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Modeling and Simulation of Critical Infrastructure

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Abstract

The diploma thesis was written as a part of a research assignment of the Federal Agency for State Protection and Counter-Terrorism Austria. It starts with the definitions of critical infrastructures. These are essential in order to classify infrastructures as critical or less critical. These are identified and categorised. Based on the categorisation, an Impact Matrix will be created. This matrix shows which infrastructures are very critical or less critical. In addition, a time component in the form of a sigmoid function comes into the game. The aim is to determine over a fixed time frame, whether a critical infrastructure is increasing or decreasing in criticality. Additionally to consider the dynamic behavior of critical infrastructures, System Dynamics is used as a modelling and simulation method. The focus is set on the water and power generation sectors. In order to simplify modelling, a workshop was held with master students. The results of the workshop serve as a first basis, in the sense of brainstorming, for the creation of a model. A Causal Loop Diagram was created and the possibility to convert it into a Stock and Flow Diagram was presented conceptually. Based on the models, the suitability of System Dynamics for modeling and simulation of critical infrastructures in Austria is confirmed. The feedback structure enables the analysis of dependencies and cascade effects of the individual infrastructures. The biggest problem in modeling and simulation is the access to suitable data beacuse they are often classified. Due to the increasing interaction of physical and digital systems in the field of critical infrastructures, System Dynamics can serve as a suitable method to simulate all-hazard szenarios. Based on this it can contribute to the development of protection and resilience of critical infrastructures in Austria.

Kurzfassung

Die Diplomarbeit ist im Rahmen eines Forschungsauftrags des Bundesamt für Verfassungsschutz und Terrorismusbekämpfung in Österreich entstanden. Einleitend geht es um die Definitionen von kritischen Infrastrukturen. Diese sind essentiell, um Infrastrukturen als kritisch einzuordnen. Diese werden im Bezug auf Österreich identifiziert und kategorisiert. Basierend auf der Kategorisierung wird eine Impact Matrix erstellt. Diese zeigt welche Infrastrukturen sehr kritisch oder weniger kritisch sind. Zusätzlich kommt eine Zeitkomponente in Form einer Sigmoid Funktion ins Spiel. Ziel ist es, über einen festgelegten Zeitrahmen festzustellen, ob eine kritische Infrastruktur an Kritizität zunimmt oder abnimmt. Um zusätzlich das dynamische Verhalten der kritischen Infrastrukturen mit zu berücksichtigen wird System Dynamics als Modellierungs- und Simulationsmethode angewendet. Dabei liegt der Schwerpunkt auf den Sektoren Wasser und Energieerzeugung. Um die Modellierung zu vereinfachen, wurde ein Workshop mit Masterstudenten abgehalten. Dabei dienen die Ergebnisse des Workshops als erste Grundlage, im Sinne Brainstorming, für die Erstellung eines Modells. Es wurde ein Causal Loop Diagram erstellt und die Überführungsmöglichkeit in eine Stock and Flow Diagram konzeptionell dargestellt. Basierend auf den Modellen, wird die Anwendbarkeit von System Dynamics zur Modellierung und Simulation von kritischen Infrastrukturen in Österreich bestätigt. Durch das Feedback verhalten können Abhängigkeiten und Kaskadeneffekte der einzelnen Infrastrukturen analysiert werden. Das größte Problem bei der Modellierung und Simulation stellt der Zugang zu geeigneten Daten dar, da diese zum Teil als Verschlusssache eingestuft sind. Durch die zunehmende Vermischung von physischen und digitalen Systemen im Bereich der kritischen Infrastrukturen kann System Dynamics zukünftig als geeignete Methode dienen um Gefahren aller Art zu simulieren und basierend darauf, zum Ausbau des Schutzes und der Resilienz von kritischen Infrastrukturen in Österreich beitragen.

Contents

List of Figures

Index of Abbreviations

AB	Agent Based
AI	Artificial Intelligence
AS	Active Sum
BKA	Federal Criminal Police Office
BM.I	Ministry of Internal Affairs Austria
BSI	German Federal Office for Information Security
BSI-KritisV	German Federal Office for Safety and the Ordinance on the Determination of Critical Infrastructures
BVT	Federal Agency for State Protection and Counter-Terrorism Austria
CERT	Computer Emergency Response Teams
CI	Critical Infrastructure
CIIP	Critical Information Infrastructure Protection
CIP	Critical Infrastructure Protection
CIPMA	Critical Infrastructure Program for Modeling and Analyses
CIPRNet	Critical Infrastructure Preparedness and Resilience Research Network
CIR	Critical Infrastructure Resilience
CIWIN	Critical Infrastructure Warning Information Network
CLD	Causal Loop Diagram
CSIRT	Computer Security Incident Response Team
DE	Discrete Event

DHS	Department of Homeland Security
EEA	European Economic Area
EFTA	European Free Trade Area
EISAC	European Infrastructures Simulation and Analysis Centre
EPCIP	European Programme for Critical Infrastructure Protection
ERNCIP	European Reference Network for Critical Infrastructure Protection
ETH Zurich	Eidgenössische Technische Hochschule Zürich
FP7	Framework Program 7
H2020	Horizon 2020
HSPD-7	Homeland Security Presidental Directive 7
ICT	Information and Telecommunication Technologies
IoT	Internet of Things
IT	Information Technology
KIRAS	Security Research Program
M&S	Modeling and Simulation
MIT	Massachusetts Institute of Technology
MSC	Munich Security Conference
NCI	National Critical Infrastructure
NIPP	National Infrastructure Protection Plan
NIS	Network and Information Security directive
NISG	National Network and Information System Security Act Austria
ÖSCS	Austrian Strategy for Cyber Security
ÖSS	Austrian Security Strategy
PATRIOT Act	Providing Appropriate Tools Required to Intercept and Obstruct Terrorism Act
PDD-63	US Presidential Decision Directive 63
PPD-21	Presidental Policy Directive No. 21
PPP	Public Private Partnerships
PS	Passive Sum

R&D	Research and Development
SD	System Dynamics
SFD	Stock and Flow Diagram
SME	Small and Medium-sized Enterprises
ST	System Thinking
TISN	Trusted Information Sharing Network
UNISDR	United Nations Office for Disaster Risk Reduction
WEF	World Economic Forum

1. Introduction

Nowadays, we are living in a more and more connected world than ever before. We are also facing new challenges through climate change, and we are increasingly being forced to face new situations through strategically-minded threats like cybercrime, terrorism, hybrid threats or criminal activities.
Unfortunately all these points can influence our lives dramatically not always in a positive manner. Thus, to sustain economic and social well-being a network with a variety of different infrastructure sectors is needed. Since all of these infrastructure sectors can have a large-scale impact on our society and economy.

1.1. Ambition and Motivation

The motivation for this diploma thesis arises from our everyday life and the fascination how our life is influenced and highly interconnected within a network of *Critical Infrastructure* (CI) sectors. Right at the moment due to a European extended long drought period some countries facing extraordinary threats related to forest fires or less electricity generation.
The initial point of this diploma thesis was already set a few months ago as the *Federal Agency for State Protection and Counter-Terrorism Austria* (BVT) gave a research assignment to the *Institute of Engineering and Business Informatics* an apartment of

the *Graz University of Technology*. As the first step of the research assignment, this diploma thesis should give the BVT a strategic framework as well as the basics for a *Modeling and Simulation* (M&S) approach for CIs in Austria.

To no degree CI is a modern appearance only. Even in the past centuries critical infrastructure already existed. However, through industrialization, globalization and digitization, the CI connectivity as well as interdependencies between the single CI sectors, results in an increasing complexity of the whole system. Due to this circumstances government departments, safety authorities, aid agencies, and emergency services have to think in an entirely new way to get one step ahead to protect the society in a best possible manner against attacks or natural disasters. Thus, it is essential to develop well-working strategies for a multitude of scenarios. Most of these scenarios can be simulated. Therefore one of the most popular but at the same time also one of the most demanding M&S approaches is *System Dynamics* (SD). This approach was developed by *Jay W. Forrester* in the mid-1950s at the *Massachusetts Institute of Technology* (MIT) to model and simulate complex and dynamic systems. A benefit of this modeling technique is that it is characterized by feedback loops, dynamic behavior and the advantage to consider a significant amount of external factors. In other words to develop a real-life problem model.

Furthermore, in a holistic view SD can be seen as a system that can be used for strategic decision-making and mapping of socioeconomic systems. Meanwhile, a whole SD community has been established where experts of different research fields use the effect of knowledge sharing to improve models and simulation techniques. Unfortunately, experts are rare within the field of SD especially in companies. That makes it more challenging to develop SD models in a wide range.

1.2. Statement of Task

On the one hand the aim of this diploma thesis is to bring light into the widely ramified world of CI. How does the international community and Austria deal with CIs. Since infrastructures in general represent a broad field, not every one is critical and not every one uncritical. Therefore it is necessary to develop a basic CI structure list. Based on this it is important to show a risk analysis of the most CIs in Austria, and on the other hand, to provide the principles of a SD framework which can be used as a basis for a support tool for strategic decision making in case of all hazard scenarios in Austria. To model and simulate CI dependencies and dynamic behavior makes SD a suitable method to investigate the facts. In particular, the methodologies behind SD to act in feedback loops, to use stock and flow diagrams and to use causal loop diagrams makes the method appropriate to real life challenges. In collaboration with the BVT, it was decided to develop a framework to make interdependencies and cascade effects between the different CI sectors visible. For the SD framework, the critical sectors water and energy supply have been selected. Finally, all outcomes are summarized in a strategic advice.

2. Critical Infrastructure

For thousands of years, CI have played an essential role in the civilization. Already in ancient Egypt important buildings, communication ways like papyrus scrolls and military facilities were sensitive areas and therefore critical. During the time not only ancient Egypt but other advanced civilizations like ancient Greece or Rome built and developed their own important facilities which ensured well being of the population and economic resilience. Over the years the outer circumstances of CI shifted a bit. New technologies have been developed, new interests of the society and governments occurred, and increasing globalization contribute to the creation of a large-scale network of individual CI elements.
Not always CI and their protection were considered necessary. However, the last decades due to terrorism, natural disasters and cybercrime results in an increasing awareness of CI protection and resilience. Related to that fact the impotence can also be shown in increasing risk scenarios. One risk is the liberalization and privatization of infrastructure providers. Another risk shows the connectivity due to *Information and Telecommunication Technologies* (ICT) as well as the expectation of the population to have all services 24/7 available. Furthermore, urbanization and with that interdependencies of infrastructures pushes the risks to their limits (Setola et al., 2016). Unfortunately, the complexity even starts by specify a definition of CI.

2.1. Definition and Approach of Critical Infrastructure

On the one hand CI is described by definitions , and on the other hand, it consists of a structure of approaches. Both are essential to understanding the respective strategies of the individual countries in the CI environment.

2.1.1. Definition

As already mentioned before, there is no allover accepted and uniform definition of CI. However, all definitions show up with at least the same content elements. Therefore the role of CI to the society and the influence due to disturbance are crucial. For this reason, the *European Council* published a *Directive 2008/114/EC* on the identification and designation of critical European infrastructures and the assessment of the need to improve their protection in 2008 (European Council, 2008a). In this directive the definition of CI is given as:

> *"'critical infrastructure' means an asset, system or part thereof located in Member States which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact in a Member State as a result of the failure to maintain those functions"*

Compared to the European Union the Clinton Administration set a *US Presidential Decision Directive 63* (PDD-63) already in the 90's to ensure CI protection in the US. Therefore, the importance of CI and its influence on society was recognized and written down a few years earlier than in the EU. In the US context, the PDD-63 is often seen as the first genertion break away from the cold war towards modern threats (The White House, 1998). The definition for CI as it is given in the PDD-63 says:

"'critical infrastructure' are those physical and cyber-based systems essential to the minimum operations of the economy and government."

Later in 2001, the *107th Congress of the United States of America* (USA) adopted the public law: *"Providing Appropriate Tools Required to Intercept and Obstruct Terrorism Act"* (PATRIOT Act) as a result of the 9/11 terrorist attacks (Senate and House of Representatives of the United States of America, 2001). In the Law the CI definition is already being specified which says:

"Systems and assets, physical or virtual, so vital to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health and safety, or any combination of those matters."

These simple examples show that all definitions allow room for interpretation. This says a lot about the understanding of different nations on CI and its content. Even some member states of the EU have their own *National CI* (NCI) definition which differs more or less from the overall *Directive 2008/114/EC* of the *European Council*. Besides, the US and the EU and many other nations which emphasize CI, which makes it even more complicated to find synergies or an everyday basis for cross-national security arrangements.

2.1.2. Approach

There is no full protection for CI worldwide. Nowadays many countries have strategies for their CI protection, but international cooperation is often still lacking. Therefore the countries are pursuing different approaches. Nevertheless, three approaches have been identified.
Approach 1: The *Critical Information Infrastructure Protection* (CIIP) approach has a focus on security and protection of the *Information Technology* (IT) Infrastructure

in detail IT Connections and solutions within all the CI sectors. To ensure the protection of the physical components, another organizational framework was introduced. Meanwhile, almost every country integrated the private sector to all sectors of *Critical Infrastructure Protection* (CIP).
Approach 2: This approach includes both protection of critical IT infrastructure as well as physical protection of CI. It is often named *All Hazard* scenario because there is no separation between the individual components of physical protection and IT security.
Approach 3: It mainly concerns the Chinese approach; thus it makes it to a particular case. There is no cooperation between the private and public sector at all. The approach protects less the CIs itself than it protects the government and its system and the organs that substitute the interests of the state.
Over the last years, the legislative implemented an increasing collaboration to Approach 1 and 2 for *Public Private Partnerships* (PPP) to the national security strategy. Which ensures a steadily progressively *Critical Infrastructure Resilience* (CIR) and CIP. (Bundesamt für Sicherheit in der Informationstechnik Deutschland, 2004)

2.2. Critical Infrastructure in an International Context

Nowadays CI gets more experience on the increasing relevance on the international stage. This shows quite clearly that there is a reason why security-relevant topics are becoming the focus of the *World Economic Forum* (WEF). That is why in the last year, 2018, headlines such as: *"Cyberwar without Rules"*, *"Launch of the Global Centre for Cybersecurity"* or *"What Could Trigger a Major Security Crisis in 2018?"* gained more and more importance. (World Economic Forum, 2018a)
However, also conferences like the *Munich Security Conference* (MSC) which takes place since 1963, shows the international topicality. Besides worldwide growing interconnectivity between the countries, many of them established national, some-

times even international, laws and guidelines especially after the terrorist attacks on 9/11 to ensure the economic power and the well-being of their population by protecting CI. (Elgin Brunner and Manuel Suter, 2008)
Already in 2004, the German *Federal Office for Information Security* (BSI) published a paper with the topic *"Critical Infrastructure Protection: Survey of World-Wide Activities"* which says that many nations worldwide have approaches to face challenging tasks on CIP. The BSI clustered the information of each country concerning their approach, strategy, responsible agencies, and transparency. (Bundesamt für Sicherheit in der Informationstechnik Deutschland, 2004)
Over the years, the requirements, the risks, and the safety issues have changed in general within the CI sector. Everything is getting more complex and pushes international institutions and governments to their limits. This makes it clear that new tools are needed to meet the new requirements. Never the less several programs with a modeling, simulation, and analyses background have been set up to handle highly complex CI networks and their dependencies. (Setola et al., 2016)
Nowadays the focus moved from CIP towards CIR as one result of climate change and the associated increase of natural disasters which results in steadily growing challenges. In the meantime, it is no longer just the protection of CI as the recent events of heavy snow falls have shown it. Thus, it is becoming increasingly important to develop resilient, preventive measures in order to keep possible damage as low as possible. In recent years, due to the rapid digitization and further development of technologies especially in the cyberspace, many opportunities have been created. But in the same way also many threats occurred like hacker attacks which are on the agenda of every security authority's working day. For that reason, the international efforts for CIP and CIR created new national strategies, programs, and laws in the near past.
Elgin M. Brunner and Manuel Suter from the *Eidgenössische Technische Hochschule Zürich* (ETH Zurich) researched in their *"International CIIP Handbook 2008/2009"* the different CIIP policies development of 25 nations and 7 organizations. In this

diploma thesis, the international focus is set on the US and Australian approaches since in both countries the CI national strategies are very well developed on a high level. In comparison, Russia and China only provide rare information about their strategies.

2.2.1. The US Strategy

The first thing to note is that the US strategy is very complex with regard to CI as many authorities and departments are involved. In addition to the authorities there are also a variety of laws and directives which have grown over the years historically and do not contribute to simplification.
One of the core elements of the CI relevance in the US is the PDD-63. The US government recognized the increasing importance of CIs early in the 90's. Thus, very early CIP strategies could be decided (The White House, 1998). Furthermore, the definition of CI is given by the *PATRIOT Act* (Senate and House of Representatives of the United States of America, 2001). Based on the *PATRIOT Act* the *Homeland Security Presidental Directive 7* (HSPD-7) has been published in 2003. In this HSPD-7 17 CI and key resources but also the roles and liability for the protection of these sectors have been identified (The White House, 2003).
Currently, the *Presidental Policy Directive No. 21* (PPD-21) contains key elements of the US Strategy on CI security and resilience undertaking into account the *All-Hazard* approach. The PDD-21 updated the 17 sectors from the HSPD-7 down to presently 16 whereby the energy and communication sectors prove on their importance due to their necessity to the operations of other infrastructures. A peculiarity of the USA is the more detailed listing of the sectors as well as the allocation of defense and security departments and the armaments industry. Further, it also highlights the *Directives* importance of both physical and cyber threats on CI. Thereby PPD-21 called for the development of a situational awareness capability as well as to evaluate the existing PPP model. Besides the *Directive* claims for a periodic update of the

National Infrastructure Protection Plan (NIPP) and the *Research and Development* (R&D) Plan. (House, 2013)
One example that can be traced back to the PPD-21 and at the same time underlines the significance of this diploma thesis is the launch of the *US National Infrastructure Simulation and Analysis Center*. It belongs to modeling, simulation and analysis tasks to prepare and share results of CI including their dependencies, consequences, vulnerabilities and other complex issues within the *Department of Homeland Security* (DHS) and under the direction of the *Office of Cyber and Infrastructure Analysis*. (Sandia National Laboratories, 2013)

2.2.2. The Australian Strategy

The Australian CI strategy is very well structured compared to other nations. That makes it more precise and easier to understand an already very complex topic.
Also in Australia, the importance of CI is becoming increasingly crucial. Since 2010, the new policy has focused on *Essential Services* for everyday life. For this purpose, the *CI Resilience Strategy* was launched (Australian Government, 2010). Just as the international trend, the strategy shows a change towards resilience and the *All-Hazard* approach. The Australian strategy additionally includes dependencies and potential cascade effects between CIs and sectors. Like in the USA the policy aims to build a PPP proposal to strengthen the cooperation between businesses and government and therefore established the *Trusted Information Sharing Network* (TISN) (Setola et al., 2016, p.12).
Furthermore, other important topics in the strategy are the launch of a research and development program and the implementation of the *Australian Government's Cyber Security Strategy* to obtain a secure, resilient and trusted cyberspace for both owners and operators. Another collaboration exists between businesses and governments to identify cross-sectoral dependencies and vulnerabilities. A best practice development on CIR as well as resilience capabilities to incorporate on daily business

activities for cyber and physical infrastructure is a key element of the *Cyber Strategy*. (Australian Government, 2010, p.25)

In order to implement the *Australian CI Resilience Strategy*, it is one of the key initiatives to build up the *CI Program for Modeling and Analyses* (CIPMA) competencies. The program uses available data to model and simulate the behavior and cascade effects of CI systems. Using the *All-Hazard* approach, CIPMA cooperates with stakeholders like CI owners and operators to model and simulate consequences of different scenarios whether natural or human-caused on CI. Owners can use the results of the simulation, providers and government agencies to help prevent, prepare for, respond to or to recover from threats (Australian Government, 2010, p.19). The last comprehensive review of the *CI Resilience Strategy* was in 2015. Every five years the strategy has to be revised and adapted to the latest developments.

2.3. Critical Infrastructure within the European Union

The European approach has, in comparison to other regions, the same as well as different interpretations of the implementation of measures. For the protection of CI in Europe the *European Programme for Critical Infrastructure Protection* (EPCIP) forms the corresponding framework along all EU states. Similar to other directives of other Nations the EPCIP also follows an *All-Hazard* cross-sectorial approach which includes threats in terrorism, criminal activity, and natural disasters. The EPCIP consists of the following components (Europäische Kommission, 2006):

- A procedure to identify and designate European CIs and a common approach to improve the protection of such CIs.
- Measures to establish a relevant action plan and a *Critical Infrastructure Warning Information Network* (CIWIN). Therefore the creation of an EU expert group is

necessary for the exchange of information on CIP and the identification and analysis of dependencies.

- A support of the member states within the CI topic that can be used by them as it is needed.
- Funding for CIP projects especially in context with the proposed EU program *Prevention, Preparedness and Consequence Management of Terrorism and other Security Related Risks*.
- Expert meetings between the EU, the USA and Canada. Also to cooperate internationally with the nations of the *European Economic Area* (EEA) and the *European Free Trade Area* (EFTA).

In 2008 the *European Council* established the new heart of the 2006 EPCIP program. The new directive is the first step in a gradual approach with the aim to identify European CIs and assesses the need to improve their protection. Thus the focus is on, the sector's energy and transport, but it also should be reviewed in order to assess its impact and the need to involve other sectors like ICT to consider their scope. Still, it is the the member states and owners, together with the operators of such infrastructures, are primarily and ultimately responsibility to protect them. However, the supranational cooperation of the member states must be given at any time. Often bilateral agreements already exist or are at least in negotiations. Like in other countries the private sector plays a significant role in risk management, disaster preparedness, and recovery after a disaster within the EU. Therefore a PPP approach is essential for the EU member states. Beyond a review process is demanded in the directive. (European Council, 2008a)
Hence in 2012, a comprehensive review has been implemented in close collaboration with the member states and stakeholders. The temporary outcomes have been compendious in a *Commission Staff Working Document*. The *Commission* promulgated the results and other elements of the current directive in a *Staff Working Document* on a new approach to the EPCIP. It gets a more practice-oriented focus within the

three primary activities prevention, preparation, and reaction. It should better take into account interdependencies and create common tools and a common approach for the protection and resilience of CIs within the EU. (European Commission, 2013)
Just as important are measures for cyber resilience and security across the EU. To this end, the *European Commission* issued a 2016 directive concerning measures for a high standard level of security of network and information systems across the Union (NIS). It is also known as the *NIS Directive*. It is the first cybersecurity legislation of the EU. The *Directive* specifies three priorities (The European Parliament, 2016):

- Member state preparedness to be equipped for every scenario like with a *Computer Security Incident Response Team* (CSIRT) as well as a national NIS authority.
- To identify essential services and their providers which forms the backbone of the economy and society.
- Build up cooperation across the EU by setting up cooperation groups, strategic cooperation and to ensure an exchange of information between member states.

