risk is done by investigating high values in the DSMs. The high reliability risk component pairs are depicted in Figure 9.3. The highest reliability risk is assigned by the DSM to the component pair: Supervisory control and Safety equipment (incl. vessel detection). The high availability risk components are depicted in Figure 9.7. The highest availability risk component pairs, according to the availability DSM, are the Vessel and the Lock chamber wall, and the Vertical lift gates and Actuators vertical lift gates. This last component pair is suggested as a high risk component pair for both reliability and availability.

In the analysis of component risk, two different approaches were used to determine the risk of a component. For both the reliability and the availability risk analysis, these two approaches suggested similar components as high risk. If a component is assigned a high risk by each of the two approaches, this is interpreted as an increase of confidence of the result. The reliability risk assessment for components suggested the Operator/maintenance personnel, the Supervisory control and the Actuators leveling system as high risk components for both approaches. RRM1 also suggests Safety equipment (incl. vessel detection) as a component with a high reliability risk, which corresponds with the high CRI value assigned to this components. The two risk metrics used for the availability risk assessment both suggested the Operator/maintenance personnel and the Lock chamber wall. The rest of the components did not directly correspond to the impact

values assigned to them in Section 9.2. Including the dependency structure of the system in its reliability and availability analysis thus yields different results than solely investigating the reliability and availability characteristics of the individual components.

The analysis of the reliability and availability risks on module level is analyzed via three metrics. The first two metrics appoint the bus module as the highest risk for both reliability and availability. This is due to the fact that these two metrics include the connectivity of the modules in the assessment of their risk. The third metric cancels out the effect of the amount of interactions, not the strength of interactions, and focuses on high risk components pairs within a module. The third metric suggests Cluster 1: Navigation lock mechanical as the highest risk module for reliability and Cluster 1: Navigation lock mechanical and Cluster 2: Navigation lock civil as the highest risk modules for availability.

The different metrics that have been used to asses the reliability and availability risks that exist within the lock system's dependency structure suggest different approaches to overcome these risks. A detailed analysis on how the risks identified in this chapter can be reduced via standardization is provided in Chapter 10.

Chapter 10

Towards standardization

Standardization can be a powerful tool to improve the reliability and availability of a system (Smith, 2011). For lock system Eefde the standardization opportunities to improve the reliability and availability of the function: Allow ship passage, are investigated.

By using standardized components or component interfaces, the reliability and availability of the component and its interfaces can be improved. According to David and Bunn (1988), standardization of interfaces is best used to improve the sustainability of components since it allows the components itself to be re-used. Garud et al. (2009), furthermore states that a modular system architecture enables standardization and that product performance can increase by component standardization. Standardization also has its disadvantages. By standardizing either a component or its interfaces, their innovation and development is blocked. Hence, an effective standardization strategy needs to be determined that finds a balance between standardization and innovation.

The qualitative reliability and availability characteristics as determined in Chapter 9 can be used to develop a standardization strategy. Garud et al. (2009) distinguish two standardization strategies: 1. standardization of a component or, 2. standardization of its interfaces with other components. A combination hereof is also possible.

In Chapter 9 various perspectives to investigate reliability and availability risks are developed. Since the metrics that represent these various perspectives stress different characteristics, (e.g. high connectivity or high impact values) they can be used to help decide on the two approaches.

- standardizing the component: reduces the component reliability risk and availability risk (CRI and CAI) values of a component, or
- standardizing the component interfaces: reduces the risks of interface failure. It furthermore increases sustainability of associated components.

From the definition of availability risks, it follows that the standardization effort may be focused on either reducing the $MTTR$ of a component by increasing its maintainability or on reducing its failure frequency. Both approaches reduce the CAI of a component. For reliability risks, the standardization effort should focus on reducing the failure frequency of a component.

10.1 Standardization for high reliability and availability risk component pairs

Component pairs have been identified that are assigned high reliability and availability risks. By analyzing the origins of these risks, suggestions for standardization are identified. The risk is

influenced by both the impact of the components and the interaction between the components.

The Supervisory control and Safety equipment (incl. vessel detection) pair appears to pose a high risk for the reliability of the system. By investigating the CRI values of both components, respectively 2 and 5, it can be seen that the high risk is mostly due to the high reliability impact value assigned to the Safety equipment (incl. vessel detection). Reducing the failure frequency of this component via standardization will therefore reduce the risk of this component pair.

The component pair: Leveling system and Actuators leveling system has a high reliability risk value. Their CRI values suggest that standardization effort should be focused on the Actuators leveling system.

The component pair: Lock chamber wall and Vessel has a high availability risk value. The CAI value of the Lock chamber wall (5) is much higher than the CAI of the Vessel (2). This suggests that standardizing the Lock chamber wall would be more effective than "standardizing" a Vessel.

A high AIS in combination with a reasonable to high CAI implies that the interaction is critical. The interactions must consequently be properly investigated to determine if it can be improved via standardization. The interaction between Lock chamber wall and Vessel is formed by the Bollards and a Hawser, see Figure 10.1.



Figure 10.1: Interaction between the Lock chamber wall and a Vessel.

The availability DSM suggests to investigate this interaction. Thus, even though the Bollards and a Hawser are not part of the decomposition, they are implicitly apparent via the interaction between the Vessel and the Lock chamber wall and issues with these components surface during analysis.

The component pair: Vertical lift gates and Actuators vertical lift gates has been assigned a high risk value in both the reliability and the availability DSM. Since these components have reasonable impact values, the interaction between them is investigated. This is made by a series of parts, amongst others this includes a chain and various cables. Since this interaction both transmits force and exchanges (mechanical) energy, the AIS reaches the remarkably high value of 10. With such a high AIS, even mediocre IAI values yield a high AR value. The availability DSM thus suggests to thoroughly investigate the connection between the Vertical lift gates and Actuators vertical lift gates.

On the 3rd of January 2012, the interaction between the Vertical lift gates and Actuators vertical lift gates failed and the Vertical lift gates fell down. This failure caused a downtime of 8 weeks, leading to a high impact on non-availability, (TNO (2013)). TNO subsequently started an investigation for the cause of the failure. After the research was completed, it was concluded that the cause of failure was the connection of the cables to the Vertical lift gates. The failure caused the

complete interaction between the Vertical lift gates and Actuators vertical lift gates to fall down, see Figure 10.2.



Figure 10.2: Failed interaction between the Vertical lift gates and Actuators vertical lift gates

10.2 Standardization for high reliability and availability risk components

In Chapter 9, the reliability and availability risk of components have been investigated via two different metrics. The first metric yields high risks due to a high impact value of the components and a tight coupling with the rest of the system. The second metric is determined by dividing the first metric by the amount of interactions a component has (its connectivity). The second metric thereby cancels out the effect of the number of interactions and assigns a high risk to components that have a strong interaction with high impact components. The high risk components suggested by these two metrics should therefore be treated differently.

The leveling system is assigned a high risk value for both reliability and availability by the second metric. Since the second metric cancels out the quantity of interactions, and the impact values for both reliability and availability of this component are low, the high risk is due to strong interactions with high impact components. Indeed, by investigating Table 9.3, it can be seen that the Leveling system has a strong interaction with the high reliability impact component Actuators leveling system. Hence, by standardizing the Actuators leveling system, the Leveling system itself will be assigned a lower risk value by the second metric.

The Actuators leveling system itself is also assigned a high reliability risk by both the metrics. Since the CRI value of this component is 4, this is mostly due to the high impact of the component itself. The Actuators leveling system also appears twice in the top 5 of high reliability impact component pairs. The suggestion is therefore to investigate both the standardization of the component and of its interactions.

The Operator/maintenance personnel is assigned a high risk for both reliability and availability by both metrics. Since this component is not assigned a high impact value for either reliability or availability, the fact that this component appears in all four analysis, suggests that the high risk is caused by a combination of a tight coupling with the system and strong interactions with high impact components, see Figure 10.3 for a section of the availability DSM. The reliability DSM shows a similar result.

The fault tree analysis performed by Arcadis (2013a) also determined human errors as a top external cause of failure.

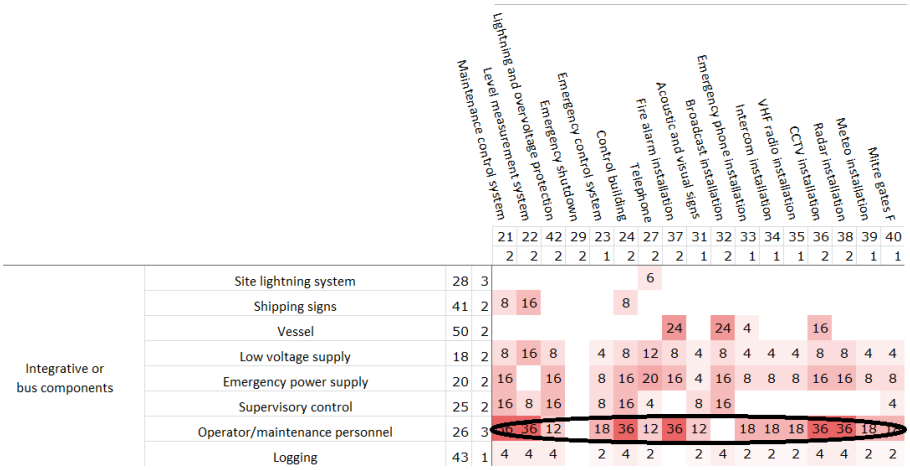


Figure 10.3: Section of the availability DSM depicting high availability impact of the Operator/-maintenance personnel

Since, standardizing the Operator/maintenance personnel is a difficult task, and the analysis suggests that the impact of this component is not the greatest source of risk, a more practical option is to standardize the interfaces between Operator/maintenance personnel and the various components it is connected to. The top six highest RR and AR values for the Operator/maintenance personnel consist of interactions with the various control systems and communication systems. The reliability and availability DSMs can therefore be interpreted as a suggestion to standardize their interfaces with the rest of the system, i.e. the software governing these interactions.

Another interesting component is the Supervisory control system. The minimal cut sets suggested moderate impact values for both reliability and availability, this means a significant improvement of the Supervisory control system is required to reduce its RA impact. Since the first metric shows a very high value, a more effective solution appears to be to standardize the software governing the interactions between the Supervisory control system and the rest of the system.

10.3 Standardization for high reliability and availability risk modules

For the assessment of the reliability and availability risk of modules three metrics have been investigated in Chapter 9:

- metric 1 assigns higher risks to modules that are tightly coupled to the rest of the system,
- metric 2 focuses more on high impact component pairs existing within the module, and
- metric 3 assigns high risks based on high impact values and strong interactions with high impact components and cancels out the effect of an integrative character.

The metrics for respectively reliability and availability are depicted in Table 9.6 and Table 9.10.