The EU has also invested heavily in R&D programs in recent years. On the one hand, under the *Framework Program 7* (FP7) over 300 projects on security-related issues such as a better understanding of criticality and dependencies of CI have been co-funded by the program. On the other hand, many projects with a strong focus on CI security were also covered by the *Critical Infrastructure Preparedness and Resilience Research Network* (CIPRNet). In addition to the security-related programs, there is another EU program, *Horizon 2020* (H2020), which was also considered by the *European Commission* with funding for security-related topics. Also in the context of H2020, there are currently more than 150 different R&D projects concerning CI. Over time, the program evolved from a technology-oriented approach to a problem-solving approach. (The European Commission, 2019)
Driven by EU R&D programs, the *European Commission* decided to set up a *European Reference Network for Critical Infrastructure Protection* (ERNCIP), which links leading

laboratories and facilities across Europe to ensure faster knowledge sharing and a more efficient technology transfer. Finally, under the CIPRNet umbrella virtual center of shared and integrated knowledge and expertise in CIP have been established and will be the foundation for the 2020 planned *European Infrastructures Simulation and Analysis Centre* (EISAC) which will focus on the key technology in M&S. (Critical Infrastructure Preparedness and Resilience Research Network, 2019)
Summarizing, table 2.1 compares the US and EU efforts on CI. Compared to the USA and the EU, Australia has a very few clearly structured programmes and is therefore not listed in more detail.

Table 2.1.: CI Programs in comparison

	USA	EU
Directves	PDD-63	EPCIP
	PATRIOT Act	CIWIN
	PPD-21	2008/114/EC
Cyber Initiatives	NIST Cybersecurity Framework	NIS
	CISPA	ENISA
R&D	CISR R&D Plan	CIPRNet
	CIRDA Act of 2013	Horizon 2020
Modeling&Simulation	NISAC	EISAC

2.4. Critical Infrastructure in Austria

For Austria as an EU member state, the protection of CIs has been a security policy issue for years. In order to safeguard the public interest for the Austrian population and thus to remain an attractive business location, it is essential to pay attention to the availability and function of the infrastructures. The security of supply in Austria is one of the most progressive. Due to this fact it is crucial to ensure the functional safety of these infrastructures. In particular, the security of supply is endangered by natural disasters, technical accidents, human failure, cyber threats, crime, and terrorism.

On the basis of greater security, protection, and resilience for Austria, the national master plan *Austrian Program for Critical Infrastructure Protection* (APCIP 2008) was launched under the impulse of EPCIP. In 2011, bilateral agreements were signed with Germany, the Czech Republic, and the Slovak Republic to protect European CIs better. Just one year later, the identification of strategically important companies and organizations (strategic companies) for Austria was completed. The CIWIN-AT portal was also set up as part of the European warning and information exchange by the CIWIN program (EUROPEAN COMMISSION, 2019). In order to ensure the protection of CI in the Austrian cyberspace, the *Federal Government* decided and implemented the *Austrian Strategy for Cyber Security* (ÖSCS) in 2013 (Cyber Sicherheit Steuerungsgruppe Österreich, 2018). Only a short time later, the *National Council* passed the *Austrian Security Strategy* (ÖSS) which reflects a general concept for the protection of CIs and for increasing the resilience of Austria (Bundeskanzleramt Österreich, 2013). ÖSS is currently the rationale for further development of the APCIP 2014 (Bundeskanzleramt Österreich, 2015).

In order to implement the EU NIS Directive, the *National Network and Information System Security Act* (NISG) was submitted in autumn 2018 (Bundeskanzleramt Österreich, 2018). The contents are based on the *German Federal Office for Safety and the Ordinance on the Determination of Critical Infrastructures* (BSI-KritisV) (Deutscher Bundestag, 2015). In particular, the operators and the state institutions should be given more responsibility for compulsory registration and reporting in order to ensure the best possible protection for Austria, the population and the economy. For acute crises, the adoption of a computer emergency team is planned as well.

Like the European parent program EPCIP in the vanguard role, Austria also works at a national level for cooperation between operators of strategic companies and

the state in the role of a PPP. To this end, some measures have been adopted to intensify cooperation and exchange of information in order to ensure the best possible protection and resilience of infrastructures.
The expansion of research activities in the field of CI is also one of the central building blocks in the interest of the APCIP in order to be up to date with R&D approaches anytime. For this purpose, the *Security Research Program* (KIRAS) was launched for Austria.(Bundeskanzleramt Österreich, 2015)

2.5. A Call for Resilience

In recent years, there has been a gradual recovery from the missed need to protect CIs which is ultimately leading to a solid foundation. This allowed science, but also governments and organizations, to deal more deeply with the issue beyond protection. It quickly became clear that the durability and recoverability of a system is at least as important as the actual protection itself. Resilience plays a significant role not only in the latest regulations or laws on the subject of CI but also in science. The issue of resilience is increasingly being addressed. To this end, the first *International Infrastructure Resilience Conference* took place in Zurich in 2018 at *ETH Zurich*. This again emphasizes the importance of this topic. (ETH Zurich Risk Center, 2016)
At the conference, the question of the definition of resilience immediately came up. Similar to the definition of CI, there is also no agreement on the term resilience. Many nations, scientific institutions, and technical literature use different interpretations of the term. That is why international consensus becomes more important for unity in dealing with the topic. Austria uses the official definition of resilience which is given by the *United Nations Office for Disaster Risk Reduction* (UNISDR) (United Nations Office for Disaster Risk Reduction, 2017):

"The ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management."

Within the ÖSS it is written that it needs a concept to increase the level of resilience in Austria, which is given by the APCIP strategy update. Further, the ÖSS highlights the PPP to increase CI resilience. Right now the protection standard of strategically important companies is based on self-commitment. The upcoming *Network and Information System Security Act* (NISG) directive will require stricter conditions and interpretations of private companies. Special audits and certifications, as well as a notification requirement, are to be introduced. This is necessary in order to provide a resilient Austria in the future. (Bundeskanzleramt Österreich, 2013) (Bundeskanzleramt Österreich, 2015)
In order to better assess effects, duration and performance in particular in the modeling process the graph 2.1 can be helpful.

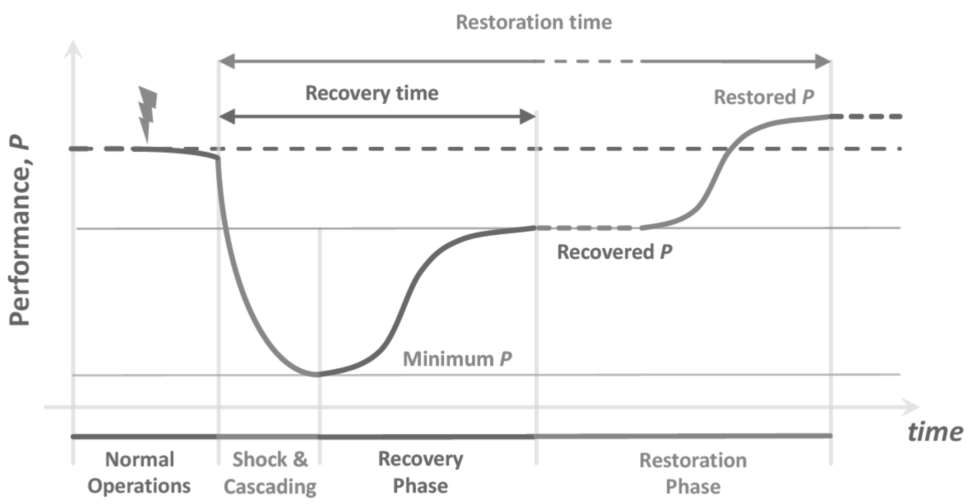


Figure 2.1.: Resilience curve (Giovanni Sansavini, 2018)

While looking at the resilience curve 2.1, it is getting perspicuous which significance resilience can have. Recovery phase and restoration phase require a very long time until the initial state is restored. Especially cascade effects have a considerable influence on the time component.
One focus of the *Infrastructure Resilience Conference* was to consider the impact of risk to improve resilience. Simon Hodgkinson et al. (2018) from the *University of Birmingham*, identified that risks could improve resilience (Hodgkinson et al., 2018). For this purpose, it is necessary to operate for a focused and comprehensive risk management to ensure an improved resilience of CIs. Similarly, Dr. Stefan Brem from the *Federal Office for Civil Protection in Switzerland* said that the criticality of own infrastructures is used as a basis for strategic planning to protect CI (Brem, 2018). Risk on the one side and uncertainty on the other side causes in a resilience valuation. Which shows Murray Richard M. et al. (2013) in their graph 2.2. Therefore a resilient system has a lower risk impact than conventional systems in unexpected, unknown scenarios.

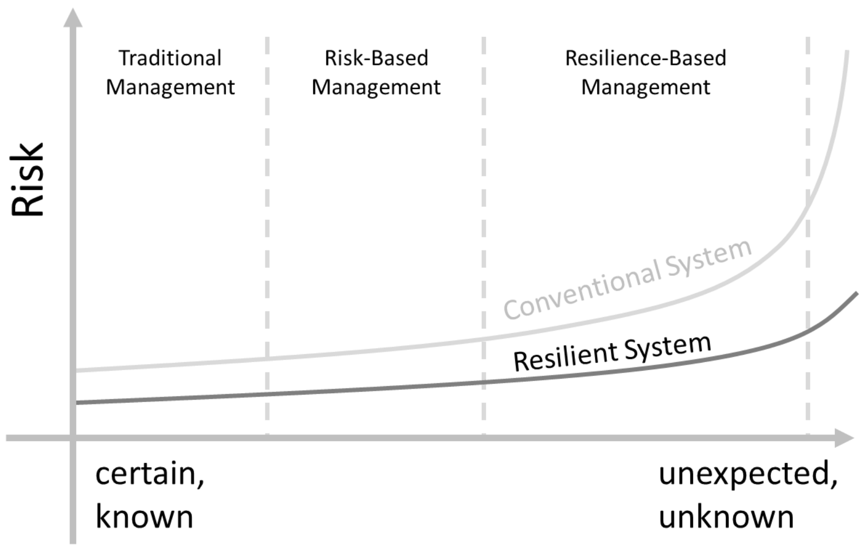


Figure 2.2.: Risk Interaction Diagram (John C. Day et al., 2013)

In addition to risk, the complexity of the system plays also a key role in improving sustainability and resilience. Above all, the dependencies of the individual systems are considered and also known as the *"system of the systems"*. The highly interconnected dependencies of the systems are very efficient, but at the same time, they become more vulnerable. Especially cascade effects are feared in such systems because not all dependencies in complex networks are always clear. Thus even small failures can have huge impacts. Here the criticality can be taken as a measure of the possible impact too. Prof. Dr. Yiping Fang (2018) from the *Centrale Supélec, Université Paris-Saclay* came to the same conclusion in his presentation (Fang, 2018). The topic of resilience was also one of the key-subjects during lively discussions of a meeting with the BVT.
For a better understanding of resilience, it is necessary to look at the building blocks in table 2.2 briefly. Table 2.2 shows the act of every individual building block and shows how it is assembled to the ability to resist.

Table 2.2.: Resilience Building Blocks (Heinimann, 2018)

Enabling Functions	Cognitive Functions	Biophysical Functions
Prevent	Stay aware	Reconfigure
Cope	Anticipate	Rebuild
	Remember	Restabilize
	Adopt	Resist

2.5.1. Resilience vs. Lean

Lean and resilience can it work in coexistence? Opinions differ in this topic. It was also discussed in the meeting with the BVT. For example, a key message of the lean management method is that it increases the profitability and thus the

competitiveness of a company with the help of lean processes. This is done under the approach of avoiding waste of any kind.
The practice often looks like, that the profitability of a company is maximized. The question that arises is, how resilient are such companies even when everything has been streamlined? If buffers are reduced to a minimum, how many reserves are there in an exceptional situation or scenarios under uncertainty? The system will collapse and without buffers the cascade effects will getting more uncontrolled and vaster. This is currently an up-to-date topic, which is of particular interest to the security sector since nobody wants to be involved in cascade effects of unknown proportions.

2.6. Threats on Critical Infrastructure

CIs are a very diversified field which is interpreted differently depending on the country or organization. There are also various threats. Some threats already exist for centuries, some are current issues or just starting to emerge. Dealing with threats on CI and its implications is a continuous process and will never reach a final state. The complexity behind CI is enormous and is continually being changed and supplemented. Due to the rapid development of technology and increasing globalization as well as global warming, new challenges are continually arising. In summary, table 2.3 shows an outline of the critical infrastructure clustering and various threats.

With this a sector is an overall term for different categories which ensures holistic the economic and political functionality within a society. A subsector splits the sector in single product lines, services or supply activities and is a more detailed view. All essential services together provide the functionality of the subsector. Behind every essential service, a provider must be given.

Table 2.3.: Threats and Categorization of CI

Categorization	Threats
Sectors	Terrorism
Subsectors	Criminal Activities
Essential Services	Cyber Attacks
	Hybrid Threats

2.6.1. Terrorism

Terror has become a significant word of the present with the attacks on 9/11. Terrorism is meant above all criminal acts of violence against humans or things to reach a political, religious or ideological goal. The primary goal is to spread insecurity and terror or force sympathy and willingness to support. (Waldmann, 2003)
It is precisely, these reasons that make terrorism a dangerous tool to attack critical infrastructure. Unfortunately, exactly this happened in the past and is still happening. Virtually every critical infrastructure sector is in the interest of terrorist groups. Since terrorists know very well that targeted attacks can cause the highest possible damage to these sectors with corresponding cascade effects. Furthermore, there is a trend now, whereby the focus increasingly changed from physical targets to digital targets. Accordingly, the effort of governments and organizations are to ensure the highest possible protection for the population. There will never be a 100% protection of critical facilities, but it is possible to maximize protection and minimize the risk of terrorism (Voronkov and Coninsx, 2018). Despite all efforts, unfortunately, there are always individual attacks on CIs such as the simultaneous attacks on the airport and metro in Brussels in 2016. Whereby 32 people lost their lives and over 300 people were injured. Another example is the targeted attack on the water infrastructure in the years 2013 to 2015 in Syria and Iraq by the terrorist organization ISIS (United Nations Security Council Counter-Terrorism Committee Executive Directorate, 2017).

At that time, the pipeline network, sewage treatment plants, and bridges were deliberately destroyed. Also, dams were purposefully closed to prevent a water supply. Another frightening example is the targeted steering of trucks in crowds at events.
Fortunately, many successes against terrorism could be achieved. Regularly planned anti-terror missions by the security forces are carried out. Not least due to the excellent cooperation between the governments and the implementation of anti-terror strategies to protect CI, successes against terrorism are increasingly prosperous (Voronkov and Coninsx, 2018).

2.6.2. Criminal Activities

Unlike terrorism, which is politically motivated, criminal activities are primarily financially motivated acts. This is a lawless act which is usually punishable by the law. Especially when it comes to criminal activities to damage CI, the action is not only harmful to the individual but also the state and society. (Edwards, 2014, p.47)
One example of criminal activity against CI is piracy of the coast of Somalia. Piracy is a criminal act. For the protection of freighters, several naval missions were carried out from different countries. In order to protect international trade interests and thus the economic interests of the EU, the*Naval Mission Atalanta* was decided. (European Council, 2008b)
As terrorism, criminal activities are divided into cyber-crime and normal criminal activities where cyber-crime is gaining ground and established its category due to its explosiveness. (Cyber Sicherheit Steuerungsgruppe Österreich, 2018)

2.6.3. Cyber Attacks

The digital revolution is making great strides. Especially postindustrial societies or highly developed states use cyberspace for their daily activities and strategies. However, they are exposed to constant attacks from the cyberspace, which represents an immediate danger to the security, the functioning of the state, the economy, science, and society. (Cyber Sicherheit Steuerungsgruppe Österreich, 2018)
Jean-Claude Juncker said in 2017 Juncker, 2017:

> *"Cyber attacks can be more dangerous to the stability of democracies and economics than guns and tanks."*

This statement underlines the danger and power of cyber attacks on modern society. Especially by non-state actors such as criminals or terrorists, but also by state actors such as intelligence agencies and the military, cyberspace can be abused for its purposes and its functioning impaired. It is precisely CI that always comes into focus, as it allows to go unnoticed, across borders and over long distances to cause significant damage. This can be a direct attack on the infrastructure, but there are now more and more cases of serious extortion attempts by cyber attacks. As a result, it is one of the top priorities of almost every state to work on securing the cyberspace. (Munich Security Conference, 2018)
A well-known example of a cyber attack on CI was the attack on the *Maersk-Møller* company on 27th June 2017. The company was unable to use its IT infrastructure for 10 days. This could only be compensated manually with very high human resilience and this at a company where every 15 minutes a ship with 20,000 to 30,000 containers enters a port worldwide. Nevertheless, the *Maersk* attack caused damage of about 300 million dollars. (World Economic Forum, 2018b)

2.6.4. Hybrid Threats

In a very modern kind of threat, attackers deliberately rely on a combination of traditional military deployments, cyber attacks, and economic pressures, and even propaganda in the media and social networks is not uncommon. Such kind of threats are named hybrid warfare. The overriding goal of the attackers is to influence public opinion and thereby destabilize society. With this CIs are once again in a direct and indirect focus of the attackers. Extraordinarily pluralistic and democratic societies are easily vulnerable. (Bundesministerium der Verteidigung, 2016a)
The hybrid threats are mostly unassignable because they are disguised. Thus, the attackers remain anonymous or deny participation in incidents and conflicts. This is never used deliberately to overstep the threshold to an official war. This is what makes such attacks unpredictable. The cyberspace, in particular, is the battlefield of the 21st century. The focus is on influencing public opinion, and that is precisely the difficulty of the defense of such threats. Often very well disguised, attackers are rarely identified. (Bundesministerium der Verteidigung, 2016b)
The conflict in Ukraine symbolizes the use of hybrid methods that can not be assigned to any state. Propaganda and a stateless armed group are causing a hybrid war there. This illustrates the far-reaching power of such hybrid threats as well (Dengg and Schurian, 2015).

2.6.5. Natural Disasters

The picture of natural disasters has changed in recent years. First and foremost, it is not the natural hazard itself that is relevant, but rather the impact of natural disasters on society, the environment and politics. Due to the increasing interconnectedness of society, the effects of natural disasters are becoming globally noticeable. (Fekete, 2018)
Natural disasters do not know any national borders and can, therefore, be a major

threat. Even the indeterminate time of the occurrence of environmental events make it necessary, especially for CIs, to provide protection. Especially earthquakes, storms, and floods are among the most common hazard scenarios. As a result, almost all CI sectors can be hit by natural disasters. This also makes it a particularly incalculable risk. Due to the ongoing global warming future consequences are not yet foreseeable. Therefore, it is important to keep appropriate prevention and prevention strategies up to date. (Bundesministerium des Innern, 2005)
Heatwaves or cold periods regularly disrupt the infrastructure of rail companies in Central Europe. Only with great effort, rail traffic can be reasonably maintained. Natural disasters have an impact on CI in Europe almost every month, whether due to heavy snowfall, heat or volcanic eruptions. (Rossnagel, 2013)

2.7. Cyber Security

With the leap into the *5th Generation Mobile Networks*, a big step towards total connectivity of the society is taking place (Calabuig, Monserrat, and Gomez-Barquero, 2015). At the moment many new *Internet of Things* (IoT) devices are added every day, and that is only the beginning. New technologies such as *Artificial Intelligence* (AI) or *Human Machine Interaction* in which the physical and digital systems progressively blur into each other, open up many new attack points in cyberspace (He et al., 2016). This creates highly networked systems which also link CIs. That is why cyber-security strategies, which contain the latest developments, are becoming increasingly important. In cyber-security, it is necessary to move from reactive politics to a pioneering role in order to ensure the best possible resilience and the most significant protection of CIs and society (Cyber Sicherheit Steuerungsgruppe Österreich, 2018).
The economic and socioeconomic damage can have enormous effects on a state or region. Some companies have already taken this initiative and striving for market

leadership in cyber-security. Best example of *Maersk-Møller* who more than doubled their expenses on cyber-security after the hacker attack in 2017. *Maersk-Møller* believes in a unique selling point through excellent cyber-security.(World Economic Forum, 2018b)

Just as relevant are the national and international directives and strategies to protect the cyberspace in the best possible way. From a private sector perspective, which includes most of the CI operators, there are some initiatives in the PPP network with governments and authorities to promote cyber-security to protect their economy (Cyber Sicherheit Steuerungsgruppe Österreich, 2018). An excellent example is the establishment of a *Global Center of Cyber Security*, initiated by the *World Economic Forum*. There are also *Cyber Security Summits* organized by the *Munich Security Conference* (Munich Security Conference, 2018). This, in many cases, reflects the importance.

Similar to the European area, the number of cyber-crime delicts in Austria increased by approximately 53% between 2016 and 2017, and is growing rapidly. Besides, a considerable number remains in the dark. It is pleasing to sensitize companies to more cyber-security measures so that almost all companies in Austria have increased their spending on this sector or at least remained the same level. (Cyber Sicherheit Steuerungsgruppe Österreich, 2018)

In Austria, government cyber-security is covered by the Europe-wide NIS Directive and a *Cyber Security Strategy*. The following priorities are set (Bundeskanzleramt Österreich, 2018):

- Implementation of the NIS strategy and the launch of *Computer Emergency Response Teams* (CERT).
- A mandatory risk management and reporting obligation of incidents of CI operators.
- Creation of cooperation groups in the European Union and internationally.
- Establishment of a cybersecurity steering group that accompanies the imple-

mentation of the ÖSCS strategy.

- Prevention of cybercrime by *Ministry of Internal Affairs* (BM.I) and *Federal Criminal Police Office* (BKA).
- Setting minimum security standards to define timely responses with stakeholders.
- Creating an annual report from the *Cyber Security Steering Group*.
- Strengthen *Small and Medium-sized Enterprises* (SME) awareness and government support in the development of risk management plans.
- Increasing resilience of CIs by adapting to contemporary security architecture.
- Research and teaching should focus on cyber-security in order to keep up international with its own resources.

Only targeted measures can be used to expand cyber-security in the best possible way, cascade effects are reduced and thus probably well protected for a modern society.