The first metric depicts the bus module and Cluster 4: Control and facilitating systems as high risk modules for both reliability and availability. The other two metrics do not suggest a high impact for Cluster 4. Hence, The risk assigned to Cluster 4 is primarily caused by its tight coupling with the rest of the system. In Figure 10.4 a section of the availability DSM showing the interactions of cluster 4 is depicted.

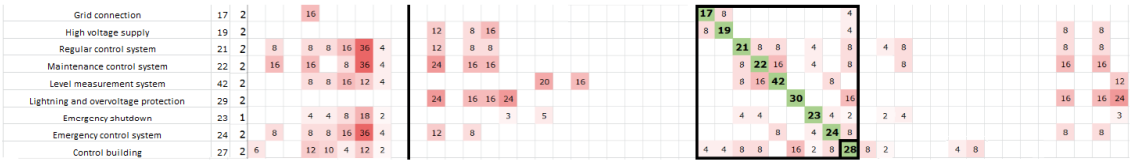


Figure 10.4: Section of the availability DSM depicting cluster 4 and the AR values of its interactions.

As can be seen in the figure, the majority of the AR values are located in the interaction between the cluster and the bus module. The figure hereby confirms the suggestion that the risk is mostly due to a tight coupling with the rest of the system. Standardization effort should therefore be focused on the interfaces of Cluster 4.

The bus module also has a high risk assigned by the second metric for both reliability and availability. This means that the bus module contains a high number of high risk component pairs. By investigated the impact values of the components in the bus module, it can be seen that they are moderate. Hence, the high risk assigned to the component pairs in the bus module is mostly due to strong interactions between the bus components. Hence, the DSMs suggest to focus standardization effort for the bus module on the interfaces between the components in the bus module.

The third metric cancels out the effect of connectivity of the module. This means that this metric represents the risk of the module caused by high impact components and strong interactions between them. Clusters that are assigned a high risk score by this metric could therefore be considered for standardization of the module itself.

For reliability, Cluster 1: Navigation lock mechanical shows the highest risk value. The reliability DSM hence suggests to investigate the possibilities of standardizing the components of Cluster 1 and the interfaces between these components. For availability, Cluster 1: Navigation lock mechanical and Cluster 2: Navigation lock civil are assigned the highest risk values. Since Cluster 1 is assigned a high to moderately high risk value by all metrics for both reliability and availability, the suggestion is to investigate its potential for complete standardization.

10.4 Conclusion

The various metrics that have been used to determine the risks within the dependency structure of the lock system represent various viewpoints on reliability and availability risk. They are used to suggest different approaches to reduce these risks. None of the proposed viewpoints claims to be the sole source of reliability and availability risk, but they do propose substantiated conclusions regarding the areas within the dependency structure that show potential for standardization.

The various sources of reliability and availability risk require investigation to develop a suitable standardization strategy.

For component pairs that pose a high RA risk on the lock system, it needs to be investigated if this is caused by the component impacts or by a highly integrative character. If the component contributions are high, the component with the highest value should be considered for standardization. Examples of these components are: the Lock chamber wall, the Actuators vertical lift gates and the Safety equipment (incl. Vessel detection). If the interaction contribution is high, interface standardization should be considered. Examples of suitable interfaces for standardization are: the interface between Vessel and Lock chamber wall, the interface between Supervisory control system, Actuators leveling system and the interface between the Vertical lift gates and the Actuators vertical lift gates.

The distinction between component standardization and interface standardization should also be considered when analyzing high RA risk components. If the high RA risk is caused by a high component impact, the component itself should be considered for standardization, e.g. the Actuators leveling system. If the impact is mostly caused by the interactions with the rest of the system, the component might be suitable for interface standardization. The Supervisory control system is assigned high risk values for both reliability and availability, but the component impact values assign to it are moderate. Hence, it is expected that the high risk is mostly caused by its interactions. Standardizing its interface would therefore yield a greater improvement than standardizing the Supervisory control system itself.

A similar distinction is applicable to modules. By investigating the different risk values assigned to the modules by the various metrics, standardization opportunities can be deduced. The bus module appears to be suitable for standardization focused on the interfaces between the components of the module. Cluster 4: Control and facilitating systems, is suggested as a candidate for interface standardization of the interaction between the module and the rest of the system. Finally, Cluster 1: Navigation lock mechanical is assigned a high risk by the third metric for both reliability and availability. Hence, the suggestion is to investigate its potential for complete standardization, i.e. of the components within this module and the interfaces between them.

In an expert study carried out by Iv-Infra (Iv-Indra, 2015), disciplines and components that pose high risk for reliability and availability in a generic lock were identified. The disciplines: "Control and electrical engineering" and "Mechanical engineering" were identified as high risk. Within these disciplines, the Energy supply, Actuators gates were identified as most critical.

Comparing these results with the results in this study, shows that they overlap. The disciplines match the modules that have been identified as high risk in Chapter 9. For reliability these are: Navigation lock mechanical and Front lock mechanical. For availability these are: Navigation lock mechanical, Navigation lock civil and Front lock mechanical. The module that most closely matches the "Control and electrical engineering" discipline of the Iv-Infra study is Cluster 4: Control and facilitating systems. It received a high AMM1 value which indicates that the risks associated with this module are mostly due to the tight coupling with the rest of the system. Furthermore, both the Actuators of the vertical lifting gates (availability) and Emergency power supply (reliability) have been identified as high risk, which also corresponds (partly) to the results of the study of Iv-Infra.

Another encouraging discovery is made regarding the interactions between the lock components. If the RA DSMs depict an interaction as the cause of a high RA risk, the actual components responsible for this interaction can be determined by investigating documentation. Hence, even if the components responsible for a particular interaction are of a granularity level that is too high to incorporate in the decomposition, by investigating critical interactions, they can still be determined via the reliability and availability DSMs.

Chapter 11

Conclusion

Design Structure Matrix (DSM) based methods have successfully been used to identify components and modules of components within the lock's dependency structure that pose a high risk for the reliability and availability of the lock with respect to the function: providing ship passage.

The first sub-objective: "Obtain a representative DSM of the dependency structure between the lock components" has been achieved. A representative DSM has been obtained by combining data governing physical dependencies, interviews with systems experts and data on physical-functional dependencies. This has been done by:

Decomposing a system into its comprising components can be done in a great number of ways. Varying viewpoints on the lock system significantly influence the resulting decomposition. However, by incorporating the decomposition of various sources, the different viewpoints of distinct disciplines have been incorporated into a decomposition suitable for coupling structure analysis. By reviewing the resultant decomposition with system experts, it was found that granularity level issues surfaced that were not identified via documentation. A discussion with these system experts proved to be the best way to improve the granularity consistency of the decomposition.

Identifying four interaction types that govern the system's dependency structure. These are: spatial, information, energy and location. To objectively distinguish between weak and strong interactions, a rating scheme proved to be convenient. The techniques found in literature regarding the development of a representative physical DSM of the system can be used in a complementary manner. The preliminary DSM developed by examining documentation performed adequately in providing a reference. It was found that a graph representation of the dependency structure is most suited for interviews as it does not require detailed knowledge of DSMs. By using the preliminary DSM, a graph representation of the dependency structure of interesting components can be made. The system experts found it easier to answer questions regarding the dependency structure when using these graph representations.

And, transforming a Design Matrix (DM) that depicts the physical-functional dependencies, into a functional DSM. This transformation yields useful insights, even if the DM is incomplete. By comparing the functional DSM with the physical DSM in a compare DSM, see Figure 7.1, missing interactions can be identified. By examining these interactions, the physical DSM was improved and a representative DSM has been obtained.

The compare DSM also suggests improvements for the DM that could be incorporated to obtain an improved functional representation of the system. The interactions that solely appear in the physical DSM, and not in the functional DSM (type 2 interactions in the compare DSM) can be used to determine which functions are missing from the function set and which dependencies are missing from the relationship description of the functions that are already in the function set.

The second sub-objective: "Use this DSM to explore the underlying coupling structure and to identify areas within the lock's dependency structure that pose high reliability and availability risks for the ship passage function" has been achieved by:

Applying coupling structure analysis on the DSM in such a fashion that other, more naturally emerging subsystems have been identified. By adapting the subsystem decomposition obtained in Chapter 1 with the naturally emerging subsystems, this coupling structure analysis defined a new decomposition, depicted in Figure 8.15, that groups components together in subsystems in such a fashion that they have strong interactions with other components in the same subsystem but little interaction with components outside their subsystem. Some of these subsystems contain overlapping components by which they are connected to other subsystems. But all subsystems are connected via the bus module, see Figure 8.14. The resultant modularized DSM furthermore shows that the coupling structure of the lock system is modular and thus allows subsystems to be treated relatively disjoint from other subsystems. The channels over which these subsystems communicate are displayed in the DSM, see Figure 8.13.

And, identifying RA risks in the coupling structure of the lock components. the method developed by Brady (2002) to identify technology risks in NASA's Pathfinder is successfully adapted to identify reliability and availability risks in the dependency structure of the lock system. The techniques used for determining the risk for both reliability and availability work in the same way, only the aggregation of interaction types and strengths and assigning impact values to components differs.

The analysis of RA risks has been performed on: component pairs, components and modules. The RA risk of these aspects of the lock system have been investigated from a variety of viewpoints. These viewpoints can be considered complementary in the identification of areas in the dependency structure that are suitable for standardization, i.e. by combining the insights gained via these viewpoints a standardization strategy can be developed that incorporates all aspects of RA risk.

The high reliability risk component pairs that have been suggested are: the Supervisory control and the Safety equipment (incl. vessel detection), and the Leveling system and the Actuators leveling system. High availability risk components pairs that have been suggested are: Lock chamber wall and the Vessel, the Vertical lift gates and the Actuators vertical lift gates, and the Lock head construction and the Actuators vertical lift gates.

The Actuators leveling system is assigned high reliability risk values by each of the two metrics that has been used. The Leveling system, the Operator/maintenance personnel and the Supervisory control show high risk values for both reliability and availability.

The bus module shows high risks for both reliability and availability for two of the three metrics that have been used. The definition of these metrics suggests that the high risk is caused by the integrative character of the bus module and by the strong interactions within this module. The third metric used to assess the RA risks of modules assigns high risk values modules that contain high impact modules and high risk component pairs. The modules that showed a high risk value for this metric are: Cluster 1: Navigation lock mechanical for reliability, and Cluster 1: Navigation lock mechanical and cluster 2: Navigation lock civil for availability, closely followed by their counterparts in the Front lock.