2.8. Cascade Effects

CI is not isolated from others; instead, they are interdependent in complex networks and strategically of enormous importance for social well-being. Often, the word interdependence coincides with CI. Unlike dependency, interdependence work in both directions, forward and backward. This is important, even for operators, to correctly understand the complexity and the effects of interdependency (Macaulay, 2016, p.12). No matter which CI failures, the impact can be seen on CIs. This gets us to the cascade effect, on which can follow an impact on all areas of society quickly. CI and its dependencies are also called *"system of systems"*, which they are. This prevents high order cascade effects on CIs. (Laugé, Hernantes, and Sarriegi, 2015) Many scientists are concerned with the subject of CI dependencies, but they are continually coming up against their limits. Many data from CI are sensitive and therefore not readily accessible to scientists. Research is made even more difficult by the time-dependent dynamic variable to the anyway rare data sets. However, with increasing collaboration between operators, government and science, it is increasingly possible to explore interdependencies and their effects. (Setola et al., 2016) There are differences in the dependencies of two or more CIs (Xu, Wickramarathne, and Chawla, 2016). A distinction is made between the first-order dependency (figure 2.3), which means that "A" directly dependent on "B", so it is a unidirectional relationship. Then there is a second-order dependency, which means that two infrastructures are interdependent whether direct or indirect. Here "B" has a second order dependency on "A". The last case is the interdependency, which has bidirectional relationships between two or more infrastructures. This means that each infrastructure is correlated or dependent on another. (Setola et al., 2016) Often there

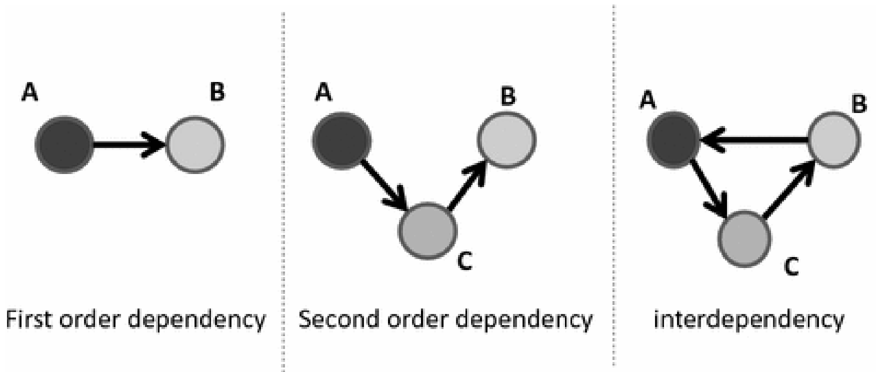


Figure 2.3.: Higher Order Dependency (Setola et al., 2016)

are problems that CI operators do not realize the dependencies of the individual CIs and possible cascade effects. Disturbances caused by dependencies can be divided into 3 classes. Furthermore, depending on the characterization of the infrastructures, dependencies are divided into five different classes. In table 2.4 the classes are listed. (Setola et al., 2016)

Table 2.4.: Failure and Dependency (Porcellinis, Panzieri, and Setola, 2009)

Failure	Dependency
Cascading	Physical
Escalating	Cyber/Informational
Commoncause	Geographic
	Logical
	Social

In order to be able to estimate the influence of disturbances on the infrastructure, it is possible to use different methodologies. On the one hand, there is the holistic approach, which is easily developed by the low abstraction and is therefore strategically oriented as it can be seen in figure 2.4. On the other hand, there are the simulation-based solutions, which can turn an output to an usable operative information (figure 2.4). However, the simulation approach requires very detailed data sets due to represent very detailed models. The problem here is to obtain the required data in the appropriate level of detail which is necessary for a validated simulation. (Papa and Shenoi, 2008)

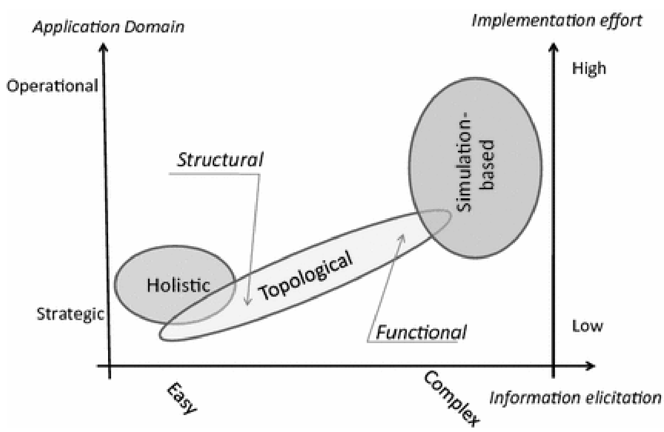


Figure 2.4.: Holistic to Simulation Approach (Setola, 2010)

3. Modeling and Simulation

Looking into the future, making the unpredictable predictable, this is the desire close to every human being. Sounds absurd, but it is feasible. Maybe not in the way it would be desirable, but the approaches are developed and available. Computer games, AI or Scenario Analysis are just a few examples where everyone can look slightly into the future in their own way. This is not magic, it is based on models that can be simulated using mathematics and statistics. (Fenstad, 2018, p.47)
M&S are part of the *Systems Engineering* (Department of Engineering- an Business Informatics, 2016, p.27). In addition, they are the most important interdisciplinary developments of the *third way* science for systems with challenges of high complexity (Fenstad, 2018, p.47). M&S allows a variety of scenarios to be mapped and analyzed over a period of time that would not be feasible in the real world. One particularly noticeable advantage is that non-linear dynamic systems can be calculated within certain boundaries. Thus, nonlinear equations do not serve for long-term forecasts, but rather simulate possible developments of the future. Otherwise, now it is feasible to prepare for possible effects using simulation methods. M&S are at the same time both art and science that makes the methodology very powerful even if they do not depict the "real" reality but represent possible scenarios (Carson, 2005). Especially with the modeling of crisis scenarios there are no independently isolated systems, but only mutually influencing ones (Setola et al., 2016, p.44).
This provides crucial support in creating strategies for crisis management. In addition, it is an important tool to show operators of CIs measures against possible

disruptions or resulting cascade effects. In the further course it helps to continuously develop and improve the existing models. This is why many nations have established authorities that explicitly deal with the M&S of crisis scenarios recently. Science and security agencies work together closely to keep CIP and CIR up to date and prepared for possible scenarios. (Setola et al., 2016, p.45)
There are a lot of M&S paradigms which could be used. Each paradigm has its own functioning and is used for different tasks. Important methods are *System Dynamics M&S*, *Agent-Based M&S* and *Discrete Event M&S*.

3.1. System Theory

Probably every person heard the word *System* in their live. Whether at work, on vacation, in the newspaper, at the university or in education. There are various numbers of systems in diverse kinds and disciplines. But most systems have one common basis, it is an explicit representation that mirrors parts of the reality (Ropohl, 2012, p.52). Ludwig von Bertalanffy (1949) tried something similar in his work *"General System Theory"*, while the definition of *"System Theory"* is also to be traced back to his name (Bertalanffy, 1950). Together with the notion of *Cybernetics* by Norbert Wiener, both concepts, system theory and cybernetics, form the basis of the scientific approach of modern systems theory (Wiener, 2007). Originally, both approaches had no connection to each other. Bertalanffy saws open systems which share an open exchange with their environment in its elaboration. Whereas cybernetics can be seen as a closed, controlled mechanism, which can be described with the mathematical systems theory of technology. Together, both approaches shape the concept of modern systems theory these days. Extensions of the cybernetics represent the system theory 2nd order, self-organization or system dynamics. Important developments of system theory can be seen in table 3.1. Bertalanffy (2017) and Rosnay (2000) show the most important key data of the development in their papers.

Table 3.1.: History System Theory (Bertalanffy, 2017) and (Rosnay, 2000)

Year	Paradigm	Description
1950	Open Systems and General Systems Theory	Based on the concept of Ludwig von Bertalanffy
1950	Cybernetics	Among others, Norbert Wiener and Stafford Beer. Information flow through a system to control itself through feedback mechanisms.
1970	Catastrophe Theory	Based on the mathematical description of sudden changes due to small impulses
1980	Chaos Theory	Describes mathematically non-linear dynamic systems, chaotic movements and attractors
1990	Complex Adaptive Systems	Among others, John H. Holland, W. Brian Arthur. Based on the theory of the Santa Fe Institute and includes topics of emergence, adaptation and self-organization

A system itself consists of components that can interact with each other. There are boundaries around the system which limit the system to the environment. In principle, decentralized systems which are connected to the main system are not uncommon. A system consists of elements which can be seen as building blocks. These elements have properties and functions. For example properties are colors or dimensions. Whereas functions describe the correspondence between two or more elements. The functions are always interact within the framework of the system context. But individual elements can represent their own systems. The links between the individual elements are called relationships. Relationships can be understood in a general sense like material flow, information flow, or other relationships. The basic components of a system are listed below. (Haberfellner et al., 2012)
Basic components of a System: (Bossel, 2013, p.98)

- **State Variables, *q***

  A collection of variables q_1,q_2,...,q_n are called State Variables if:

  - the values of these variables are at time t_0, and
  - the external inputs affect the system for all time $t \geq t_0$.
  - There are enough relationships between variable q_i and external inputs to calculate the value of the variables q_1,q_2,...,q_n for all $t \geq t_0$

  All relevant past information are included in the variable value at t_0. The variables have to be:

  - independent of each other.
  - required to describe a system's state.

- **Parameters, *p***

  System parameters can not be affected by system components because they are properties of the system which can change independently. Independent properties are able to change over time. There are two Parameters. Whereby *Environment Parameters* summarize all external influences which are outside the system boundaries and therefore off-limits to any system component. The other ones are *System Parameters* which are a part of the system and can change independently from any state variable.

- **Intermediate Variables**

  This variables can be *Calculated Parameters* and *State Variables* by implication, this means they are not independent.

- **Input Variables, *i***

  They arise outside the system boundaries for example from other systems. In addition, they summarize all environmental behaviour on a system.

- **Output Variables, *o***

  These Variables summarize all behaviours of a system to the environment outside a system.

- **System Boundary, *o***
  A system boundary is set randomly between the system and its environment. Systems or elements which are located outside the boundaries can influence the system, or the other way around the system can influence the outside elements.

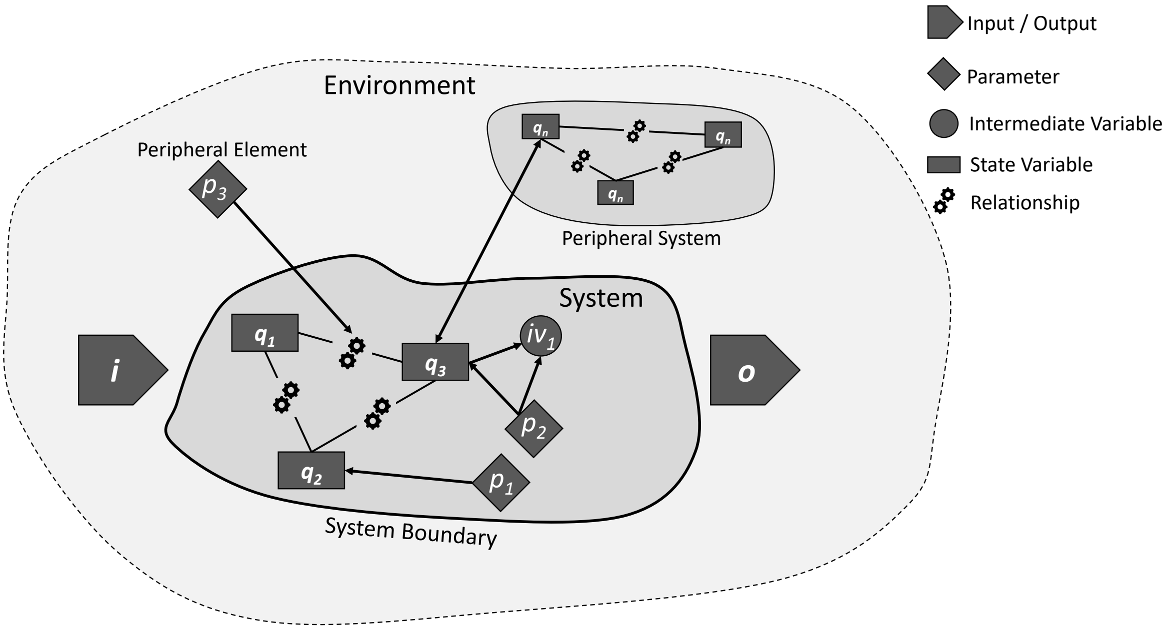


Figure 3.1.: A system and its components referring to (Haberfellner et al., 2012)

A system Structure with its components is shown in figure 3.1. The general system behaviour depends on a few regulations. In general all systems are dynamic and have the ability to change their state over time. It is important to differentiate between observed and internal system behaviour. Because a prediction of the future behaviour of the system is not enough by only regarding the observed behaviour. Due to the fundamental grasp of the system the behaviour and structure is essential to know.

3.2. Cybernetics

The word cybernetics is linked to the name Norbert Wiener (1949). In his book *"Cybernetics, or the study of control and communication in the animal and the machine"* he elucidated the fundamental principles of cybernetics (Wiener, 2007). Due to development on mechanical control systems and communication technology during wartime, Wiener developed his theory of control and organizational relations in systems. The content of cybernetics is control and communication theory, not only in technical artificial systems, but also in evolved natural systems such as societies or organisms. In doing so, the evolved systems set their own goals and will be no longer controlled by their creator. Among Wiener a number of other post-war scientists worked on cybernetics related topics. One result was that the field of cybernetics expanded quickly (Heylighen and Cliff, 2001). Social systems as the basis for Stafford Beer's (1959) development of management cybernetics and his *Viable System Model*, other further developed systems were added over time (Beer, 1959).

In principle, cybernetics is the science to define and understand the functions and processes within a system. Whereby the system has a defined aim which works in circular, causal chains to reach the defined aim through periodically sensing. That means it works like a thermostat. Ongoing feedback loops ensure the self regulation of the system that the set level of value will be reached nonetheless when it has to be lower or higher. In one case it is a positive feedback loop, in the other case it is a negative feedback loop to hold the system in balance. The overall goal of cybernetics is to make systems more effective and efficient. (Umpleby, 2008) Based on Umpley (2008) and Rosnay (2000) the most important developments of cybernetics can be seen in table 3.2. Today, the research approaches are seen more differentiated compared to the original cybernetics idea. Thus, specializations to the individual science fields have formed over time. The development of the original cybernetics has created a powerful mathematical system theory which is

Table 3.2.: History Cybernetics (Umpleby, 2008) and (Rosnay, 2000)

Year	Approach	Scientists
1945	Cybernetics	Norbert Wiener
	Connectionism	W. S. McCulloch et al.
	Information Theory	C. E. Shannon
1950	Control and Feedback Control Systems	
	Computer Architecture and Computer Science	J. Neumann
1956	Artificial Intelligence	J. McCarthy
1959	Management Cybernetics	S. Beer
1960	System Dynamics	J. Forrester
1970	Cybernetics 2nd Order	H. Foerster
1980	Sociocybernetics	
	Biocybernetics	

able to map highly complex and highly networked systems. Recently the focus has been on decision-making and game theory which are primarily concerned with decision-making processes in complex situations of multi-dimensional target levels. Especially for the military and security forces this is of increasing relevance and interest.

3.3. The Art of Interconnected Thinking

Frederic Vester published his book *"The Art of Interconnected Thinking: Ideas and Tools for a New Approach to Tackling Complexity"* in 2007. His work deals with the interconnected approach which implies that there are no self-sufficient regulatory cycles, but interconnected open systems with appropriately connected feedback control whose target values are interdependent. It is crucial how the systems are interconnected. In other words which interactions between the systems exist. They

can be linear or nonlinear, strong, weak, they can suddenly change from support to destruction, and suddenly they can make new connections with entirely different effects. Therefore, every interaction between two systems has its own mathematical dynamics. (Vester, 2007)
In order to map a system-oriented planning and action the biocybernetics rules must be constantly kept in mind. For each new planning process which uses the sensitivity model, the rules represent an evaluation of the feasibility. The feasibility is based on eight rules. According to Vester (2007), to satisfy with these rules results to *"achieving a higher degree of cybernetic maturity"*. These rules are not fictitious but based on basic laws of nature. All rules are considered less as prohibitions but more as an infraction of innovation and therefore they are indispensable for successful management strategies. (Vester, 2007)
The eight basic rules of Biocybernetics according to Vester (Vester, 2007):

- **Rule 1: Negative feedback must dominate over positive feedback**
  Positive feedback puts things in motion due to self-reinforcement. Negative feedback gives stability towards disruption and excesses.
  E.g. Predator and Prey.
- **Rule 2: The functioning of the system must be independent of quantitative growth**
  The flow-rate of energy and matter in viable systems is constant in the long run. This minimizes the influence of uncontrolled crossing of boundaries.
  E.g. a caterpillar which becomes a butterfly instead of a bigger Version of itself.
- **Rule 3: The system must operate in a function-oriented, not a product-oriented manner**
  A corresponding replaceability of the supply increases flexibility and adaptation. The system will continue to exist even when the demand changes.
  E.g. car industry to develop every expertise further instead of building faster and faster cars.

- **Rule 4: Exploiting existing forces in accordance with the jujitsu principle rather than fighting against them with the boxing method**
  External energy is used (energy cascades, energy chains), while internal energy is mainly used as control energy. Using existing forces benefits from current situations and promotes self-regulation.
  E.g. nature and its energy use among photosynthesis and others reaches a high degree of efficiency every engineer would dream of.
- **Rule 5: Multiple use of products, functions, and organizational structures**
  Multiple use reduces throughput, improves interconnectedness and reduces energy, material and information efforts.
  E.g. products and processes that kill several birds with one stone.
- **Rule 6: Recycling: Using circular processes to keep refuse and sewage 'in the loop'**
  Merge initial and final products. Circular material flows. Reversals and dependencies are reduced.
  E.g. the nature does not know waste. The population has to think further in a kind of recycling circle.
- **Rule 7: Symbiosis. Reciprocal use of differences in kind through link-ups and exchange.**
  The symbiosis prefers small processes and short distances. It reduces energy consumption, throughput and external dependency it strengthens internal dependency instead.
  E.g. technical driven symbiosis replace short-sighted exploitation by stable cooperation.

- **Rule 8: Biological design of products, processes, and forms of organization through feedback planning**
  The biological design considers endogenous and exogenous rhythms, uses resonance and function adaptation, harmonizes the system dynamics and facilitates the organic integration of innovative elements according to the eight basic rules.
  E.g. all processes have to be compatible with the biology of humanity and of nature. Most of modern architects only fullfill themselves without taking care of the peoples needs.

The eight basic rules are obligatory for system modeling. Because the systems like for CIs are very complex and interconnected therefore the rules can keep the system simple and manageable. At the same time they form the central element of the *Sensitivity Model* which can be seen in figure 3.2.

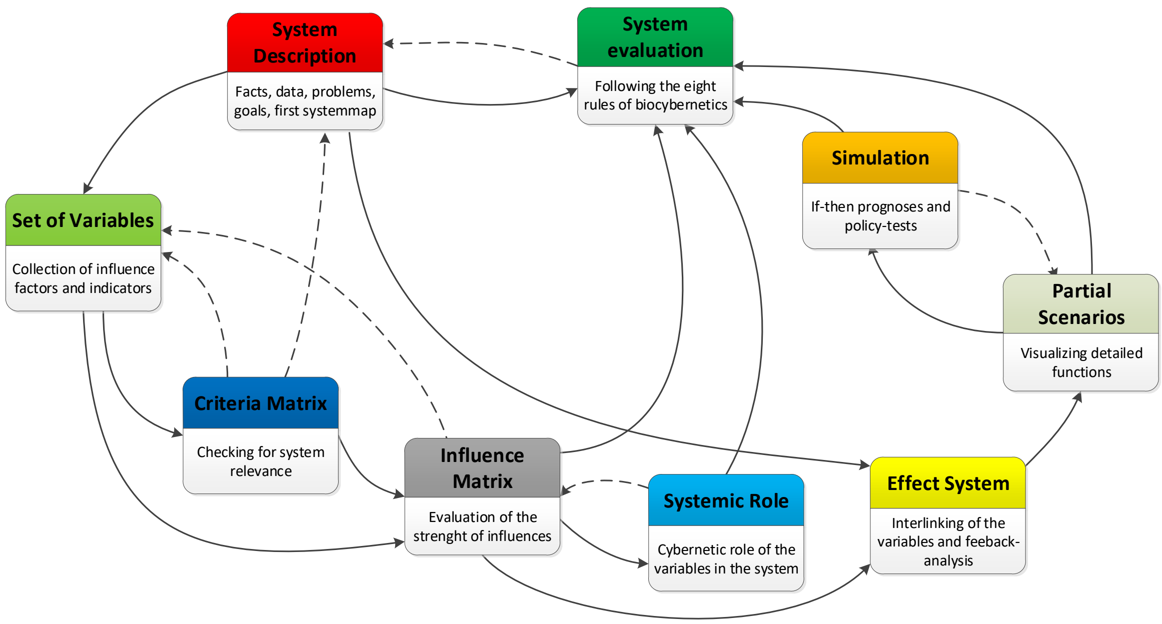


Figure 3.2.: Sensitivity Model (Vester, 2007)

After the first step to synchronize the system description containing goals, facts, problems with the eight rules of biocybernetics it follows the step to set the variables. Therefore, it is important to find plausible characteristics and its indicators. Key areas, factors and drivers which affect the system from inside and outside must be considered as well as recognize important relationships, interactions and dependencies. Ultimately the sum over all factors generates a first draft of relevant influencing variables. An example for Variables of rail cargo is shown in table 3.3.

Table 3.3.: Example on Variables in case of Rail Cargo (Malik Management Zentrum St. Gallen, 2009)

Characteristics	Indicator
Capacity of the rail network	Number of current and possible cargo trains
Amount of terminals	Pricing for cargo transport

The next step is to design a criteria matrix to ensure completeness and relevance of every variable. Each variable is rated with the criteria between 0-not relevant, 0,5-partly relevant and 1-fully relevant. In doing so, the sum of a single variable results in the total relevance of the set variable. However, the sum of a single criteria shows the completeness. A criteria matrix is necessary to create a solid and reasonable foundation of variables for the impact matrix. The concept of a criteria matrix can be seen in figure 3.3. (Malik Management Zentrum St. Gallen, 2009) and (Vester, 2007) To follow the concept of the sensitivity model the influence matrix evaluate the strength of influence concerning the variables. In an influence matrix the level of description of a variable moves to the level of its effect. The result is a matrix in which the effect of every single variable on each other is prompted. During the evaluation process some variables will possibly be redefined. The result is an impact matrix in which the influence index of every variable is calculated to an *Active Sum* (AS) and *Passive Sum* (PS). Dependent on the ratio between AS and PS of a variable it shows information whether the variable is active, reactive, critical or buffering.

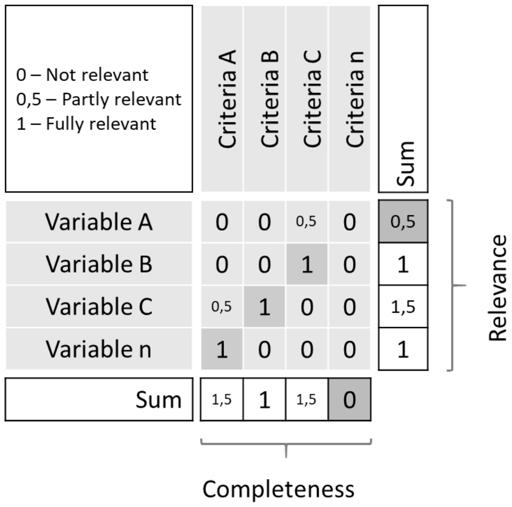


Figure 3.3.: Criteria Matrix referring to (Vester, 2007)

In case of a high active sum this means that there is no need for big changes to trigger new variances in the system model. But if it is a minor sum the variable has to change itself before it will get a great influence on the system model. On the other hand the passive sum provides information how sensitive the variable reacts to changes on the system. A high passive sum means as soon as something happens in the system the variable will change significant.