The various viewpoints that were used to assess the RA risks within the dependency structure of the lock system are represented by the variety of metrics used. These metrics focus on different sources of RA risk and can therefore be used to device a standardization strategy. The following table is a summary of the suggestions for standardization as deducted from the origin of the various RA risks as suggested by these metrics, see Table 11.1

R/A	Subject	Suggested focus of standardization
1. R	Supervisory control and Safety equipment	Vessel detection
2. R	Leveling system and Act. leveling system	Act. leveling system
3. A	Lock chamber wall and Vessel	Bollards and Hawsers
4. A	Vertical lift gates and Act. vert. lift gates	Interface
5. R	Act. leveling system	Component
6. A	Leveling system	Component
7. A	Operator/maintenance personnel	Interfaces
8. R and A	Supervisory control	Interfaces
9. R and A	Bus module	Interfaces within module
10. R and A	Cluster 4: Control and facilitating systems	Interface with system
11. R	Cluster 1: Navigation lock mechanical	Module
12. A	Cluster 1: Navigation lock mechanical	Module
13. A	Cluster 2: Navigation lock civil	Module

Table 11.1: Suggested areas and strategies for standardization for both reliability and availability.

The first column on the left hand side indicates whether it concerns the reliability or availability or both. The subject of standardization is denoted in the middle. The subjects can be either component pairs (1 to 3), components (4 to 8) or modules of components (clusters) (9 to 13). In the column on the right hand side, the suggested focus as pointed out by the various viewpoints is indicated. This can be:

- a specific component within a components pair, e.g. Vessel detection as part of the Safety equipment,
- the interface of a component with the rest of the system, e.g. the Supervisory control,
- the interfaces of components within a module,
- the interfaces of a module with the system, and
- the module itself.

By investigating the details of an interaction, the actual components that constitute this interactions surface. Hence, even if the components responsible for a particular interaction are of a granularity level that is too high to incorporate it in the decomposition, the proposed DSM method is able to identify the associated components.

Chapter 12

Future work

The objectives of this study are met, but some results can be elaborated and provide inspiration for future work. This section provides a summary of the possible extensions to this study.

12.1 Elaborating on results

The physical DSM that has been obtained through the examination of data and the subsequent improvement via interviews with system experts is thought to faithfully represent the lock's dependency structure. Since there is no way to verify whether the obtained dependency structure is complete, a sensitivity analysis could be performed to determine the effect of a non complete DSM on the performed analysis. This could be done by removing X percent of the interactions from the physical DSM and to subsequently repeat all steps with this incomplete DSM. For each sub results, e.g. the modularized DSM and the reliability DSM, etc. it can then be determined to what extend the results vary.

A similar sensitivity analysis could be performed on the assumptions made in Chapter 9 regarding the applied aggregation method and assigned component impact values. By applying a (small) variation on these parameters, the sensitivity of these assumption can be investigated.

About 60 percent of the CRI and CAI values, that were used to determine respectively the individual reliability impact of components and the individual availability impact of components, had their values assigned by interpreting data. This data governs the current situation of lock system Eefde. The remaining 40 percent has been estimated by the author. Whenever a component was assigned a high value, it has been carefully considered if this is representative. It can however not be guaranteed that all of the remaining 40 percent has been assigned the most representative impact value. It is therefore advised to further review the estimated reliability and availability impact values with system experts.

This study identified component pairs, components and modules with a high RA risk. It subsequently used the characteristics of these impacts to define a suitable standardization strategy. The next step towards standardization is to perform a cost-benefit analysis to determine the most effective standardizing strategy when the financial aspect is taken into account. This analysis should include the consideration of a potential block on innovation.

Finally, performing this study for the new lock system in Eefde, which includes a new Lock chamber, could yield interesting insights as it compares a before and after situation. By performing this study for other lock systems, the reliability and availability DSMs of a variety of locks is obtained. By comparing these DSMs, high risk components that occur in multiple systems can be identified. These components deserve extra attention when investigating standardization possibilities.

Hereby, a RWS wide improvement of its position with respect to standardization and innovation is obtained.

12.2 Suggestions for related work

The DM that has been used to obtain the functional DSM is incomplete and contains some granularity level issues in the function set. As explained in Chapter 6, it has however been successfully used to suggest missing interactions for the physical DSM. The nature of the incompleteness and issues that were encountered, can be used to suggest improvements for the functional description of the system.

By constructing the compare DSM in Chapter 7, the functional and physical DSM can be compared element wise. The type 2 interactions, which denote that an interaction that was found in the physical DSM is not present in the functional DSM, can be caused by either a incomplete function set or an incomplete relationship description of the functions.

If not all the functions are incorporated in the function set used in the DM, components that are only required for these missing functions will not appear in the resulting functional DSM. Hence, by investigating the type 2 interactions in the compare DSM, missing functions can be suggested.

The other cause for type 2 interactions is an incomplete dependency description of functions. If the set of components that are physically required for a particular function is not completely included in the dependency description of a particular function, the functional DSM obtained by converting this incomplete DM, will not depict an interaction between these components. Hence, also incomplete dependency descriptions can be identified via the type 2 interactions.

By applying these suggestions, an improved DM of the lock system can be obtained. This DM can subsequently be converted to a DSM that depicts the dependency structure between the functions of a lock. By improving this functional DSM and converting it, via the DM, into a physical DSM, it can be checked if the functional dependency description is complete. Hence, improving the DM can serve as a base to investigate the functional dependency structure of a lock system.