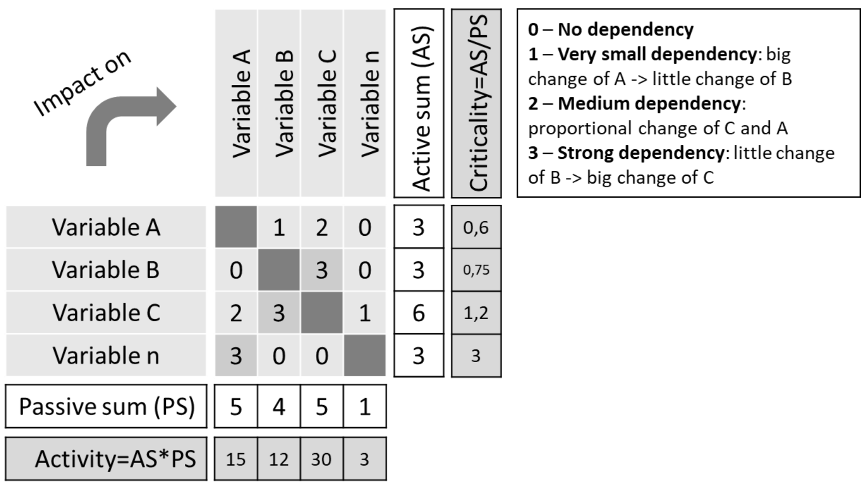


Figure 3.4.: Impact Matrix referring to (Vester, 2007)

If the passive sum is small, the impact on the variable will be the opposite. Figure 3.4 shows an impact matrix concept. (Malik Management Zentrum St. Gallen, 2009) A visualization of the impact matrix is the impact diagram which shows figure 3.5. Below an overview of different types of elements in an impact matrix can be seen: (Vester, 2007)

- **Active Elements**
  which embody control lovers after certain changes they stabilize the system.
- **Critical Elements**
  they give an uncontrolled build up and overbalance.
- **Reaction Elements**
  which are good as indicators and more practicable for symptom solutions.
- **Changes on Buffering Elements**
  have no effect until crossing the given thresholds.
- **Neutral Elements**
  which are good for self regulation not for steering action.

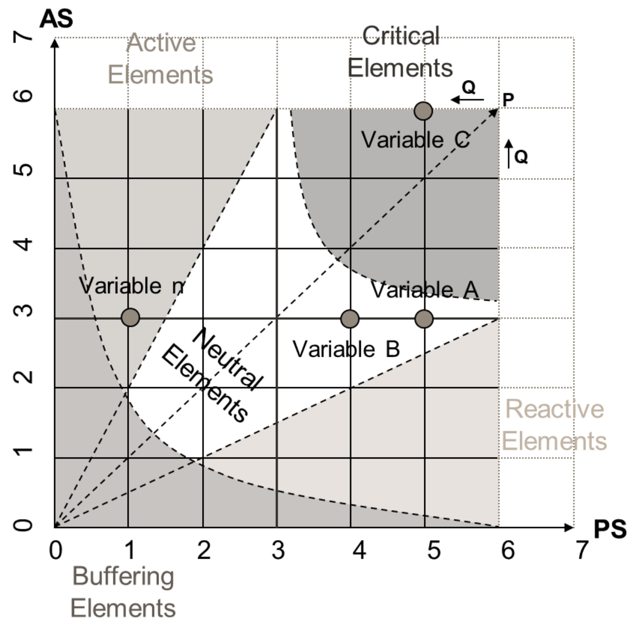


Figure 3.5.: Impact Diagram referring to (Vester, 2007)

3.4. Modeling and Simulation Paradigms

Modeling is a method to map real world scenarios to get a solution for a problem formulation. often it is used instead of expensive prototyping or experimenting. The problem formulation in the real world is mapped into a model in the virtual world. Through analysis and simulation the possible solution will be integrated into the real world. In general, it has to be differentiated between analytical and simulation models. Whereby an analytical model is a static method which depends on input parameters. But a solution can not always be found. In case of a simulation model it shows a dynamic method which contains a set of rules. These rules are responsible for how the current model state will change over time. For problem formulation of high complexity the simulation method is recommended. (Borshchev and Filippov, 2004)
For certain problem formulations at simulation modeling it is important to know the level of abstraction. Due to the abstraction level the most efficient paradigm can be chosen. In this case physical modeling of individual objects with exact characteristics have generally a low level of abstraction. In a higher level of abstraction factory floor or warehouse models can be found because they use average timings. All management or business oriented topics have a high level of abstraction. They work with trends or global feedback and do not consider individual elements like products or vehicles anymore. For problem formulation with this high level of abstraction *System Dynamics* (SD) is usually used as M&S paradigm. (Borshchev and Filippov, 2004) The graphic 3.6 shows the different M&S paradigms. All mentioned paradigms *System Dynamics* (SD), *Agent Based* (AB) and *Discrete Event* (DE) are the most used methods.

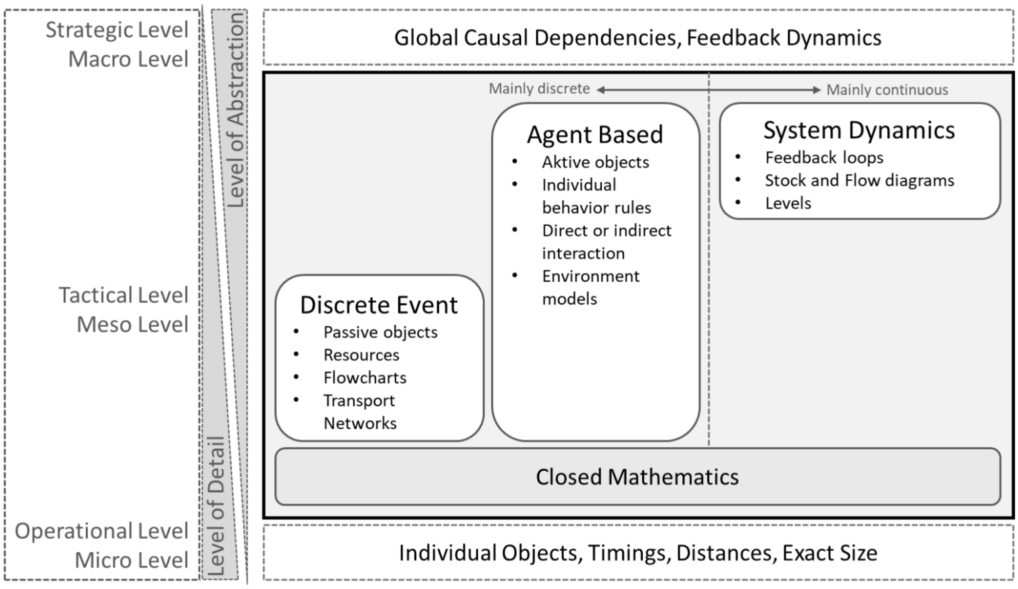


Figure 3.6.: Modeling and Simulation Paradigms (Borshchev and Filippov, 2004)

3.4.1. Agent Based Modeling and Simulation

The roots of Agent Based Modeling lies in the modeling of cellular automata and in certain areas of AI. One of the most well-known developments of a cellular automata is the *"Game of Life"* developed by John H. Conway in 1970. Especially in recent years, the method has been developed further (Bonabeau, 2002). At the moment there are many developments on AB modeling due to its actuality. Often the discussion is about the proper level of detail. But there is simply no right answer. Basically AB modeling can be used universally like for artificial intelligence or game theory models. Agents can have properties among others for example social ability, ability to learn or even intellect. But all AB models have something in common they are all decentralized. This means there is no global system behaviour defined instead the global system is a result of many individual agents (Borshchev and Filippov, 2004). Every agent follows its own behavior rules communicating with each other and with the environment or living together in it. They either physical or virtual and have their own skills. This results in an individual behavior. (Macal and

North, 2013). Due to this agent approach AB is often called bottom-up modeling. All key elements can be found summarized in table 3.4.
Most common software application for AB modeling are among others, Repast, Swarm, Mason, AnyLogic or Netlogo.

3.4.2. Discrete Event Modeling and Simulation

The discrete event system specification was first described in the book *"Theory of Modeling and Simulation"* by Zeigler in 1976. The history of discrete event simulation began with the *Monte Carlo* simulation and the limitations of analytic queuing analysis. This resulted in the four main concepts of DE simulation event scheduling, activity scanning, three-phase approach and process interaction (Zeigler and Muzy, 2017).

Table 3.4.: Key Elements of Discrete Event and Agent Based referring to (Schieritz and Milling, 2003)

Key Parameters	Discrete Event M&S	Agent Based M&S
Basic building block	Block charts	Agent
Unit of analysis	Entities / Resources	Rules
Level if modeling	Micro	Micro
Perspective	Bottom-up	Bottom-up
Adaption	Change of flow	
Handling of time	Discrete	Discrete
Mathematical formulation	Logic	Logic
Origin of dynamics	Events	Events

DE modeling is a traditional M&S method. The building elements are defined through entities and resources. With the help of block charts the entity flow and resource sharing can be described. Whereby entities are passive objects representing people, tasks, etc. Every block is set up with delays, processes, split, combine, etc..

During the simulation the entities will be pushed through the blocks and its given settings. Thereby variables only change at discrete or countable points in time. For that reason DE modeling is often used for manufacturing or logistic issues. A comparison of the key elements of AB and DE is shown in table 3.4. (Borshchev and Filippov, 2004)
Due to the specialization possibility there are various software tools available like Arena, FlexSim, Simul8, ExtendSim or AnyLogic.

Beyond the mentioned M&S paradigms are also some others. Thereby the common approach of SD will be described in detail in Chapter 4. The other M&S paradigms are popular as well but in case of the aim of this diploma thesis they are just mentioned and not described in detail. The M&S Paradigms can be seen in table 3.5.

Table 3.5.: M&S Paradigms (Special Interest Group (SIG) on SImulation and Modeling, 2019)

Nr.	Paradigms
1	Discrete Event M&S
2	Continuous M&S
3	Monte Carlo M&S
4	System Dynamics M&S
5	Gaming-based M&S
6	Agent-Based M&S
7	Artificial Intelligence-based M&S
8	Virtual Reality-based M&S

4. System Dynamics

In today's world, people have tried to solve their real-life problems through counter-measures. But most of the counter-measures are too short-sighted. Villages and cities have been hit by heavy rainfall in recent years. Often, dams were raised along the major rivers to prevent flooding scenarios. At the same time, the economic advantages of rivers should become more profitable. For this reason, many rivers were expanded and straightened. As time passed, the dimension of the measures became visible. After many cities had their flood protection optimized, it resulted in a disaster. The new flood protection worked for the first city and for the second and third, but the flood protection was no longer enough for the fourth city, as floods of water piled up from city to city the protection could no longer be provided. Potential alternative river basins were not constructed. Here, possible cascade effects and impacts on other areas were not taken into account which can have far-reaching consequences to the environment, population and economy.
Forrester (1971) calls this kind of scenarios in his paper "counterintuitive behavior of social systems" (Forrester, 1971a). While people try to stabilize systems they do the opposite due to not minded and unanticipated side effects. For this kind of complex environmental scenario system dynamics aims to be a proper method to solve it sustainable. Therefore system dynamics helps to simulate disaster situations as a tool and to understand dynamic complexity at the same time. One of the difficulties of system dynamics is the interdisciplinary approach. It is more than a technical tool which is able to create mathematical models. It is a tool combining among

others human behavior, physical and technical systems as well as cognitive and social psychology, economics and other ongoing social sciences. Thereby the main building blocks of SD are the theory of nonlinear dynamics and feedback control. Basically SD is able to solve real world problems on a very abstract and strategic level. (Sterman, 2000)

According to world problems like increasing population, increasing pollution and the discussion about renewable and non-renewable resources J. W. Forrester developed the first WORLD model using SD which is also known as WORLD1. He adapted newest data and upgraded the model to a WORLD2 model in 1971. Forrester published the WORLD2 model in the book World Dynamics (Forrester, 1971b). Commissioned by the *Club of Rome* under the scientific direction of Dennis L. Meadows, the WORLD3 model was developed on the basis of Forrester's WORLD2 model (Meadows, Randers, and Behrens, 1972). In 1972 the WORLD3 model was published in the worldwide famous book *"The Limit to Growth"*.

The WORLD models caused a sensation, as it was predicted that the population growth threshold would be exceeded with subsequent collapse, assumed that the attitude of the current population does not change in topics like pollution, growing population, industrialization, globalization or waste of resources. According to this, the model calculates that humanity will face serious ecological problems if the fundamental limits of economic growth are not taken into account. (Meadows, Randers, and Behrens, 1972)

In 1992 and 2004 an update of the WORLD3 model was done to keep the data up to current states (Meadows and Randers, 1992) (Meadows and Randers, 2004). Regardless of various extensions and adaptions of the WORLD3 model the key message even of the WORLD2 model, always was and still is, more or less the same with only a variation of the exact collapse year. The WORLD3 model makes it feasible which highly complex and dynamic models can be simulated by SD.

4.1. The Beginning

Forrester came as an electrical engineer to the MIT in 1939. His research focused on the early stages of hydraulic and electrical feedback control systems for military applications. The system dynamics method was developed by Forrester in the mid-1950s at MIT's *Solan School of Management* (Forrester, 2007). The primary focus of SD is the study of feedback characteristics in the industry such as time delays, organizational structure or policies that can impact the company's success (Borshchev and Filippov, 2004) (Forrester, 1958). The first article *Industrial Dynamics* to SD was published in the *Harvard Business Review* (Forrester, 1958). In addition to Forrester, there were also other innovative scientists who dealt with system theory and feedback structures. These include, among others, Norbert Wiener, John von Neumann, Alan Turing and Gordon Brown (Sterman, 2007).
Under the lead of Forrester a colleague developed the first computer modeling langugage SIMPLE (Simulation of Industrial Management Problems with Lots of Equations). Around the same time and under the same lead, Jack Pugh continued to develop the first system dynamics compiler, known as DYNAMO (DYNamic MOdels). As a result, DYNAMO's expansions have shaped the industry's modeling language for thirty years. (Ford, 1999) (Richardson and Pugh, 2000)
After the publication of *Industrial Dynamics*, which is also considered as the birth of SD, the method became popular especially in management science. Finally, the book *Urban Dynamics* was published in 1969 and caused emotional reactions. Because the publication changed the construction policy of the cities (Forrester, 1969).
The final breakthrough for the SD method was a contact with the *Club of Rome* in 1970. A meeting of the club resulted in discussions about the problems of the world. This resulted in the first model of Forrester WORLD1. The model issues problems such as pollution, waste of resources, global warming and many more. The WORLD2 model was a further development and published in the book *World Dynamics* in 1971 (Forrester, 1971b). On behalf of the *Club of Rome*, the development

from WORLD2 to the WORLD3 model was pushed forward (Meadows and Club of Rome and Potomac Associates, 1974). Meadows was responsible for the further development of the model (Meadows, Randers, and Behrens, 1972). WORLD3 was released in *Limits of Growth* in 1972. The main message of the models were controversially. Thus, a limit of growth is predicted within the next hundred years if nothing changes in the habits of the population. Further developments of the model in 1992 and 2004 did not change the core statement of the model (Meadows and Randers, 1992) (Meadows and Randers, 2004). It always comes down to an overshoot and collapse scenario.

Today, SD is increasingly used by governments, organizations and corporations because complex dynamic real world scenarios can be modeled and simulated (Sterman, 2007). Besides, SD in Business (Business Dynamics) becomes one of the most important methods in modern executive science (Morecroft, 2007, p.xxxii).

4.2. System Thinking

Basically *System Thinking* (ST) is a tool from SD. Therefore ST is used to solve real life problems by applying the concepts of causal relationships and feedback loops. If cause and effect are understood, it is possible to analyze changes in common problem formulations, whether they are temporary or spatial. This is also known as mental modeling. To illustrate the problem formulation accurately it must be understood in a whole. A *Causal Loop Diagram* (CLD) makes this transparent and visible to other stakeholders. (Haraldsson, 2004)

ST has evolved steadily over the last decades, so it increasingly influences science. In doing so, science is primarily engaged with the organization of logic but also with the integration of disciplines. This helps to understand better the relationships and patterns of complex problems. The way ST is used involves systemic or holistic thinking. The approach is based on an understanding of connections and relation-

ships between seemingly isolated elements. In general, ST is, on the one hand, the mental modeling and structuring of logic, on the other, it is the practical application through SD and system analysis. (Haraldsson, 2004)
Basically the population usually uses two types of thinking, event-oriented and ST. Often people are in situations they do not want to be. This results in a discrepancy which has to be solved. The problem is linear, event-oriented thinking (figure4.1) and not thinking in feedback loops. Often, event-oriented thinking do not aspire solution taking organizational and social environment into account it is more like to fix a problem as soon as possible within a vacuum (Morecroft, 2007, p.34). It is assumed that there is a problem and a solution. However, the fact that the solution in turn has an influence on the original starting situation and possibly also other interests involved is rarely considered. One of the most important rules is to understand that problems and solutions coexist - they are interdependent.

Figure 4.1.: Linear Thinking Approach referred to (Sterman, 2000, p.10)

Sterman gave an illustrative example which can be seen in figure 4.2 (Sterman, 2000, p.10). To increase the sales volume of a company the price will be reduced. Now the problem seems solved because more products are being sold. But now, competitors are also starting to lower their prices. The result is a decline in sales due to similar prices of the competitors. From the event-oriented point of view, this was not recognized; only system thinking consider such feedback loops (Morecroft, 2007, p.32). The following figures 4.1 and 4.2 shows Linear vs. System Thinking.

Figure 4.2.: System Thinking Approach referred to (Sterman, 2000, p.11)

4.3. Causal Loop Diagram

A CLD is the tool of a system designer. This allows the most complex issues to be presented in an easy design. Basically, a CLD is made up of the simplest elements. They consist mainly of words, phrases, links and loops and a few special properties to name variables or set the polarity of the loops (Morecroft, 2007, p.39). When looking at a CLD, it becomes clear that the complexity of systems does not depend on individual elements but on the connections between the individual elements. A system can have several thousand loops. The dynamics of these systems arise from the alternating dynamics of the feedback network (Sterman, 2000, p.14). CLDs are mainly used in SD models because they are easy to create and contain much information. Meanwhile, other applications also use CLD to visualize complex problems here, frequent keywords are sustainability or circular economy (Kasonen, 2017).

Feedback connections can vary between two characteristics. The main building blocks of a CLD represent negative and positive feedback arrows as it shows figure 4.3. However, positive or negative feedback loops does not mean criticizing or praising, in the system thinking context is means self-reinforcing or self-correction processes. The constituents of a CLD are variables represented by nouns and causal relationships between them which are basically verbs (Lannon, 2018). Additionally, the causal link may still have a delay, the meaning there is a lag in form of a time component between the two variables.

Figure 4.3.: Causal Loop Diagram Properties referred to (Sterman, 2000)

The arrows indicate the direction - provided with a polarity "+" or "-". A plus signifies a positive feedback and is marked with a "+". It means if variable A is increases, variable B increases as well. Conversely, minus means negative feedback and is marked with a "-". This means instead if variable A increases, variable B decreases (Morecroft, 2007, p.40) (Sterman, 2000, p.139).

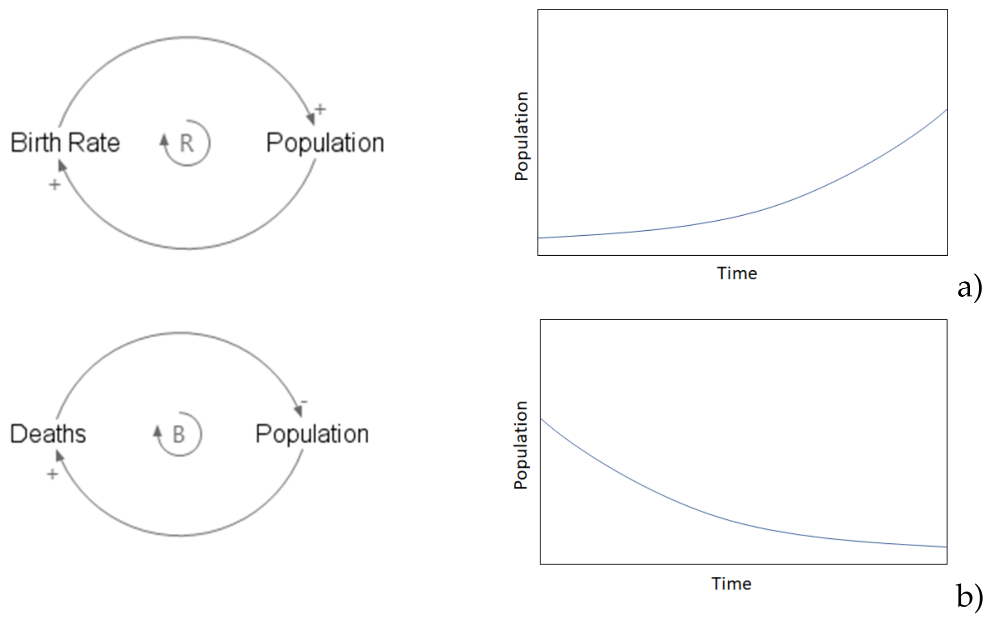


Figure 4.4.: a) Reinforcing Feedback Loop; b) Balancing Feedback Loop; referred to (Sterman, 2000)

As figure 4.4 a) above exhibits a self-reinforcing loop that means all arrows have a positive property. Therefore the variable Population rises over time due to no balancing situation - as is known nothing can grow forever. The reinforcing effect can be seen by the R in the middle of the loop. The opposite situation is shown in figure 4.4 b) that is a typical balancing loop the Population is self-decreasing over time caused by a negative arrow. Therefore it has a B to show the balancing effect of the loop. Every system has to have a balancing loop otherwise it will continuously increase exponentially. By link these both single loops a small system is created.

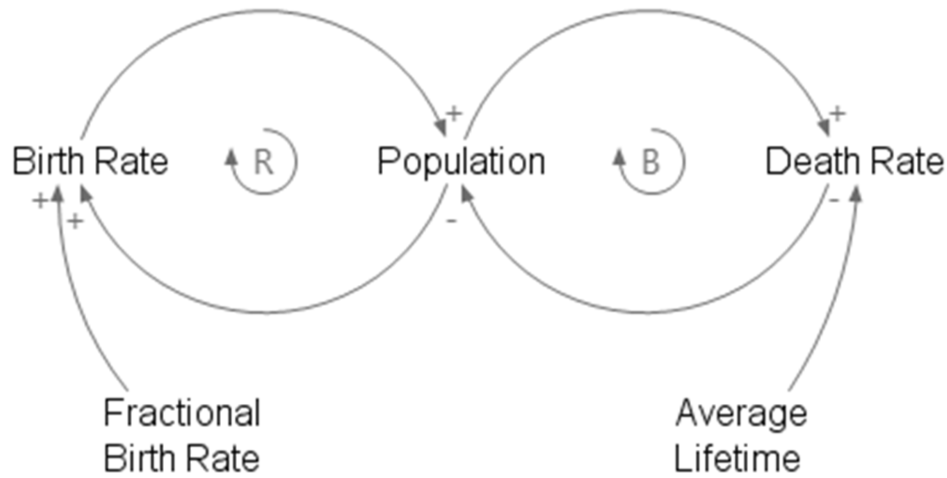


Figure 4.5.: Causal Loop Diagram referred to (Sterman, 2000, p.138)

In the figure 4.5 the positive reinforcing feedback loop influences the Birth Rate which is given by people per year. Due an increasing Fractional Birth Rate the Birth Rate is getting influenced and therefore the Population raises. But nothing is forever and after a while people are going to die. This situation is mirrored in the second negative balancing feedback loop. Thereby the Death Rate - people per year - is dependent on the Average Lifetime of human beings. If the Average Lifetime increases the Death Rate shrinks. However, that figure illustrates very well how small systems can generate dynamic behaviors.

These kind of qualitative models achieving a good transparency and understanding of the feedback processes and interdependencies. They map mental models in the early stage of SD. But they are not suitable for simulation methods due to the missing stock and flow structure.

4.4. Stock and Flow Diagram

Stock and Flow Diagrams (SFD) and feedback processes are the heart of SD. Compared to CLD, the method of SFD describes the real system more detailed. Stocks are accumulations and can reflect the current status of the system at any time. Stocks increase by inflow and drain with outflow. They generate delays while matching the delta between inflow and outflow (Sterman, 2000, p.195). At the same time they represent the dynamic imbalance of a system. In addition, Stocks give systems inertia and memory (Morecroft, 2007, p.59). Flows are nothing but rates. They are adjustable by valves, thus the flow can be limited or increased.
Stocks are displayed by rectangles, inflows and outflows are represented by arrows as is shows figure 4.7. If the arrow points into the stock this means inflow. If the arrow points fromward the stock it is an outflow. To control the flows the valves are added. The clouds are often named source or sink. They represent a flow from outside the model's boundaries. Whereby flows from a source going to be into the Stock and flows from the Stock end up in a Sink cloud. (Sterman, 2000, p.192)

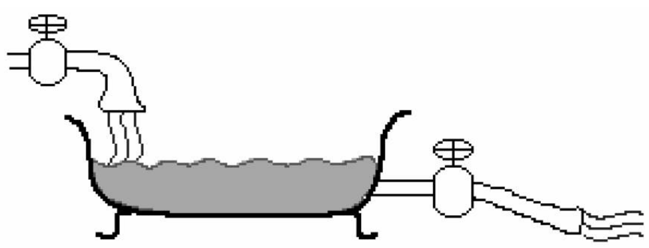


Figure 4.6.: Bathtub as Metaphor (Sterman, 2000, p.194)

A commonly used metaphor that SFD can very well curb is the bathtub in figure 4.6. The bathtub itself is the accumulation of water. The water inflow arises from the tap and the outflow through the drain. As long as the inflow is always more than the outflow, it is possible to bathe in it. However, if the outflow is greater than the inflow, the tub attempt to be empty and that results in accumulation of water. If the bathtub is translated into an SFD, the result is the following scheme 4.7 inclusive all the basic elements and its wording.

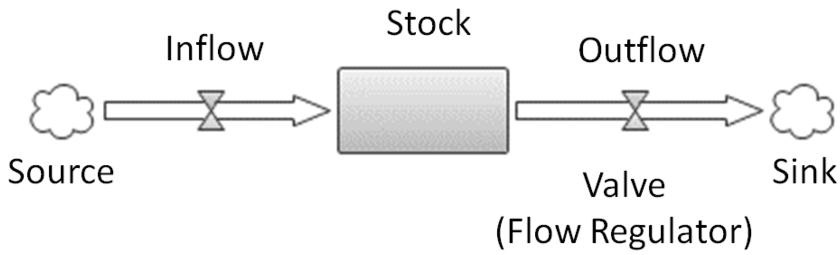


Figure 4.7.: Stock and Flow Diagram referred to (Sterman, 2000)

Mathematically, the following integral (4.1) and differential equation (4.2) results from the SFD.

$$Stock_{(t)} = \int_{t_0}^{t} (Inflow_{(s)} - Outflow_{(s)})\,\mathrm{d}s + Stock(t_0) \tag{4.1}$$

$$\frac{dStock}{dt} = NetChangeInStock = Inflow_{(t)} - Outflow_{(t)} \tag{4.2}$$

During the simulation, the stock can reflect the status of the system at each point. Tracking the status of each stock during simulation provides a good sense of the system behavior. Depending on the simulation method used, additional notations may also be added. The key elements of SD are summarized in table 4.1. The most common software applications for SD are among SIMPLE and DYNAMO, Vensim, Powersim, Studio, Stella, NetLogo and AnyLogic.

Table 4.1.: Key Elements of System Dynamics M&S referring to (Schieritz and Milling, 2003)

Key Parameters	System Dynamics M&S
Basic building block	Feedback loop
Unit of analysis	Structure
Level if modeling	Macro
Perspective	Top-down
Adaption	Change of dominant structure
Handling of time	Continuous
Mathematical formulation	Integral equations
Origin of dynamics	Levels

4.5. Basic Behavior Modes

From the point of view of a modeler, basic behavior modes are important to reduce the complexity in systems. Especially real world problems are usually very complex by itself. Therefore, it is a help for the modeler to have certain basic modes as basic building blocks available (Morecroft, 2007, p.107). The well-known dynamics of the used modes help to build a system more efficient. Especially for qualitative models, the archetypes can be very powerful to describe a system (Cavana and Maani, 2000). They can also help to better understand corporate structures (Morecroft, 2007, p.107). The most fundamental modes are exponential growth, goal seeking and oscillation. All have a simple feedback structure in common. Whereby growth results from positive feedback, goal seeking from negative feedback and oscillation is also created by a negative feedback with a time delay. The other modes are much more complex as S-shaped, S-shaped growth with overshoot and oscillation, and overshoot and collapse arise from non-linear interactions of the feedback structures. The individual behavior modes are described in more detail below. They serve as basic building blocks for models. (Sterman, 2000, p.108)

4.5.1. Exponential Growth

Exponential growth represents a positive feedback loop and is therefore self-reinforcing. This is reflected in an exponential growth graph. The feedback loop can also have negative feedback connections as long as the number of negative feedback connections is even. In figure 4.8 it can be seen if one variable rises, the other variable rises as well. A good example is the birth rate. If this is used in the CLD it means the higher the birth rate, the higher the population and the higher the population, the higher the birth rate. It quickly becomes clear that it will grow exponentially.

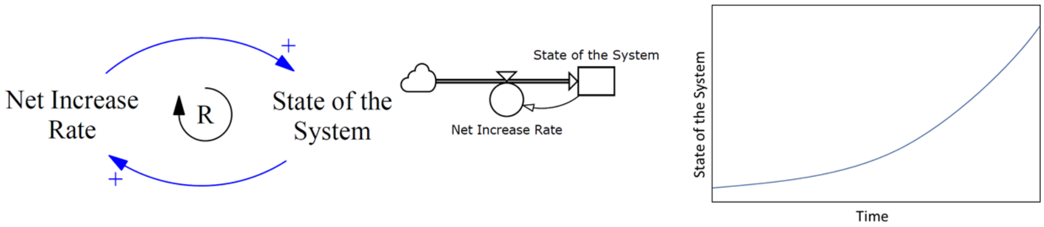


Figure 4.8.: Exponential Growth Mode CLD and SFD (Sterman, 2000, p.109) (Neubacher, 2012)

4.5.2. Goal Seeking

A certain fixed value (goal) is achieved. A certain state of the system is set, which is then compared with the current state. The negative polarity within the feedback loop causes a self correcting state (figure 4.9), which tries to bring the system

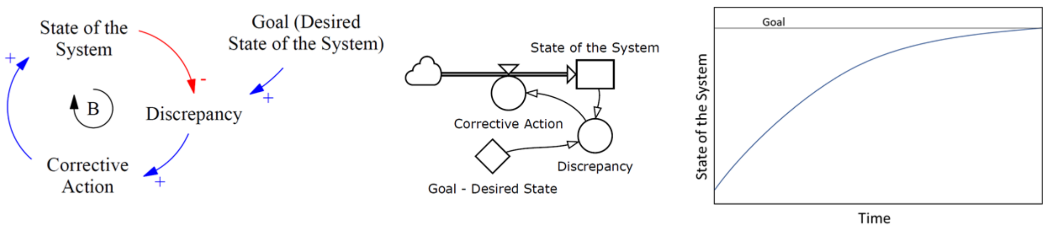


Figure 4.9.: Goal Seeking Mode CLD and SFD (Sterman, 2000, p.111) (Neubacher, 2012)

into equilibrium. At the beginning, the discrepancy between the set and current state is very large and causes a strong increase in the graph. But over the time the discrepancy decreases and the slope becomes smoother and converges to the set goal state.

4.5.3. Oscillation

The oscillating behavior of the model results from the delays between the variables as it shows figure 4.10. Otherwise the structure is the same as that of the goal seeking mode. In this case is also a discrepancy to the set state. In the beginning corrective measures are strong and try to reach the set state. As a result of the delay, the corrective measures are too large and exceed the set state of the system. Therefore, the state must be limited in order to achieve the goal. But due to the delay the value is exceeded again and must be changed again. Depending on the delays, this action can stabilize over a certain period, oscillate at a known frequency, or explode, also known as a chaos scenario.

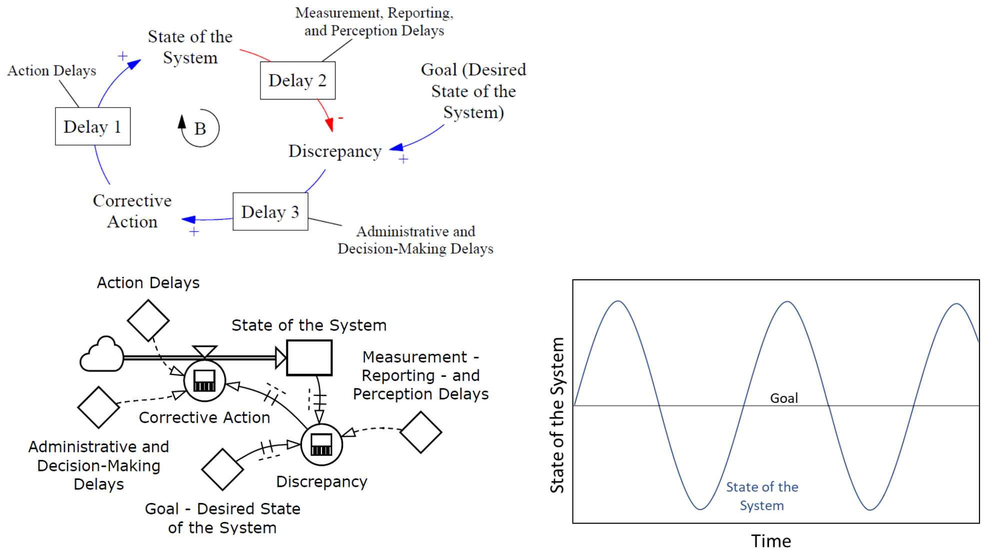


Figure 4.10.: Oszillation Mode (Sterman, 2000, p.114) (Neubacher, 2012)

4.5.4. S-Shaped Growth

The last three models were fundamental models and all are based on a single feedback loop. The following behavior modes are more complex. Nevertheless they are important because they represent real world behaviour very well. Like the s-shape growth shown in figure 4.11. The system consists of a reinforcing loop and a balancing loop which stabilizes the system. A maximum capacity is set, if the current status of the system approaches the limit, the fractional net increase rate shrinks at the same time. Therefore the net increase rate becomes zero when the capacity is reached. At the beginning is an exponential growth until the turning point and then converges to the limit and the system tends to equilibrium. The behavior occurs very often in nature.

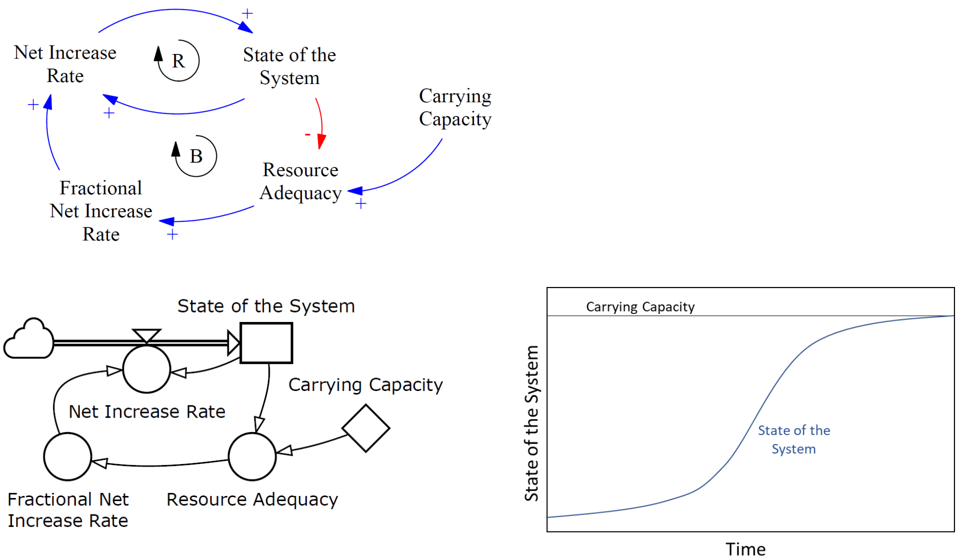
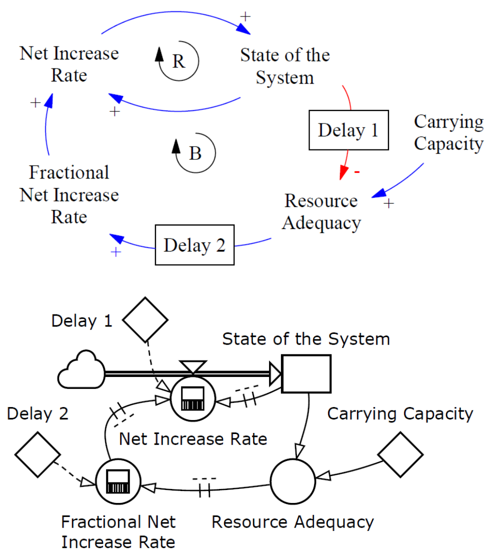


Figure 4.11.: S-Shaped Growth Mode (Sterman, 2000, p.118) (Neubacher, 2012)

4.5.5. S-Shaped Growth with Overshoot

The behavior is the same as that of S-shaped growth (figure 4.11). Delays lead to a later realization of countermeasures. In the graph of figure 4.12, the system behaves in the same way as S-shaped growth and stabilizes after the maximum is exceeded. After that the system is going to oscillate constantly or explode.



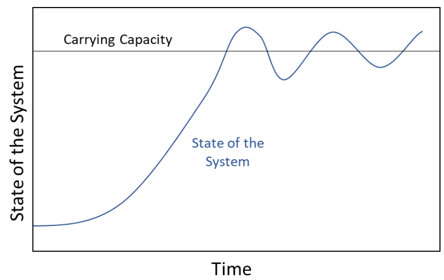


Figure 4.12.: S-Shaped Growth with Overshoot Mode (Sterman, 2000, p.121) (Neubacher, 2012)

4.5.6. Overshoot and Collapse

Here is the assumption within the S-shaped growth (figure 4.11) behavior mode that the carrying capacity is constant over time and does not change anymore. Figure 4.13 contains a second balancing loop, which erodes the capacity. In the beginning the growth is exponential similar to the S-shaped growth. Instead of a regulation that would keep the system in an equilibrium, the second loop begins to reduce the capacity. After a period of time, the net rate of increase is zero, since the current state corresponds to that of the capacity. When the graph reaches the maximum, the erosion is at the maximum and the carrying capacity shrinks very quickly. Due to the negative adequacy of the resources, the net rate of increase will also be negative and the system will continue to decrease. This behavior is known from the famous WORLD (chapter 4) model.

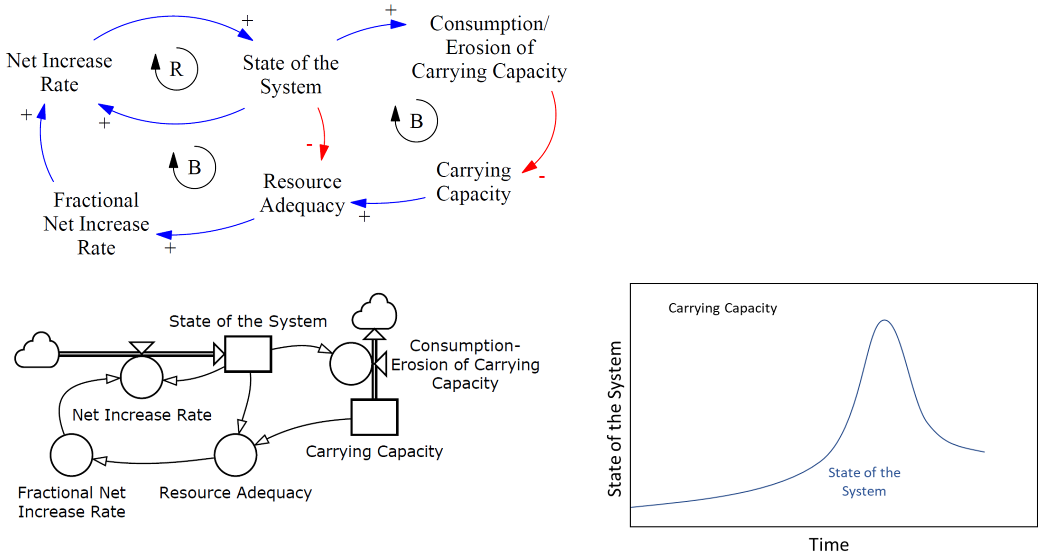


Figure 4.13.: Overshoot and Collapse Mode (Sterman, 2000, p.123) (Neubacher, 2012)

5. Modeling Critical Infrastructure

Blackout, hackers, terror, natural disasters - these are all scenarios that are very in common at the moment. They determine everyone's life in some way. Fortunately, reports on the scenarios mentioned rarely in the Austria region. Internationally, things look quite different. Almost every day one of these scenarios can be seen on TV. Europe will not be spared. Even if most scenarios were not bad enough, they usually have far-reaching consequences.
In 2006 everything began quite harmless, a power line should be switched off in the north of Germany. In this case, another power line should compensate certain capacities. But a failure caused due to a violation of the *(n-1)* criteria that the limit voltage of the power line has been reached and the emergency shutdown began. Within seconds it came to the same effect on power lines which tried to absorb the increased voltage in turn - thereby the transformer station disconnected the grid to prevent damage. Still within seconds after the first shutdown, the network agencies emergency program began to work and the power grid was separated into individual clusters to prevent further spread. Now the northeastern power grid cluster increased the grid frequency, the southwestern line cluster, however, recorded an underfrequency which could not be compensated. The consequence was widespread power outages in south-south-western Europe. Especially in Austria the Consequences were alarming, as there was a too high grid frequency in eastern Austria and a too low frequency in the western part. The power grids in Austria were clustered to prevent a collapse of the network, too. While in the east power

plants had to be taken off the grid, pumped storage power plants were activated in the west and large consumers were taken off the grid in some cities. The measures that were taken caused by power failures ranging from several seconds to several minutes. Finally, after a few attempts, it was possible to reconnect the network 45 minutes later. The power outage had far-reaching consequences, above all for rail traffic and major consumers. On the basis of this scenario it seems obvious how quickly a human caused error influenced half of Europe's power grid. However, consequences and the economic damage caused by the blackout is not negligible. This explains how complex the power grid is and what depends on it. (Bundesnetzagentur Deutschland, 2007)

Nowadays, the society's physical and economic health depends on CI networks. Different CI sectors represent the entirety of the network. The national security of states rests on the foundation of highly interdependent CIs (Rinaldi, 2004). All together they form large-scale, complex and interdependent networks. A disruption or an attack can have devastating consequences (Min et al., 2007). That is why it is very important to maintain CI's ability to model. Whether individually or collectively. Modeling efforts have to be organized to avoid double effort and to ensure capabilities (Adam, 2008). To build these models and to analyze them can be very challenging due to rare data sets, complicated infrastructures, regulations, ongoing CI development and a various number of stakeholders (Min et al., 2007). But in an increasingly fast-paced world, M&S becomes a necessity to provide CI with the best possible protection while increasing resilience at the same time (Setola et al., 2016, p.78). It is important not to act reactively, but to stay one step ahead to maintain the security level for business and society at all times. That is what M&S methods are all about.
An illustrative example of this is the recent possibility of analyzing socioeconomic effects on growth and development, which are caused by natural hazards (Salaza,

Díaz, and López, 2016).

But before the modeling process can even begin, it must be clear who and what counts as CI and which critical services they provide. In cooperation with the BVT, it became clear that the scope of CI is often underestimated. This makes a general listing of all sectors and the associated essential services essential for strategic planning. Only in this way it can be guaranteed that existing CIs also identified as such infrastructures in a country.

5.1. Sectors and Essential Services

The identification of essential and digital services and their operators is one of the most important tasks in dealing with CIs. Once each country has its own guidelines and definitions the first step is to get an overview of the country's CIs. From the multitude of infrastructures in a country some turn out to be critical and some less critical. For example, the *European Directive 2016/1148*, also known as the *NIS Directive*, includes an identification of operators of essential and digital services. According to the guideline, they should underlie to a reporting obligation and meet certain security requirements. The reporting obligation includes serious security incidents. (The European Parliament, 2016)

In figure 5.1 is an overview of the classification of essential services and sectors. That the essential services are set first and then the allocation of the sectors happens. This would represent a buttom-up principle. The buttom-up approach makes services much more accessible, in the way that it is easier to rethink the impact of scenarios instead of deduce essential services from top-down. Due to the large number of essential services of a country, such an approach can fill databases easily. Therefore the degree of detail plays a major role. It is important to achieve a proper level of detail. Because after setting the essential services there is still a more detailed structure behind - down to objects and facilities. The definition of the Elements:

- **Sector**
  ″A sector is an overall term for different categories which ensures the economical and political functionality within a society.″
- **Subsector**
  ″A subsector split up the sector in single product lines, services or supply activities.″
- **Essential Service**
  ″All essential services together provides the functionality of the subsectors. Behind every essential service a provider must be given.″

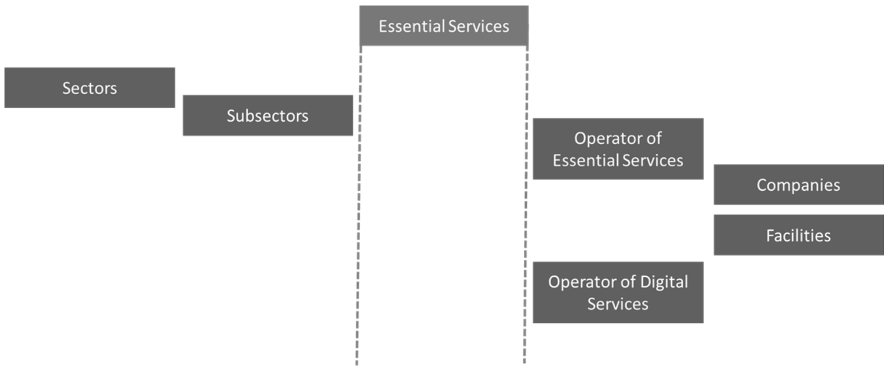


Figure 5.1.: Structure of Sectors and Essential Services

In Appendix A the whole structure of the *CI Sector List* is available. Here, in figure 5.1 just a small part of the *Electricity Supply* can be seen. Behind every service several companies are listed to maintain the supply. The list is adapted for Austrian conditions. For example open sea infrastructure like harbors or submarine facilities as well as nuclear energy producer are out of interest and therefore not critical in Austria.