The granularity level issue that has been identified in the function set used for the DM can be solved with three distinct strategies:

- By applying the zigzagging decomposition technique (Suh, 1990) on both the components and functions of a system, the granularity level of both is gradually increased. A consistent granularity level is thereby achieved in a natural fashion.
- The component decomposition can be used to elicit a function decomposition by defining the functions on the interfaces of components, e.g. “Transfer movement of the Actuators vertical lift gates to the Vertical lift gates” (see Stone and Wood (2000)). The resulting DM can thereby be converted into a functional DSM that perfectly matches the physical DSM. This method forces the function to be on the same granularity level as the components.
- A third method is to investigate the dependency description of the functions in the DM. If particular functions are identified that have a far greater number of components in their dependency description, this can suggest that the granularity level is too low and the function needs to be decomposed into more subfunctions.

The obtained physical DSM that describes the dependency structure of the lock system is used to analyze its impact on the reliability and availability of the ship passage function of the lock system. It can however be used for a multitude of other purposes; the reliability and availability impact are just two of the possible characteristics that can be studied.

Bibliography

Fabrice Alizon, Seung Ki Moon, Steven B. Shooter, and Timothy W. Simpson. Three dimensional design structure matrix with cross-module and cross-interface analyses. In *ASME 2007 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, pages 941–948. American Society of Mechanical Engineers, 2007.

Arcadis. 2nd level fault tree of ship passage function. In *Integrale rapportage sluiscomplex Eefde, Bijlage 9: Foutenbomen*, page 11. Rijkswaterstaat, 2013a.

Arcadis. 1st level fault tree of ship passage function. In *Integrale rapportage sluiscomplex Eefde, Bijlage 9: Foutenbomen*, page 6. Rijkswaterstaat, 2013b.

Arcadis. Minimal cut sets for ship passage function. In *Integrale rapportage sluiscomplex Eefde, Bijlage 11: Minimale deelverzamelingen*, pages 7–13. Rijkswaterstaat, 2013c.

Matthew R. Bagley. *Modeling an automobile steering system using Axiomatic Design's Design Matrix and the Design Structure Matrix.* PhD thesis, Massachusetts Institute of Technology, 2005.

Alessandro Birolini. *Reliability engineering*, volume 5. Springer, 2007.

Timothy K Brady. Utilization of dependency structure matrix analysis to assess complex project designs. In *ASME 2002 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, pages 231–240. American Society of Mechanical Engineers, 2002.

Tyson R. Browning. Applying the design structure matrix to system decomposition and integration problems: a review and new directions. *Engineering Management, IEEE Transactions on*, 48 (3):292–306, 2001.

Noemi Chiriac, Katja Hölttä-Otto, Dusan Lysy, and Eun Suk Suh. Level of modularity and different levels of system granularity. *Journal of Mechanical Design*, 133(10):101007, 2011a.

Noemi Chiriac, Katja Hölttä-Otto, Dusan Lysy, Eun Suk Suh, et al. Three approaches to complex system decomposition. In *DSM 2011: Proceedings of the 13th International DSM Conference*, 2011b.

Paul A David and Julie Ann Bunn. The economics of gateway technologies and network evolution: Lessons from electricity supply history. *Information economics and policy*, 3(2):165–202, 1988.

Rijkswaterstaat dienst infrastructuur. *RINK 2012/2013 Cluster 2, Sluiscomplex Eefde Integrale Rapportage, map ULTIMO.* Rijkswaterstaat, 2014.

Qi Dong. *Predicting and managing system interactions at early phase of the product development process.* PhD thesis, Massachusetts Institute of Technology, 2002.

Qi Dong and Daniel Whitney. Designing a requirement driven product development process. In *Proceedings of the ASME International Conference on Design Theory and Methodology*, volume 21682, 2001.

Steven D. Eppinger and Tyson R. Browning. *Design structure matrix methods and applications.* MIT press, 2012.

Raghu Garud, Arun Kumaraswamy, and Richard Langlois. *Managing in the modular age: architectures, networks, and organizations.* John Wiley & Sons, 2009.

Marin D. Guenov and Stephen Barker. Requirements-driven design decomposition: A method for exploring complex system architecture. In *ASME 2004 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, pages 145–151. American Society of Mechanical Engineers, 2004.

Robert Helmer, Ali Yassine, and Christoph Meier. Systematic module and interface definition using component design structure matrix. *Journal of Engineering Design*, 21(6):647–675, 2010.

Julie Hirtz, Robert B Stone, Daniel A McAdams, Simon Szykman, and Kristin L Wood. A functional basis for engineering design: reconciling and evolving previous efforts. *Research in engineering Design*, 13(2):65–82, 2002.

Katja Hölttä-Otto et al. *Modular product platform design.* Helsinki University of Technology, 2005.

Rijkswaterstaat Iv-Indra. Mww-inventarisatie sluiselementen. inpa140619 - rapport. 2015.

Andrew Kusiak. Interface structure matrix for analysis of products and processes. In *LCE 2008: 15th CIRP International Conference on Life Cycle Engineering: Conference Proceedings*, page 444. CIRP, 2008.

Maik S Maurer. *Structural awareness in complex product design.* PhD thesis, Universität München, 2007.

Michael D McKay, Richard J Beckman, and William J Conover. Comparison of three methods for selecting values of input variables in the analysis of output from a computer code. *Technometrics*, 21(2):239–245, 1979.

Hisup Park and Mark R Cutkosky. Framework for modeling dependencies in collaborative engineering processes. *Research in engineering design*, 11(2):84–102, 1999.

Thomas Udo Pimmler. *A development methodology for product decomposition and integration.* PhD thesis, Massachusetts Institute of Technology, 1994.