In Austria the BVT identified four different risk scenarios on CI. However, other countries, extend the risk scenarios on a wide range. This has to do with the political and geographical orientation of a nation. Thus, Austria differentiates natural catastrophes, cyber-threats, and man-made threats - strategic thinking and without intention. The listed services and sectors are regarded as critical. Thus they are

Table 5.1.: CI Sector List: Structure of Electricity Supply

Service	Essential Service	Subsector	Sector
Generating plant	Electricity production	Electricity supply	Energy
Combined heat and power plant			
Decentralized energy production facility			
Storage facility			
Bundling of electric capacity			
Transmission network	Power transmission		
Electricity trading			
Power grid	Distribution of electricity		
Measuring site			

particularly worth of protection against the mentioned threats. The basis structure of the *CI Sector List* is based on the German BSI Law (Deutscher Bundestag, 2015). But to cover all sectors, the list has been expanded and supplemented. Additional sectors and their essential services were included in literature or discussion rounds of the *International Infrastructure Resilience Conference*, *Munich Security Conference* or the *World Economic Forum*. The following part (section 5.1.1 and 5.1.2) describes the sectors water and energy more detail. They also serve as orientation for the later following M&S framework of CI.

5.1.1. Sector Energy

The energy sector was already one of the most important infrastructures in Austria and will become increasingly important. Especially due to digitization, networking in the energy sector will also increase constantly. Due to the critical nature of the sector, it is particularly worth of protection.

- **Electricity Production**
  Electricity Production ensures the security of electricity supply to the population using the electricity grid. At the same time, the further development towards the smart grid era increases digital interconnectivity. This applies to power transmission as well as power generation. Since the population is directly dependent on electricity supply, this area is absolutely critical.
- **Gas Supply**
  Gas continues to be a widely used energy source. Many households use gas as a heating medium. Production, transport via pipelines and distribution make gas easily accessible. Combined with the explosion potential of gas, gas supply is critical.
- **Oil Supply**
  Heating oil for heating systems, fuel for motor vehicles, airplanes and ships and as an additive for many other products, oil is not called black gold without a reason. The oil supply is particularly affected. Especially the patrol station infrastructure and oil reserves are to be particularly emphasized. Due to its extreme dependence, oil supply is a CI.
- **Heat Supply**
  Especially due to the expansion of district heating networks, heat supply is becoming more and more important for the population's well-being. Therefore this area can be also seen as critical.

5.1.2. Sector Freshwater Supply and Distribution

Freshwater and supply is a life-sustaining sector. Supplying the population with freshwater is essential in a modern society. In Austria, drinking water is supplied exclusively by springs and groundwater. This of course makes them to key elements in water supply. Wastewater treatment is also very important for sustainability. Therefore the sewage network plays an important role in maintaining hygienic standards. Due to global warming and increasingly water scarcity, easy access to freshwater can become a serious problem in the future.

- **Sewage Disposal**
  Sewage disposal is very important for the population to prevent diseases and increase well-being. Especially the sewage network and the pumping stations offer easy targets to cause unnoticed damage. Sewage treatment plants should have an emergency power supply to bridge short power failures effortlessly. In order to maintain the hygienic standard of the population, this area is classified as critical.
- **Drinking Water Supply**
  Drinking water supply is one of the vital sectors. Even the springs, the distribution network and the water tanks are considered to be strongly critical. With simple measures damage could be done very easily. Pumps are also dependent on the power grid again, which means they are connected to another critical infrastructure. Hence, possible cascade effects have to be taken into account.

The *CI Sector List* makes clear how many different CIs exist. Many of them are interdependent and can easily trigger unpredictable cascade effects. Not every sector or essential service is critical to the same degree. In order to analyze this more closely, it is necessary to create an impact matrix to determine the criticality of each sector.

5.2. Impact Matrix

If the essential services list is translated into a matrix form, an impact matrix is generated. The essential services list can be seen similar to a criteria matrix. Since the list contains only critical and therefore important elements.

Impact on ->	Electricity production	Power transmission	Distribution of electricity	Gas production	Gas transport	Distribution of gas	Oil production	Oil transport	Distribution of oil	Generation of district heating	Distribution of district heating	Air transport	Rail transport	Water transport	Road transport	Public transport	Logistics	GPS Navigation	Hospitals	Life-Sustaining Medical - Production	Life-Sustaining Medical - Deliver	Medicines and Blood and Plasma - Production	Medicines and Blood and Plasma - Distribution	Medicines and Blood and Plasma - Deliver	Laboratory Diagnostics - Transportation	Laboratory Diagnostics - Analytics	Municipal drainage	Sewage treatment and water discharge	Sewage Disposal - Controlling and monitoring	Drinking Water Supply - Extraction	Drinking Water Supply - Conditioning	Drinking Water Supply - Distribution	Drinking Water Supply - Controlling and monitoring	Voice- and Data Communication - Access	Voice- and Data Communication - Transfer	Voice- and Data Communication - Switchboard	Voice- and Data Communication - Control	Housing	IT-Hosting	Trust services	Authorization of a withdrawal	Bring-in the payment transactions	Debit customer account	Cash logistics	Card-based Payment - Authorization	Bring-in the payment transactions	Debit customer account	Acceptance of a transfer or direct debit	Contribution to payment transactions	Bring-in the payment transactions	Offsetting securities and derivative transactions	Booking securities	Booking money	Use of insurance services	Food production and treatment	Food retail	Crop farming	Livestock farming	Fishing and aquaculture	Forestry
Electricity production		3	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Power transmission	1		3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Distribution of electricity	1	1		2	2	2	2	2	2	2	2	2	3	1	2	2	2	0	3	2	0	3	1	0	1	3	1	3	1	2	2	1	1	3	3	3	3	3	3	1	3	1	1	1	1	1	1	1	1	1	1	1	1	1	3	2	2	2	1	1
Gas production	1	0	0		3	3	1	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gas transport	0	0	0	2		3	0	0	0	2	2	0	0	1	1	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Distribution of gas	2	0	0	1	1		0	0	0	2	2	0	0	2	2	2	2	0	2	1	1	1	1	1	1	2	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	1
Oil production	0	0	0	0	0	0		2	2	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
Oil transport	0	0	0	0	0	0	0		2	0	0	2	2	2	2	2	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
Distribution of oil	0	0	0	0	0	0	1	1		1	1	3	3	3	3	3	3	3	2	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	2	0	0	0	0	0	0	0	0	0	0	1	2	2	1	2	2
Generation of district heating	0	0	0	0	0	0	0	0	0		3	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Distribution of district heating	0	0	0	0	0	0	0	0	0	1		0	0	0	0	0	0	0	2	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Air transport	0	0	0	0	0	1	0	1	1	0	0		1	1	1	1	2	1	2	0	2	0	2	2	2	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	1
Rail transport	0	0	0	0	0	0	0	2	1	0	0	1		1	1	1	1	1	0	0	2	0	2	2	2	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	1
Water transport	0	0	0	0	0	0	0	2	1	0	0	1	1		1	1	1	1	0	0	2	0	2	2	2	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	1
Road transport	0	0	0	0	0	0	0	2	1	0	0	1	1	1		1	1	1	2	0	2	0	2	2	2	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	0	0	0	1
Public transport	0	0	0	0	0	0	0	0	0	0	0	3	3	2	3		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Logistics	0	0	0	0	0	0	0	2	2	0	0	3	3	3	3	3		0	2	0	2	0	2	2	2	0	0	1	0	0	0	0	0	2	2	2	1	1	1	1	0	0	0	2	0	0	0	0	0	0	0	0	0	0	1	2	1	1	1	1
GPS Navigation	0	0	0	0	0	0	0	0	0	0	0	2	2	2	2	2	2		1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1
Hospitals	0	0	1	0	0	1	0	0	0	2	2	1	0	0	2	0	2	0		2	2	2	2	2	3	2	2	1	2	2	2	1	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	2	0	0	0	0
Life-Sustaining Medical - Production	0	0	2	0	0	2	0	0	0	0	0	1	1	1	1	1	1	1	2		3	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Life-Sustaining Medical - Deliver	0	0	1	0	0	2	0	0	0	0	0	2	2	2	2	2	2	2	3	1		1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medicines and Blood and Plasma - Production	0	0	2	0	0	2	0	0	0	0	0	1	1	1	1	1	1	1	2	2	1		1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Medicines and Blood and Plasma - Distribution	0	0	1	0	0	2	0	0	0	0	0	2	2	2	2	2	2	2	3	1	1	1		1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medicines and Blood and Plasma - Deliver	0	0	1	0	0	2	0	0	0	0	0	2	2	2	2	2	2	2	3	1	1	1	1		1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Laboratory Diagnostics - Transportation	0	0	1	0	0	2	0	0	0	0	0	2	2	2	2	2	2	2	3	1	1	1	1	1		1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Laboratory Diagnostics - Analytics	0	0	2	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	2	0	0	0	0	0	1		1	1	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Municipal drainage	1	1	2	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2	0	0	0	0	0	0	0		2	2	2	2	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	1	1	0	0
Sewage treatment and water discharge	1	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	2		2	2	2	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	1	1	0	0
Sewage Disposal - Controlling and monitoring	1	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2		2	2	2	2	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Drinking Water Supply - Extraction	1	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2	2	2		2	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Drinking Water Supply - Conditioning	1	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2	2	2	2		2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	1	1	0	0
Drinking Water Supply - Distribution	1	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2	2	2	2	2		2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	1	1	0	0
Drinking Water Supply - Controlling and monitoring	1	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2	2	2	2	2	2		1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Voice- and Data Communication - Access	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Voice- and Data Communication - Transfer	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2		2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Voice- and Data Communication - Switchboard	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2		2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Voice- and Data Communication - Control	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2		2	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Housing	0	0	1	0	0	1	0	0	1	0	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	1	0	0	1	0	0	0	2	2	2	2		2	2	1	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0
IT-Hosting	0	0	1	0	0	1	0	0	1	0	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	1	0	0	1	0	0	0	2	2	2	2	2		2	1	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Trust services	0	0	1	0	0	1	0	0	1	0	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	1	0	0	1	0	0	0	2	2	2	2	2	2		1	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Authorization of a withdrawal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		2	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bring-In the payment transactions	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2		2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Debit customer account	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2		2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cash logistics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2		2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Card-based Payment - Authorization	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		2	2	0	0	0	0	0	0	0	0	0	0	0	0	0
Bring-In the payment transactions	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2		2	0	0	0	0	0	0	0	0	0	0	0	0	0
Debit customer account	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2		0	0	0	0	0	0	0	0	0	0	0	0	0
Acceptance of a transfer or direct debit	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		2	2	0	0	0	0	0	0	0	0	0	0
Contribution to payment transactions	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2		2	0	0	0	0	0	0	0	0	0	0
Bring-In the payment transactions	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2		0	0	0	0	0	0	0	0	0	0
Offsetting securities and derivative transactions	0	0	1	0	0	1	0	0	1	0	1	1	1	1	1	1	1	1	1	0	1	0	0	1	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		2	2	2	0	1	1	1	1	1
Booking securities	0	0	1	0	0	1	0	0	1	0	1	1	1	1	1	1	1	1	1	0	1	0	0	1	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2		2	2	0	1	1	1	1	1
Booking money	0	0	1	0	0	1	0	0	1	0	1	1	1	1	1	1	1	1	1	0	1	0	0	1	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2		2	0	1	1	1	1	1
Use of insurance services	0	0	1	0	0	1	0	0	1	0	1	1	1	1	1	1	1	1	1	0	1	0	0	1	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2		0	1	1	1	1	1
Food production and treatment	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		2	2	2	2	0
Food retail	0	0	1	0	0	0	0	0	1	0	0	1	1	1	1	1	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1		2	2	2	0
Crop farming	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		3	1	1
Livestock farming	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2		0	1
Fishing and aquaculture	0	0	1	0	0	0	0	0	1	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1		0
Forestry	0	0	1	0	0	0	0	0	1	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	

Figure 5.2.: Impact Matrix 60x60

When creating the impact matrix, a suitable level of detail must be selected. If a matrix is at the essential service level, it will generate a 79 x 79 matrix from the current list of essential services. In addition a logical and comprehensible filling is only possible with a team of experts. After all, knowing and assessing influences of the individual sectors on other sectors is only possible through various disciplines. If the opportunity of a team of experts is not given, a matrix based on approximation through literature, logic, comprehensible assumptions, own expertise and expert interviews can be created.

The overall aim of an impact matrix is to outline critical elements and interdependencies of the sectors. This makes it possible for certain CIs to increase the protective measures accordingly to cause a suitable level of protection. Thus, objects that are particularly worthy of protection are highly sensitive, since they have many intedependencies and, in the event of an disruption, have long-range cascade effects. The question above all: can critical elements become even more critical?

In figure 5.2 is an impact matrix with a size 60x60 essential service level. As already mentioned it is nearly impossible to fill the matrix without a team of experts. For the level of impact numbers between 0 and 3 have been chosen.

To achieve a suitable impact matrix on a strategic level it makes sense to choose the detail level of subsectors. In this case, a more definite statement has to be made, because at the strategic level it is no longer just about the direct technical influence, but rather the logical influence of the infrastructures on each other. This is shown in figure 5.3. In figure 5.3 can already be seen which elements are very active and which are more passive. In reverse, which elements are active and which are reactive. If both active and passive sum are very small, they are more likely to be buffering elements. If both values are very high, that means the opposite, and the elements are very critical and can have a big impact on the system through small variances.

Impact on -->	Electricity supply	Gas supply	Oil supply	Heat supply	Passenger services	Cargo Services	Transportation Infrastructure	In hospital health care	Supply of directly life-sustaining medical devices	Supply of prescription medicines and blood and pla	Laboratory diagnostics	Sewage disposal	Drinking water supply	Voice- and data communication	Data storage and computing	Financial services	Food supply	Agriculture	Government	Public safety	Community Services	Active Sum
Electricity supply	0	1	2	2	2	2	3	3	2	2	3	3	2	3	3	2	1	1	1	2	1	**41**
Gas supply	1	0	1	3	1	1	1	2	0	0	2	0	0	1	1	0	1	0	2	1	0	**18**
Oil supply	1	1	0	3	3	3	1	2	1	1	0	0	0	1	1	0	2	3	1	3	2	**29**
Heat supply	2	2	2	0	1	0	1	3	0	0	1	0	0	1	1	0	0	2	1	1	0	**18**
Passenger services	2	3	3	0	0	1	2	1	2	2	0	0	2	2	1	1	2	2	2	3	2	**33**
Cargo Services	1	2	2	1	1	0	1	2	2	2	1	1	1	1	1	1	3	2	1	1	1	**28**
Transportation Infrastructure	0	1	1	0	2	2	0	3	2	2	1	0	0	1	1	2	3	1	2	2	2	**28**
In hospital health care	2	1	1	1	1	1	1	0	3	3	3	3	3	3	3	2	2	1	0	2	2	**38**
Supply of directly life-sustaining medical devices	0	0	0	0	3	1	1	3	0	1	3	2	1	1	1	1	0	0	0	2	0	**20**
Supply of prescription medicines and blood and plasma concentrates	0	0	0	0	3	1	1	3	1	0	3	2	1	1	1	1	0	0	0	2	0	**20**
Laboratory diagnostics	2	1	0	1	0	2	2	3	3	3	0	2	1	1	1	1	0	0	0	1	0	**24**
Sewage disposal	3	1	1	2	1	1	1	2	0	0	2	0	3	1	1	1	0	2	1	1	2	**26**
Drinking water supply	2	0	0	0	2	1	1	3	2	2	3	2	0	1	1	1	2	3	2	2	2	**32**
Voice- and data communication	2	2	2	2	3	2	2	3	1	1	2	1	1	0	3	3	2	1	3	3	2	**41**
Data storage and computing	2	1	1	0	3	2	2	3	1	1	1	0	0	3	0	3	1	0	3	3	1	**31**
Financial services	3	3	3	2	3	2	2	1	1	1	2	1	1	1	1	0	2	1	3	2	2	**37**
Food supply	0	0	2	0	2	1	1	2	0	0	2	0	2	0	0	3	0	3	2	3	2	**25**
Agriculture	3	1	2	1	1	2	1	0	0	0	2	2	2	1	1	3	3	0	2	3	2	**32**
Government	2	2	2	2	2	1	2	1	1	1	2	2	3	3	3	3	3	2	0	3	3	**43**
Public safety	3	3	3	1	3	1	2	3	2	2	1	0	3	2	2	1	3	2	3	0	1	**41**
Community Services	2	2	1	2	1	2	2	2	1	1	2	2	2	0	0	0	1	0	2	2	0	**27**
Passive Sum	**33**	**27**	**29**	**23**	**38**	**29**	**30**	**45**	**25**	**25**	**36**	**23**	**28**	**28**	**27**	**29**	**31**	**26**	**31**	**42**	**27**	

Figure 5.3.: Impact Matrix

5.2.1. Time Factor

The matrix in figure 5.3 shows a current state. This means that the impact matrix is considered according to the current aspects. Let's assume that cargo services are currently neutral elements, right at the beginning of a blackout scenario (t_0). But after just a few days, the supply in all sectors can no longer be guaranteed, so Cargo Services shifts after a certain period of time into the critical area. Thereby a value of five days (t_5) is considered as an appropriate time horizon.

In order to take the time influence into account, the impact matrix is assigned with an additional time factor. This time factor is based on a Sigmoid function. It is not based on a linear time behavior because that would mean that a value of an element could theoretically be randomly high. But since an already strong element dependency can not become infinitely dependent, therefore the Sigmoid function sets the maximum limits. Figure 5.4 shows the graph of the function 5.1.

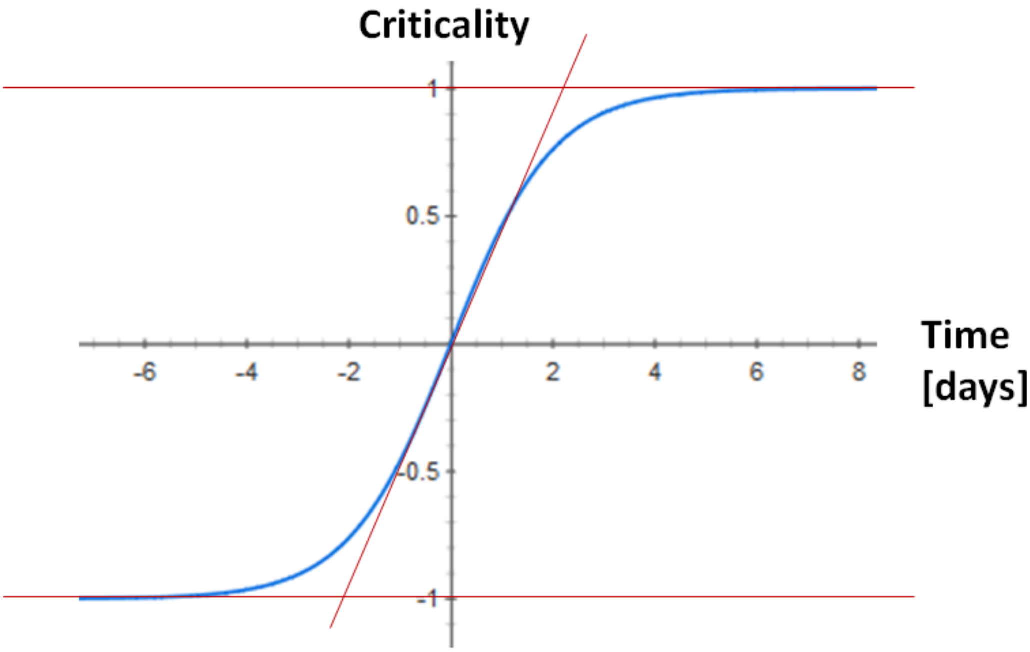


Figure 5.4.: Sigmoid Function

$$\text{Sigmoid Function: } f(x) = (\frac{2}{1+e^{-x}}) - 1 \tag{5.1}$$

Since it does not stay with a simple impact matrix to model the dependencies, it involves the creation of a database. Due to the database, there are easier ways to determine multiple numerical values and links. In order to adapt in the time variable stored Sigmoid function to the database, the original function has been adapted. Thus, the function for the value of the long-term impact (t_5) is given in equation 5.2.

$$\text{Long-Term Impact: } C(x) = k + (\frac{2}{1+e^{-x}}) - 1 \qquad (5.2)$$

Where:

- k...dependency value at t_0; $[0;3]$
- $X = t * \frac{10}{4}$...time impact; $[-1;1]$
- t...time value at t_5; $[-1;2]$
- C...long term impact; $[0;4]$

A second impact matrix was created for all t. The temporal influence is estimated in the matrix now. Thus, the influence and the impact on the criticality will decrease over time (-1), no change (0), will increase over time (1) and will increase very strong over time (2). It is also assumed that in the previous evaluation [0;3] the maximum achievable value may not exceed 4 in the long-term impact, otherwise the ration would no longer be logical. In addition, the time factor may not result in a total negative number. Otherwise that would mean that a CI would suddenly no longer be critical.

For this reason, the time variable t gets a factor of $\frac{10}{4}$. This has proven to be a reasonable factor after a few attempts. The result is represented by the variable X. The variable k is the value of the original impact matrix at point t_0. The Sigmoid function is added to this value. The end result for a third impact matrix at point t_5 is the sum of k and the Sigmoid function. The sum for the long-term impact is represented by C.

Figure 5.5 shows a section of the database. In Appendix B the full database can be found. This results in two impact matrices which must be filled with values, for this again it is important to work together with expert teams to generate a reasonable and coherent matrix. The third matrix is determined using the Sigmoid function.

In figure 5.5 two colored cells can be recognized. The grayed cell means a zero, since electricity supply on electricity supply has no dependencies. The red cell is the carryover. This means, whenever a zero appears in column k, it will also be noted as zero in column t.