Rijkswaterstaat. Failure mode and criticality analysis lock system eefde. In *Integrale rapportage sluiscomplex Eefde, Bijlage 11: Minimale deelverzamelingen*, page 3. Rijkswaterstaat, 2012a.

Rijkswaterstaat. Basis specification decomposition. In *Basisspecificatie Schutsluis*, pages 11–13. Rijkswaterstaat, 2012b.

Rijkswaterstaat. Decomposition lock system eefde according to nen 2767. In *Integrale rapportage sluiscomplex Eefde, Bijlage 1: Technisch uitgangspunten document*, page 17. Rijkswaterstaat, 2013.

Rijkswaterstaat. Logical function fulfillers, (objects) navigation lock system. In *Logische functievervullers (objecten) Schutsluis*, page 1. Rijkswaterstaat, 2014a.

Rijkswaterstaat. Otl decompositie. In *Sluizen in OTL, Modellering van sluizen in OTL*, pages 27–31. Rijkswaterstaat, 2014b.

Rijkswaterstaat. Grip printout for lock system eefde. In *'Gecoördineerde Regionale Incidentenbestrijdingsprodeduren*, page 1. Rijkswaterstaat, 2015.

David J Smith. *Reliability, Maintainability and Risk 8e: Practical Methods for Engineers Including Reliability Centred Maintenance and Safety-Related Systems*. Elsevier, 2011.

Manuel E. Sosa, Steven D. Eppinger, and Craig M. Rowles. Identifying modular and integrative systems and their impact on design team interactions. *Journal of Mechanical Design*, 125(2): 240–252, 2003.

Donald V. Steward. The design structure system: a method for managing the design of complex systems. *IEEE transactions on Engineering Management*, (EM-28), 1981.

Robert B. Stone and Kristin L. Wood. Development of a functional basis for design. *Journal of Mechanical Design*, 122(4):359–370, 2000.

Nam P Suh. *The principles of design*, volume 990. Oxford University Press New York, 1990.

Nam P. Suh. Axiomatic design theory for systems. *Research in engineering design*, 10(4):189–209, 1998.

Dunbing Tang, Renmiao Zhu, Sheng Dai, and Guangjun Zhang. Enhancing axiomatic design with design structure matrix. *Concurrent Engineering*, 17(2):129–137, 2009.

A. H. Tilstra, C. C. Seepersad, Kristin Wood, and others. Distributed modeling of component DSM. In *the Proceedings of International Design Structure Matrix Conference*, 2009a.

Andrew H. Tilstra, Carolyn C. Seepersad, and Kristin L. Wood. Analysis of product flexibility for future evolution based on design guidelines and a high-definition design structure matrix. In *ASME 2009 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, pages 951–964. American Society of Mechanical Engineers, 2009b.

Andrew Harold Tilstra, Carolyn Conner Seepersad, and Kristin L. Wood. A high-definition design structure matrix (HDDSM) for the quantitative assessment of product architecture. *Journal of Engineering Design*, 23(10-11):767–789, August 2012. ISSN 0954-4828.

TNO. Onderzoek naar de oorzaak van het bezwijken van een hefdeur van de sluis eefde. In *TNO rapport*, pages 1–43. TNO, 2013.

Stijn Van Dongen. Graph clustering via a discrete uncoupling process. *SIAM Journal on Matrix Analysis and Applications*, 30(1):121–141, January 2008. ISSN 0895-4798, 1095-7162.

T Wilschut. Systematic analysis of locks using design structure matrices. Introductionary report, Eindhoven University of Technology, 2015.

T Wilschut, Etman LFP, AT Hofkamp, AWJ Gielen, IJBF Adan, and JE Rooda. Analysis of the multi-disciplinary coupling structure of a LED system-in-package. Thesis, Eindhoven University of Technology, 2014.

Ali Yassine and Dan Braha. Complex concurrent engineering and the design structure matrix method. *Concurrent Engineering*, 11(3):165–176, September 2003. ISSN 00000000, 1063293X.

Appendix A

Latin hypercube sampling for DSM modularization

A performance indicator for the clustered DSM is the ratio between the aggregated DSM cluster density and the clustered DSM cluster density. The cluster density itself is determined by dividing the amount of interactions within a module, by the maximum amount of interactions in this module. This ratio is called the density ratio. The clustering algorithm incorporates three parameters that can be set to maximize the density ratio.

For the application of the clustering algorithm, detailed knowledge about these parameters is not required. The level variations of these three parameters are determined via practical experience.

- The expansion coefficient α, fixed at 2 (has little influence),
- The inflation coefficient β, varies between 1.2 and 3,
- The evaporation coefficient μ, varies between 1.5 and 2.5.

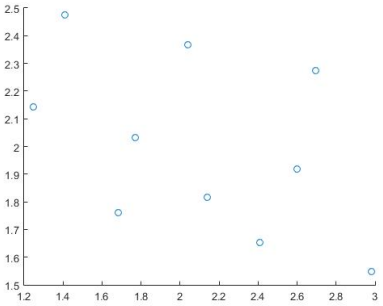
These values have to be optimized to obtain the best possible clustering. This is done by sampling the parameters over their respective range. By using Latin Hypercube Sampling (LHS) to sample the parameter levels, an efficient sampling strategy is obtained (McKay et al. (1979)).

LHS is a sampling technique that assists in determining an evenly distributed sampling of the design space with a predetermined number of samples. This predetermined number can be chosen dependent on the available resources (time and computing power). The amount of samples is equal to the amount of levels at which a parameter is sampled. Hence, each level of each parameter is sampled once.