Impact	on	k at t0	t	X	Time imp.	C at t5
Electricity supply	Electricity supply			0	0	0,00
Electricity supply	Gas supply	1	1	2,5	0,848284	1,85
Electricity supply	Oil supply	2	1	2,5	0,848284	2,85
Electricity supply	Heat supply	2	2	5	0,986614	2,99
Electricity supply	Passenger services	2	0	0	0	2,00
Electricity supply	Cargo Services	2	1	2,5	0,848284	2,85
Electricity supply	Transportation Infrastructure	3	2	5	0,986614	3,99
Electricity supply	In hospital health care	3	2	5	0,986614	3,99

Figure 5.5.: Database Table

Because it was assumed that only dependencies $k > 0$ at the point t_0 are provided with a long-term impact. This simplification was adopted to slip not into the negative area.

As already mentioned, the red marked cells in figure 5.6 implies a zero due to an equivalent zero cell in figure 5.3. The data input for both matrix happens via the database. Both matrix tables are linked to the data. To create the rating for the impact matrix t, the same expert team is needed, that worked already on the first impact matrix, assumed such a team is available. This kind of collaboration and expert teams are strongly recommended for public authorities or other security companies.

Now, the filled in value for the impact matrix (figure 5.6), the filled data of the database for impact matrix k (figure 5.3) and t (figure 5.6) in combination with the adapted Sigmoid function (5.2) results in impact matrix C (figure 5.7).

Impact on -->	Electricity supply	Gas supply	Oil supply	Heat supply	Passenger services	Cargo Services	Transportation Infrastructure	In hospital health care	Supply of directly life-sustaining medical devices	Supply of prescription medicines and blood and pla	Laboratory diagnostics	Sewage disposal	Drinking water supply	Voice- and data communication	Data storage and computing	Financial services	Food supply	Agriculture	Government	Public safety	Community Services
Electricity supply	0	1	1	2	0	1	2	2	0	0	0	1	2	2	1	1	1	0	0	0	0
Gas supply	1	0	1	2	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Oil supply	1	1	0	2	2	2	1	1	1	1	0	0	0	0	0	0	0	1	1	2	0
Heat supply	2	2	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0
Passenger services	0	0	1	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	1	0	1
Cargo Services	2	2	2	1	1	0	1	2	2	2	2	0	1	1	1	2	2	1	0	1	1
Transportation Infrastructure	0	0	0	0	2	2	0	2	1	1	1	0	0	0	0	1	2	1	1	2	1
In hospital health care	1	0	1	1	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	1	0
Supply of directly life-sustaining medical devices	0	0	0	0	0	1	1	1	0	1	1	0	0	0	0	0	0	0	0	1	0
Supply of prescription medicines and blood and plasma concentrates	0	0	0	0	0	1	1	1	1	0	1	0	0	0	0	0	0	0	0	1	0
Laboratory diagnostics	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0
Sewage disposal	1	0	0	0	0	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0
Drinking water supply	0	0	0	0	1	1	1	2	1	0	0	-1	0	0	0	0	0	1	1	1	1
Voice- and data communication	0	0	0	0	1	2	2	1	0	0	0	0	0	0	0	2	0	0	0	0	0
Data storage and computing	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Financial services	1	1	1	0	1	2	2	1	1	1	0	1	1	1	1	0	1	1	1	1	1
Food supply	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	0
Agriculture	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	1	0	0	1	1
Government	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	1	0	0	0	1	1
Public safety	1	1	1	1	1	1	2	1	1	1	0	0	1	1	1	1	1	1	1	0	1
Community Services	0	0	0	0	0	1	2	0	0	0	0	1	1	0	0	0	0	0	1	1	0

Figure 5.6.: Impact Matrix t

5.2.2. Criticality

As already mentioned in chapter 5.2.1 the values filled in are usually positive. Normally the criticality increases with the duration. But there are also exceptions, where the criticality decreases over time. In that case a minus value occur. This is the case between Drinking Water Supply and Sewage Disposal. At point t_0 it will be critical, because the sewage disposal is not available. However, during passing time, the sewage network will not be used anyway. Due to the disruption alternatives has been set up already.

Long term impact -->	Electricity supply	Gas supply	Oil supply	Heat supply	Passenger services	Cargo Services	Transportation Infrastructure	In hospital health care	Supply of directly life-sustaining medical devices	Supply of prescription medicines and blood and plasma c	Laboratory diagnostics	Sewage disposal	Drinking water supply	Voice- and data communication	Data storage and computing	Financial services	Food supply	Agriculture	Government	Public safety	Community Services	Active Sum
Electricity supply	0,0	1,8	2,8	3,0	2,0	2,8	4,0	4,0	2,0	2,0	3,0	3,8	3,0	4,0	3,8	2,8	1,8	1,0	1,0	2,0	1,0	**52**
Gas supply	1,8	0,0	1,8	4,0	1,0	1,8	1,8	2,8	0,0	0,0	2,0	0,0	0,0	1,0	1,0	0,0	1,0	0,0	2,0	1,0	0,0	**23**
Oil supply	1,8	1,8	0,0	4,0	4,0	4,0	1,8	2,8	1,8	1,8	0,0	0,0	0,0	1,0	1,0	0,0	2,0	3,8	1,8	4,0	2,0	**40**
Heat supply	3,0	3,0	2,8	0,0	1,0	0,0	1,0	3,8	0,0	0,0	1,0	0,0	0,0	1,0	1,0	0,0	0,0	2,0	1,8	1,0	0,0	**23**
Passenger services	2,0	3,0	3,8	0,0	0,0	1,0	2,8	1,0	2,8	2,8	0,0	0,0	2,0	2,0	1,0	1,0	2,0	2,0	2,8	3,0	2,8	**38**
Cargo Services	2,0	3,0	3,0	1,8	1,8	0,0	1,8	3,0	3,0	3,0	2,0	1,0	1,8	1,8	1,8	2,0	4,0	2,8	1,0	1,8	1,8	**45**
Transportation Infrastructure	0,0	1,0	1,0	0,0	3,0	3,0	0,0	4,0	2,8	2,8	1,8	0,0	0,0	1,0	1,0	2,8	4,0	1,8	2,8	3,0	2,8	**39**
In hospital health care	2,8	1,0	1,8	1,8	1,0	1,8	1,8	0,0	3,8	3,8	3,0	3,0	3,0	3,0	3,0	2,0	2,0	1,0	0,0	2,8	2,0	**45**
Supply of directly life-sustaining medical devices	0,0	0,0	0,0	0,0	3,0	1,8	1,8	3,8	0,0	1,8	3,8	2,0	1,0	1,0	1,0	1,0	0,0	0,0	0,0	2,8	0,0	**25**
Supply of prescription medicines and blood and plasma concentrates	0,0	0,0	0,0	0,0	3,0	1,8	1,8	3,8	1,8	0,0	3,8	2,0	1,0	1,0	1,0	1,0	0,0	0,0	0,0	2,8	0,0	**25**
Laboratory diagnostics	2,0	1,0	0,0	1,0	0,0	2,8	2,8	3,8	3,0	3,8	0,0	2,0	1,0	1,0	1,0	1,0	0,0	0,0	0,0	1,0	0,0	**27**
Sewage disposal	3,8	1,0	1,0	2,0	1,0	1,8	1,0	2,8	0,0	0,0	2,0	0,0	3,8	1,0	1,0	1,0	0,0	2,0	1,0	1,0	2,0	**29**
Drinking water supply	2,0	0,0	0,0	0,0	2,8	1,8	1,8	4,0	2,8	2,0	3,0	1,2	0,0	1,0	1,0	1,0	2,0	3,8	2,8	2,8	2,8	**39**
Voice- and data communication	2,0	2,0	2,0	2,0	3,8	3,0	3,0	3,8	1,0	1,0	2,0	1,0	1,0	0,0	3,0	4,0	2,0	1,0	3,0	3,0	2,0	**46**
Data storage and computing	2,0	1,0	1,0	0,0	3,0	3,0	3,0	3,0	1,0	1,0	1,0	0,0	0,0	3,0	0,0	3,0	1,0	0,0	3,8	3,0	1,0	**34**
Financial services	3,8	3,8	3,8	2,0	3,8	3,0	3,0	1,8	1,8	1,8	2,0	1,8	1,8	1,8	1,8	0,0	2,8	1,8	3,8	2,8	2,8	**53**
Food supply	0,0	0,0	2,0	0,0	2,8	1,8	1,8	2,8	0,0	0,0	2,0	0,0	2,0	0,0	0,0	3,0	0,0	3,8	2,8	3,8	2,0	**31**
Agriculture	3,0	1,0	2,8	1,0	1,0	2,8	1,8	0,0	0,0	0,0	2,0	2,0	2,0	1,0	1,0	3,0	3,8	0,0	2,0	3,8	2,8	**37**
Government	2,0	2,0	2,0	2,0	2,8	1,0	2,8	1,8	1,0	1,0	2,0	2,0	3,0	3,0	3,0	3,8	3,0	2,0	0,0	3,8	3,8	**48**
Public safety	3,8	3,8	3,8	1,8	3,8	1,8	3,0	3,8	2,8	2,8	1,0	0,0	3,8	2,8	2,8	1,8	3,8	2,8	3,8	0,0	1,8	**56**
Community Services	2,0	2,0	1,0	2,0	1,0	2,8	3,0	2,0	1,0	1,0	2,0	2,8	2,8	0,0	0,0	0,0	1,0	0,0	2,8	2,8	0,0	**32**
Passive Sum	**40**	**32**	**37**	**29**	**46**	**44**	**46**	**59**	**33**	**33**	**40**	**25**	**33**	**32**	**30**	**34**	**36**	**32**	**39**	**52**	**34**	

Figure 5.7.: Impact Matrix C

Now, the active and passive sums from the impact matrix k (figure 5.3) and C (figure 5.7) are presented in an impact diagram (figure 5.8) to understand the criticality of each subsectore better.

As it can be seen on the graphic 5.8, there are small blue dots and small red dots. Each subsector is represented by a blue dot at the point t_0. The red dots characterize the subsectors by taking into account the time variables. The orange arrows indicate the direction of the movement. There are striking movements, very well recognizable by a long arrow which grow very critical within five days. Public Safety, Cargo Services, In Hospital Healthcare, Transportation Infrastructure and Financial Services are particularly noticeable.

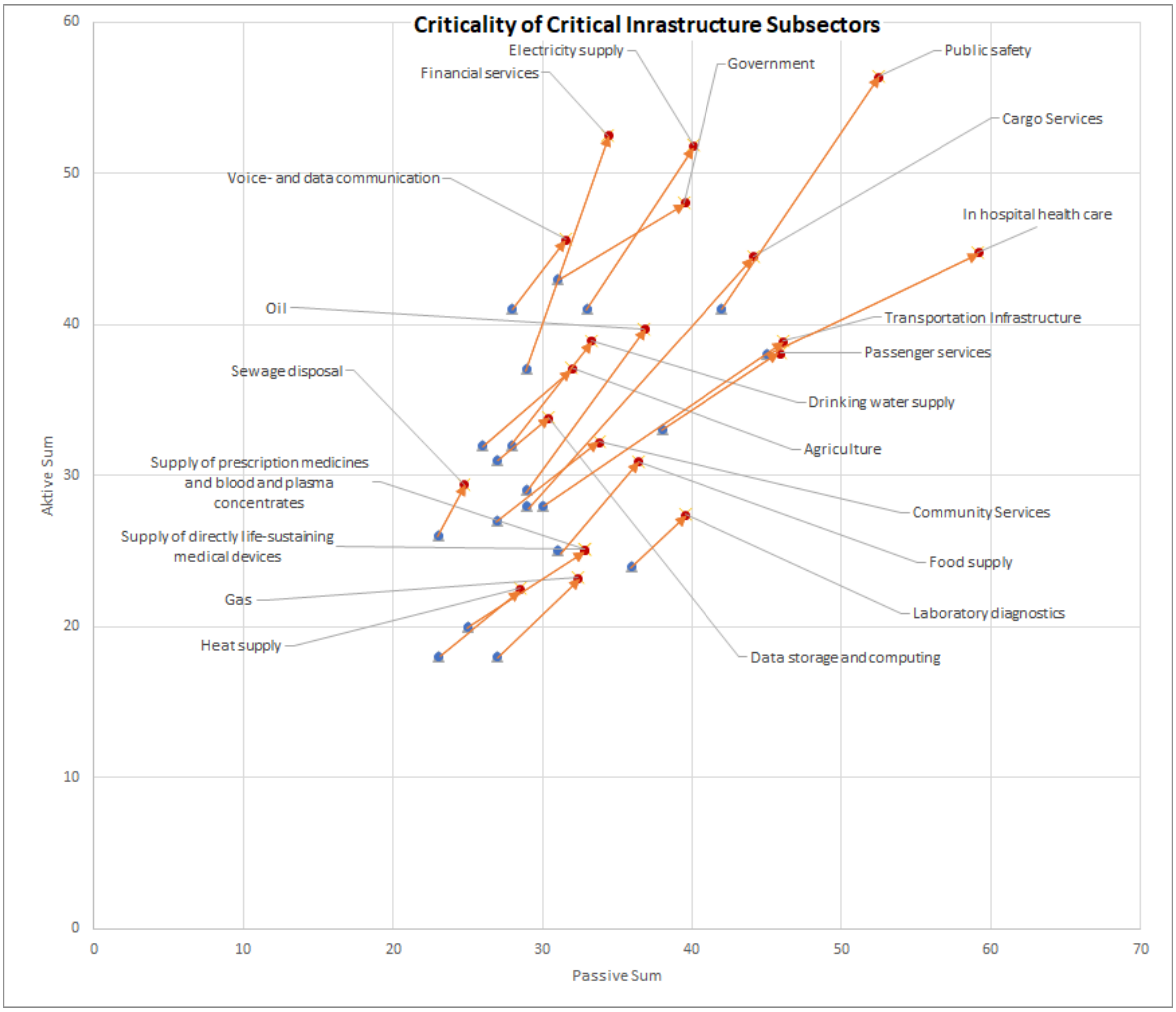


Figure 5.8.: Impact Diagram Critical Infrastructure

If the mentioned sectors are considered more accurate, it becomes apparent that the plausibility is given.

- **Public Safety**
  The longer a crisis scenario lasts, the more critical Public Safety becomes. Already in a minimum of time it can cause dissatisfaction within the population. Especially, if access to food, electricity or water is limited or not guaranteed at all. Most of the security forces are also involved in crisis situations mainly with clarification of the situation, which can lead to an increase in crime. Last but not least Public Safety has far reaching interdependencies with other sectors.

- **Cargo Services**
  Again, the significance of Cargo is shown. By very strong connections to almost all sectors. Nearly every sector depends on cargo logistics. Especially after the consumption of reserves, the criticality increases significantly.
- **In Hospital Healthcare**
  In general, hospital healthcare is classified as very critical straight from the beginning. In most cases, the impacts of a crisis scenario are directly noticeable. It does not matter whether injured people, not functioning technology or lack of medication. The longer an exceptional situation lasts, the more critical the healthcare supply for the population becomes. In addition a hospital is strongly dependent on other sectors.
- **Transportation Infrastructure**
  There are strong parallels to cargo services. This time the "stations" and their connections to each other are affected. Above all, it affects air, rail, water, road, satellite and public transportation infrastructure. Alone the large number of different infrastructures indicates strong dependencies with other sectors. In addition, the criticality increases over time, since even short failures of the transport infrastructure can lead to very strong cascade effects, from rescue helicopters to super-carriers.

Figure 5.9 shows the impact diagram of the large impact matrix (figure 5.2). This was filled with the help of literature, historical data, own knowledge and logical assumptions. Therefore, the matrix does contain some blur. This could only be prevented with a team of experts. Despite everything, a trend analysis is recognizable by accurate work. If the large diagram (figure 5.9) is compared with the small one (figure 5.8), same elements with same orientation will occur. Thus, hospitals in both matrix are classified as particularly critical. Likewise, electricity supply is one of the more critical elements as well as Logistics or Cargo. In addition, in both diagrams

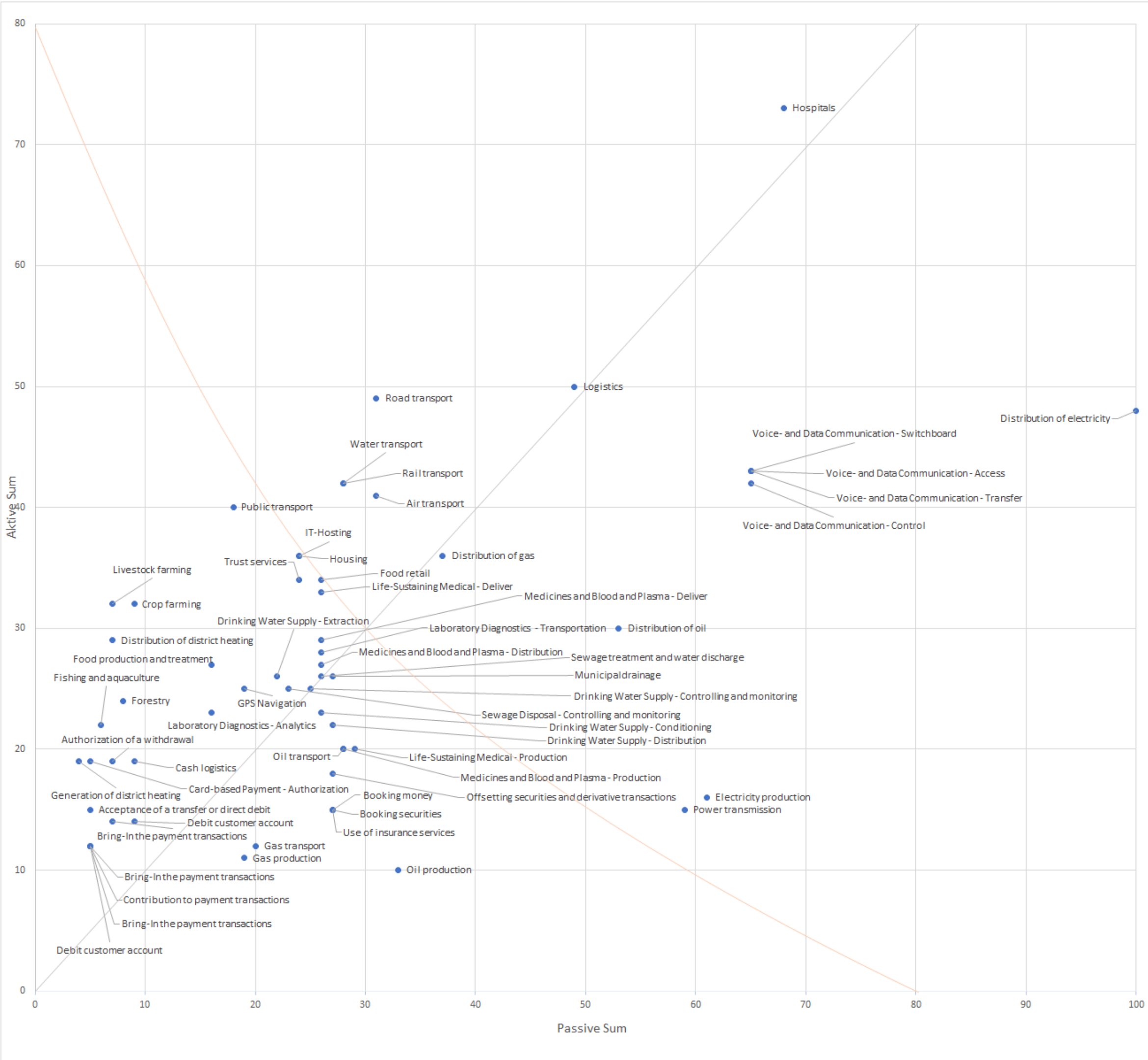


Figure 5.9.: Impact Diagram Critical Infrastructure Sectors

the elements of the neutral zone are similar. Thus, it can be concluded that a first trend analysis is available even without a team of experts. For a more competent statement, a team of experts must be consulted. In both cases the plausibility must be checked and questioned successively. In this case, both diagrams have similar results independently, which is an indication of a meaningful trend analysis, which can serve as a data base for further processing.

5.3. Modeling Critical Infrastructure

When it comes to the designing process of a model it is important to see the key elements of the system, but to think creative, to rethink well established structures reaches at least the same importance as the key elements. Exactly that is the innovative approach which systems necessarily need.

> *"...designing is one of the key disciplines and drivers to success in a cross-disciplinary environment. To think creative and and rethink the world. Basically everybody can learn something from design thinking..."*
>
> *Prof. Peter Kelly, 2017, Aalto University*

Particularly in highly complex and highly interconnected infrastructures, some of them turn out to be critical in order to preserve the social well-being and a working economy of a country. In order to better represent cascade effects and possibly even find new cascade effects, *System Dynamics* turns out to be an appropriate tool. Information that can only be obtained through appropriate modeling and simulation. Based on the results feedback structures, cascade effects and involved elements can be identified very easily. Therefore System Dynamics will be used in the further course to model and simulate a *CI Case*. In this *CI Case* the sectors water and energy are used for a representative model in order not to exceed the scope of what is practicable. Therefore is important to analyze the current research findings through literature in order to simplify the modelling process. In this case, a student task for the present *CI Case* was also created, which should show difficulties in the modelling process, but also first drafts for possible solutions. The final part includes the critical infrastructure model for water and energy.

5.3.1. Application of System Dynamics for Critical Infrastructure

In the field of modelling and simulation of critical infrastructures in the water and energy sectors there are some scientific papers. These serve as a basis for the further modelling process. Thus only *System Dynamics* papers are listed. Below in the table 5.3.1 the most important publications can be seen. Most of the papers have their focus on *Causal Loop Diagrams* as well as *Stock and Flow Diagrams* of CI.

Table 5.2.: Literature of the CI Sector Energy and Water

Title	Author	Keywords
A Simulation Framework for Integrated Water and Energy Resource Planning (2007)	Robert F. Jeffers	SFD Model of Riversystem; Input/Output parameters for Watersystem; Water Resource Planning; Water - Energy Model
A Framework for Analysis of Energy-Water Interdependency Problems (2011)	Robert Jeffers; Jacob J. Jacobson; Kristyn Scott	Coupling of Agriculture and Hydrology System; SFD of Agriculture Sector; SFD of Reservoir System; Only Hydrologic Components Modeled
Toward modeling and simulation of critical national infrastructure interdependencies (2005)	Hyeung-Sik J. Min; Walter Beyeler; Theresa Brown; Young Jun Son; Albert T. Jones	CLD of Critical Infrastructure; IDEFØ Diagram of Interdependencies; SFD of Power Generation
Modeling and Simulating Critical Infrastructures and Their Interdependencies (2004)	Steven M. Rinaldi	Factors Affecting Interdependencies Analyses; Physical and Virtual Component Description

System Archetypes in the Conceptualization Phase of Water-Energy-Food Nexus Modeling (2016)	S. A. Sohofi; A. Melkonyan; C. K. Karl; K. Krumme	Qualitative SFD of Water-Energy-Food; Used Archetypes for Conceptualization phase; Extended Limit to Success Diagram of Water-Energy-Food
A System Dynamics Approach to Integrated Waterand Energy Resources Management (2014)	Yilin Zhuang (Dissertation)	CLD Limits of Growth of Water and Energy supply; CLD and SFD of Water and Energy Sector
Water Cycle Analysis System Dynamics Model for Designing Optimal Water Reclamation Scheduling (2012)	Shinsuke Takahashi	Overall Water Energy Cycle Graphic; SD Model Analyzing Water Flow with/without Treatment; SD Model Energy Consumption
A System Dynamics Model for Integrated Water Infrastructure Asset Management (2015)	A. Ganjidoost; C. T. Haas; M. A. Knight; A. J. A. Unger	CLD of Asset Management; SD Model of Consumer/Public Policy Sector; Test Methods for SD Model Validation; SD Model of Water and Finance
A System Dynamics Model for the Simulation of the Management of a Water Supply System (2015)	Suwan Park; Vahideh Sahleh; So-Yeon Jung	CLD Relationships Among Components of the Water System; SD Model of Water Supply; CLD of Water Resource Management
The Use of System Dynamics Simulation in Integrated Water Resources Management (2007)	Ines Winz; Gary Brierley	SFD of Urban Water System; CLD on Water Quality

There are two papers to mention. One shows interdependencies between the sectors and a possibility to analyze critical infrastructures using SD. The other one is limited to the interdependencies on energy and water, there SD was also used.