Since the expansion coefficient alpha is fixed at 2, the LHS sampling is performed for two parameters: the inflation coefficient beta and the evaporation coefficient mu. A total of 10 samples are taken, hence both parameters are sampled on 10 different levels. By incorporating the suggested parameter ranges, the LHS sampling is determined, see Figure A.1a. A visualization of these samples is depicted in Figure A.1b.

Sample	*Beta*	*Mu*
1	2,98	1,54
2	2,04	2,37
3	2,14	1,82
4	2,59	1,92
5	1,25	2,14
6	2,69	2,27
7	1,77	2,03
8	1,41	2,47
9	2,40	1,65
10	1,68	1,76

(a)



(b)

Figure A.1: (a) LHS sampling for 2 parameters and 10 samples (b) Visualization of LHS sampling.

By running the clustering algorithm with these parameter settings, the density ratio on various points in the design space is determined, see Table A.1.

Sample	β	μ	Density ratio
1	2,98	1,54	1,48
2	2,04	2,37	2,51
3	2,14	1,82	2,02
4	2,59	1,92	1,82
5	1,25	2,14	-
6	2,69	2,27	1,71
7	1,77	2,03	4,46
8	1,41	2,47	5,34
9	2,40	1,65	1,82
10	1,68	1,76	5,52

Table A.1: Density ratio for various parameter settings.

The β has a stronger influence on the density ratio than the μ. For the fifth sample, it is impossible to calculate the density ratio; using these parameter settings identifies the whole DSM as a single cluster. The highest density ratio is achieved by the parameter setting of the tenth sample. By employing these settings, a first approximation of the modularization of lock system Eefde is determined, see Figure A.2.

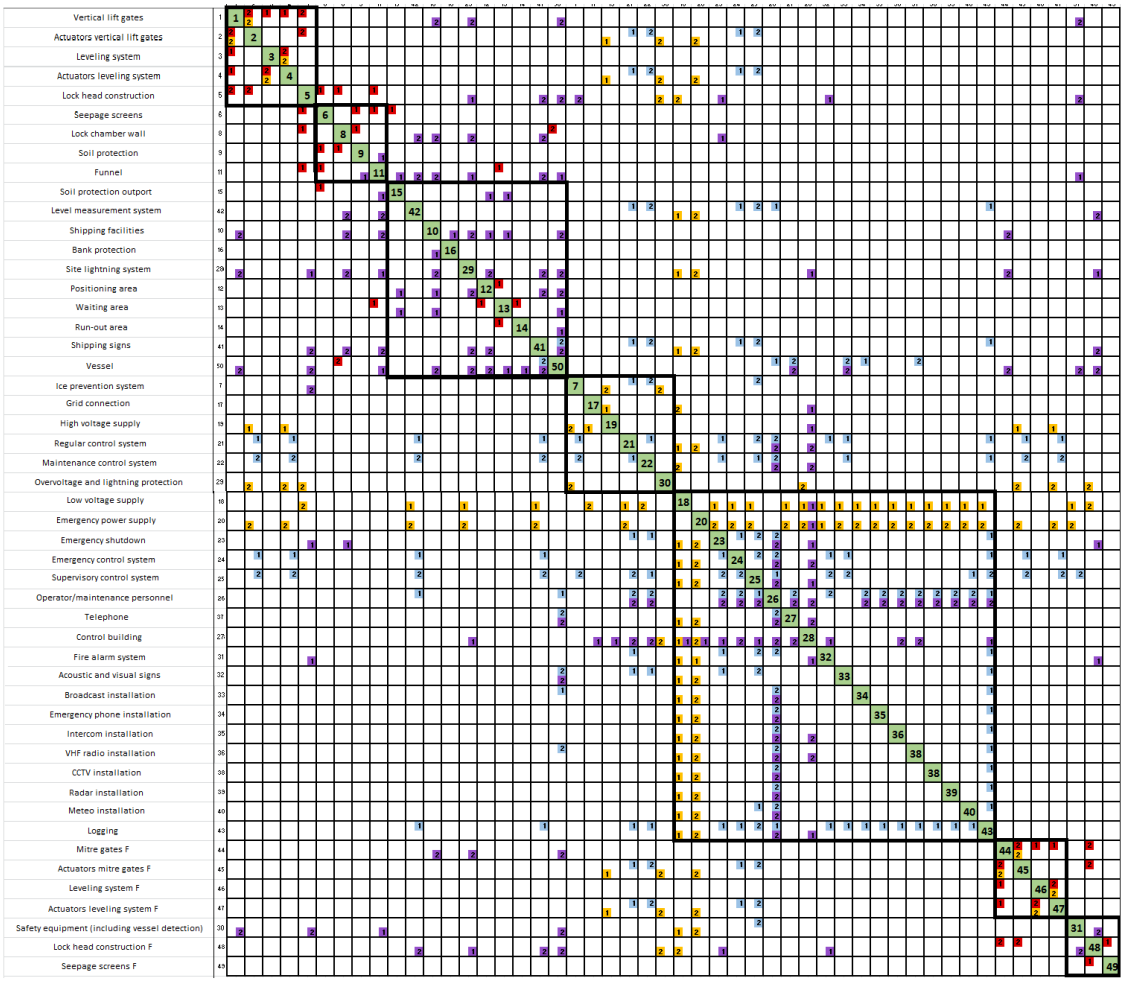


Figure A.2: Modularization as suggested by clustering algorithm.