Toward modeling and simulation of critical national infrastructure interdependencies

The article examines the entire interconnected infrastructures as it shows figure 5.10. Only then suitable measures against possible disruptions can be identified. This is an analysis possibility for the entire system of physical and economic infrastructures. Existing models of individual infrastructures will be assembled. SD can be used to analyze the dynamic and non-linear relationships. A total of 5000 variables and parameters are defined for the SD model. In addition, the effects of a possible disruptions of the infrastructure will be analyzed. The result shows that the SD model can lead to a reduction of the devastating impact of disruptions. (Min et al., 2007)

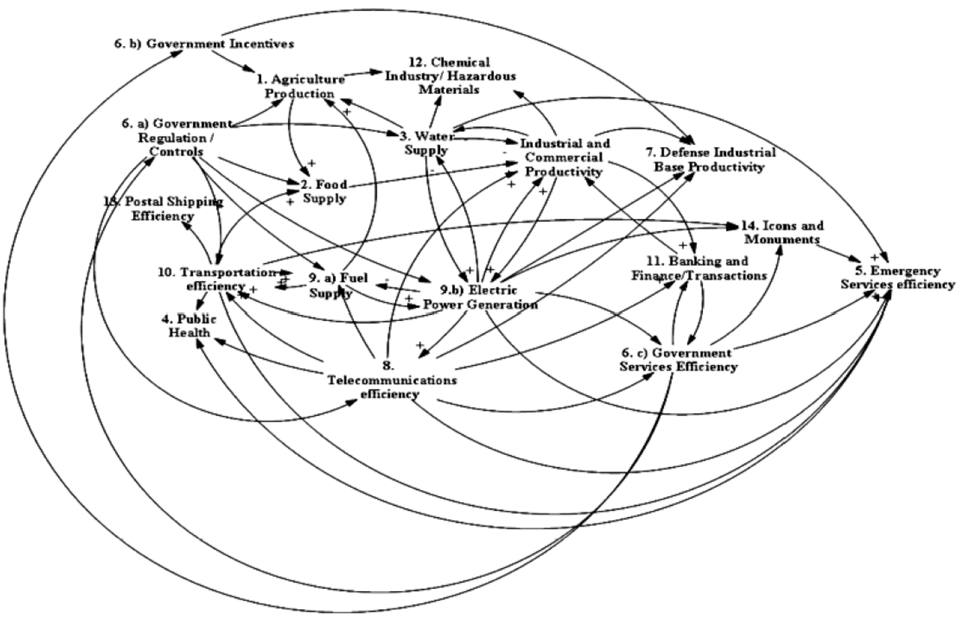


Figure 5.10.: Critical Infrastructure Interdependencies (Min et al., 2007)

A Framework for Analysis of Energy-Water Interdependency Problems

As water systems are important for many areas of the population, they are a particularly sensitive area. Certain systems are modeled on the basis of individual SD models. The central element is the water balance model. The submodels of water consumers such as agriculture or a water reservoir (figure 5.11) can complement the overall model individually. Thus, large complex overall models can be developed. In the future the next step will be to add the groundwater supply. In the end, the model should be able to show potentials to balance energy, water, and ecological needs in water constrained basins. (Jeffers, Jacobson, and Scott, 2011)

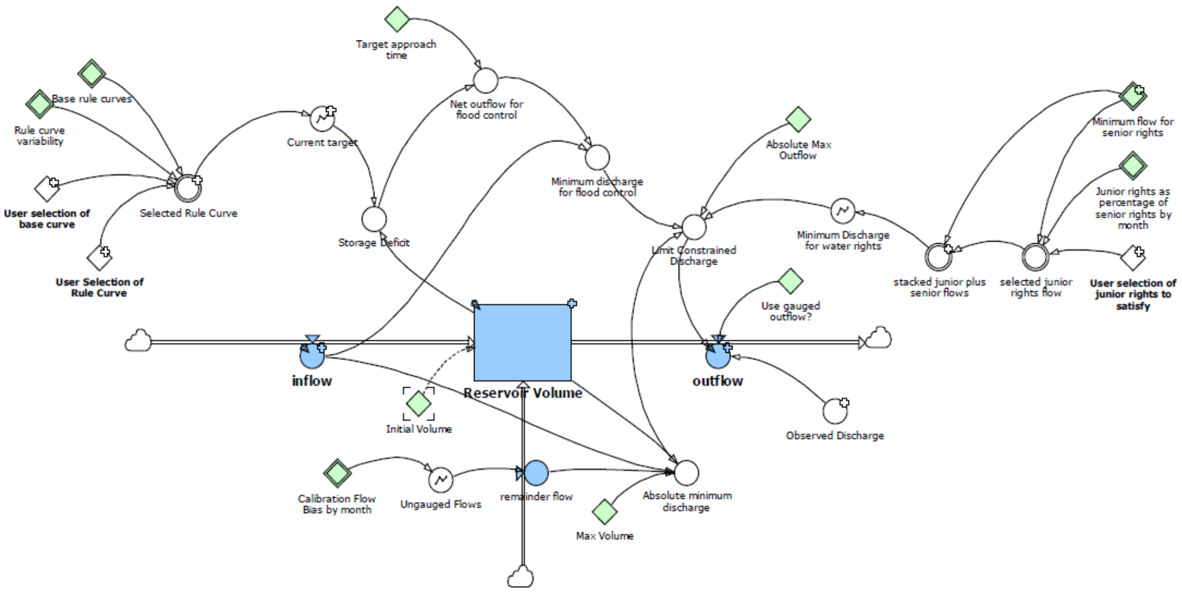


Figure 5.11.: Water Reservoir Model (Jeffers, Jacobson, and Scott, 2011)

5.3.2. Student Task on Modeling

As a part of this diploma thesis, a workshop with master degree students was held. The aim of the students was to *"Examine the critical elements of the water and energy cycle in Austria to analyze cascade effects and criticality."* In the first step, they developed a criteria matrix, which was subsequently transferred into an impact matrix. Finally, a CLD was modeled by the students to demonstrate a dynamic behaviour. The group size varied between three and four persons. Finally, the students completed a questionnaire on, in their opinion, was the biggest challenges. The questionnaire can be found in Appendix C. A summary of the workshop outcomes:

- **Criteria and Impact Matrix**
  Here, for the first time, the complexity of the topic becomes apparent. Already for creating the Criteria Matrix, there were four different variants developed by four different groups. Whereby two were nearly similar. Finding the right criteria was a major hurdle for most of the groups. The assessment, however, went very well. Also filling the impact matrix was no challenge. Only the "Impact" thinking was new for most of the students.
- **Causal Loop Diagram**
  The modeling process was a challenge for most of the students, because an adequate level of detail had to be found. Thinking in feedback loops challenged the groups. Also, seeing the dependencies between the elements was not obvious. Therefore modeling negative feedback loops was a difficult task for most of the groups.

The statistical evaluation of the questionnaires provides the following results (table 5.3) using *IBM SPSS Statistics 25*. Thereby strongly agree = 4, and strongly disagree = 1. The whole SPSS protocol can be found in Appendix D.
In summary, the questionnaire shows that 85% of respondents agree or strongly agree that it is challenging to find the right level of detail. Similarly, 75% agree or strongly agree that it is challenging to keep the level of detail. The statement agrees with the own experiences in the modeling process. Even finding the ascertain elements 66% of the students say that this is a challenge for them. This can be confirmed so far. Often finding the right elements is a challenge. About half of the respondents 50% agree that thinking in feedback loops is a challenge. In this

statement it is important to pay attention how accurate a person models due to different perception. The standard deviation is noticeably higher for this question compared to others, since it represents a personal feeling. In general, the feedback logic is not trivial and therefore demanding. Which came up again and again during the modeling process. Based on the student models and matrices first ideas for a model could be developed. This is very helpful for an initial modeling step.

Table 5.3.: Statistical Evaluation of the Questionnaire

Question	N	Min.	Max.	Mean	SEM	Standard Deviation
What was challenging?						
1. to understand the task	12	1	3	2.42	.229	.793
2. to ascertain the elements	12	2	4	2.75	.179	.622
3. to figure out dependencies	12	1	4	2.33	.225	.778
4. to estimate the impact of the elements on the system	12	1	4	2.58	.229	.793
5. to think in feedback loops	12	1	4	2.67	.284	.985
6. to link the feedback loops	12	1	4	2.58	.229	.793
7. to find the proper level of detail	12	2	4	3.08	.193	.669
8. to hold the level of detail	12	2	4	2.83	.167	.577
9. to set system boundaries	12	1	3	2.25	.218	.754

5.3.3. Causal Loop Diagram Modeling Process

As the first step for the *CI Case* the CLD modeling method is used. To show the dynamic behavior of CI these kinds of models are necessary. Although, these are not capable of simulation, they provide a very good overview of the complex and dynamic relationships and the impacting elements. CLD modeling is very common.

Mostly, the models are not further developed to the point of simulation for cost and time reasons. Since a lot of information and statements can already be made on basis of a CLD. On the one hand there is an overview of the different participants through a CLD, on the other hand feedback loops become apparent and thus interdependencies too.
Especially with a view on critical infrastructures CLD offer an important tool to design a strategic model. Usually the design process is very demanding, because feedback structures have to be considered. This is not the natural way of human thinking. In addition, dependencies and their effects must be taken into account, which is often challenging due to many different CI sectors and subsectors.
As already mentioned in order not to extend the model to an infinite level, only the energy and water sector of Austria will be taken into account. While designing the two sectors, an appropriate level of detail has to be found in order to go for a strategic level in M&S.

Structure and Boundaries

In order to limit a system, it is important to define and satisfy certain boundaries. However, in high complex systems such as CI, the risk of losing too much into detail is very high. To prevent it all, it makes sense to isolate individual systems in order to determine their range and influence.
In this *CI Case*, Austria's CI was limited to both sectors of energy and water. Especially at the beginning of the modeling process, the correct level of detail can not be estimated yet. When the model gets very large very quickly, a validation of important elements is necessary. In order to be able to make a strategic statement, it does not make sense to model down to the level of a tap, but superordinate to the general water supply level.

Depending on the requirement profile, it can happen to go into very detailed designing. In this *CI Case*, modeling and simulating CI in Austria, different boundaries have to be chosen:

- Focus only on water and energy sector, mainly on energy generation.
- Only more or less direct or second order dependencies.
- Model is foundation for a strategic advice.
- Not too detailed feedback loops.
- The scope is set to the level of water usage, surface water, groundwater, evaporation, energy generation.

Sub-Models

Usually for complex models a separate model is created per sector, key element or core theme. Because many sectors have their own special environment and their own dependencies. Only in the next step, the individual systems will be combined into a complete system.
In the *CI Case*, submodels were created of energy and water sectors. Both in compliance with previously defined boundaries in section 5.3.3. The basic structure can be well seen in figure 5.12 which shows the water model. In this stadium of modeling the direct elements are added. The energy part will be added in the second step to the overall model.
The submodel shows the water cycle of Austria. In contrast to other countries, drinking water supply is guaranteed only by springs and groundwater. Therefore, the water treatment does not contribute to the drinking water. Another special case is the energy production in Austria. Thereby the energy is not obtained from nuclear power plants, but mainly from the energy source of hydropower.

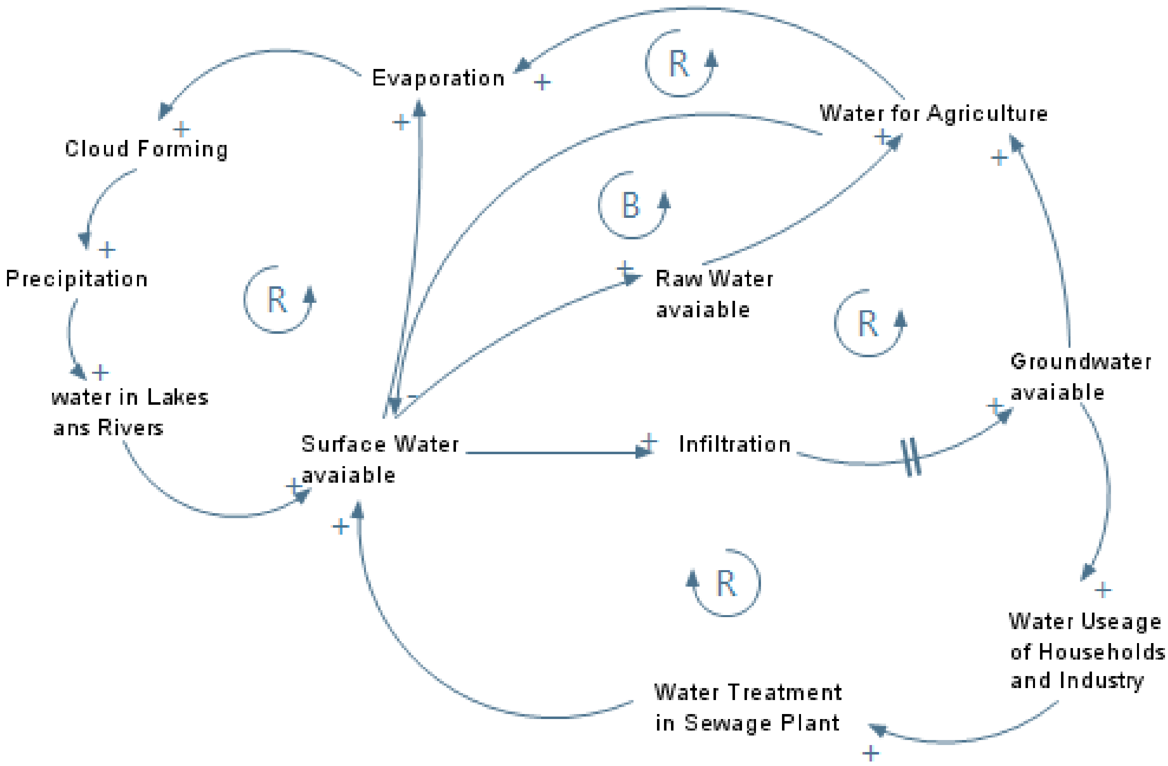


Figure 5.12.: Causal Loop Diagram of the Water Circle

This already shows the importance and criticality of hydropower. Large feedback loops show the essential circuits within the water sector. There are three main loops. On the one hand there is the classic evaporation - precipitation loop, a loop for the agricultural water consumption and one for the drinking water supply of the households.

Overall Model

When it comes to the overall CLD model the connections between the energy and water sectors becomes visible. During the last design step, the subsystem will be expanded by including the energy sector. The CLD becomes more complex now. Adding the energy sector will create some new feedback loops. Important is to keep the balance in a system which is the task of negative feedback loops to prevent a reinforcing effect of the system.

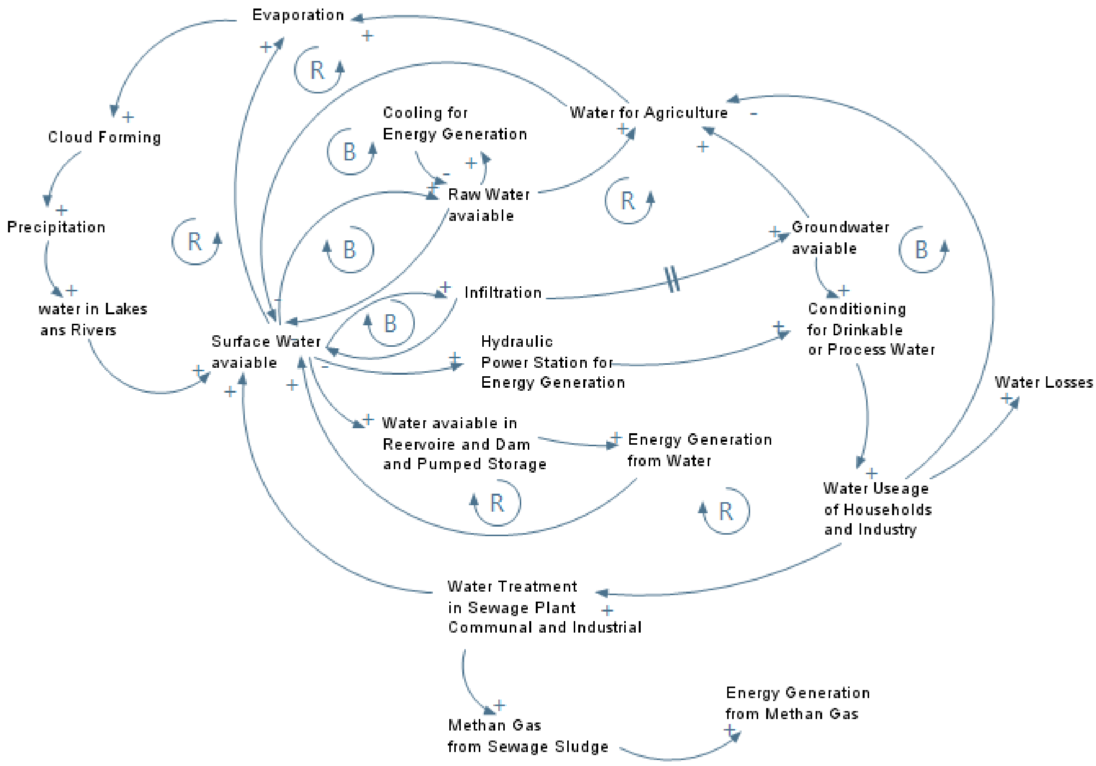


Figure 5.13.: Causal Loop Diagram of the Overall Model

The model (figure 5.13) clearly shows the energy and water sector system. Now, dependencies can be seen very well based on the feedback structures. Also scenarios of an interruption in the system can be checked. This will clarify, as already assumed, that the energy sector is strongly dependent on hydropower. In the winter months this can lead to some problems. Thus, the energy consumption on cold days is very high, but at the same time the water level in rivers and lakes is very low. Due to lean operating structures, only a few buffers are available. Therefore hydropower is usually on the edge of its efficiency during the winter months. In the model there is a time delay between infiltration and available groundwater. However, the temporal delta is relatively large in real terms. Because, until the surface water reaches the groundwater, this is very time consuming dependent on the nature of the soil.

5.3.4. Stock and Flow Diagram

One of the biggest challenges is the transition from CLD to SFD. To get a simulation-capable model, this is a necessary step. It is a considerable facilitation if already existing models can be adapted. Alternatively a modeling with the basic behavior modes offers a possibility, even if it makes the modeling process much more difficult. Usually it is not to underestimate that for a simulation-capable model several experts work together over a longer period of time.

In the present SFD two basic models of Sterman were used. First, a model (figure 5.14) for product discard and replacement purchases was adapted. Here the "adopters" are replaced by water. As a result, an adaptation to the water sector was done.

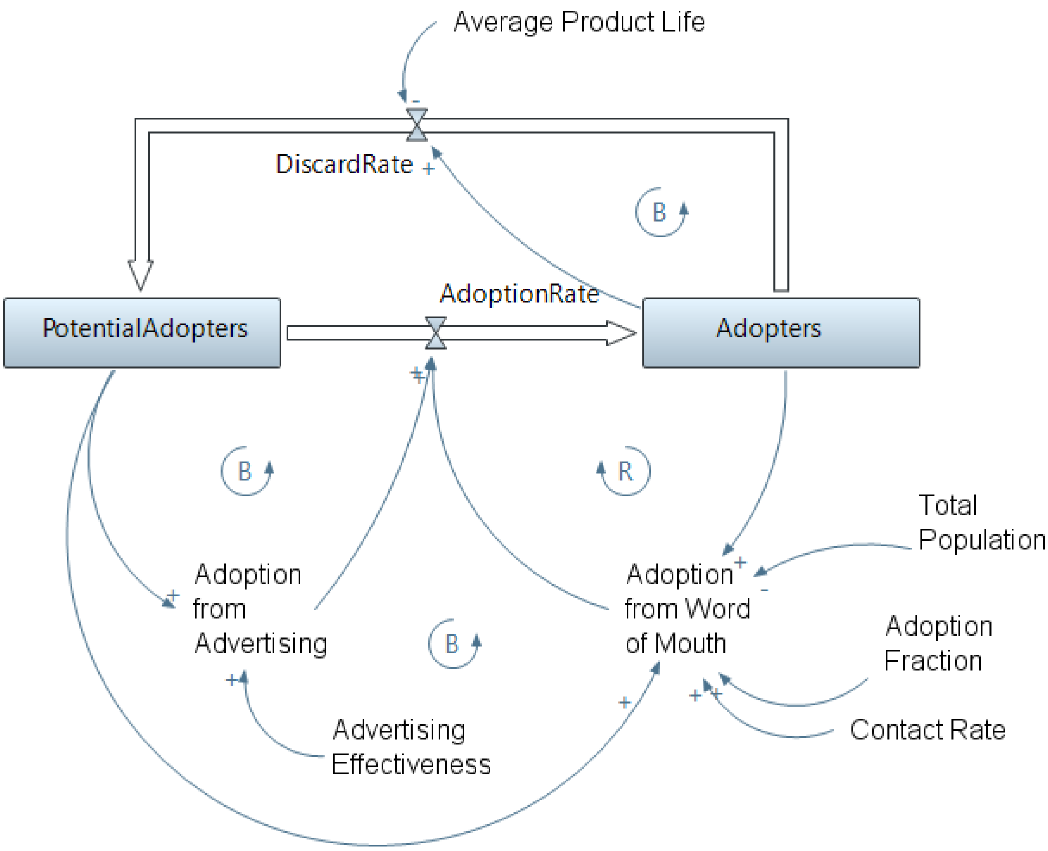


Figure 5.14.: Modeling product discard and replacement purchases (Sterman, 2000, p.343)

The second model (figure 5.15), also by Sterman, shows a promotion chain to explore worker training. Here, on the one hand "rookies" are replaced by water and all "quit" elements are replaced by the energy generation. Thus similar structures are connected under a new context.

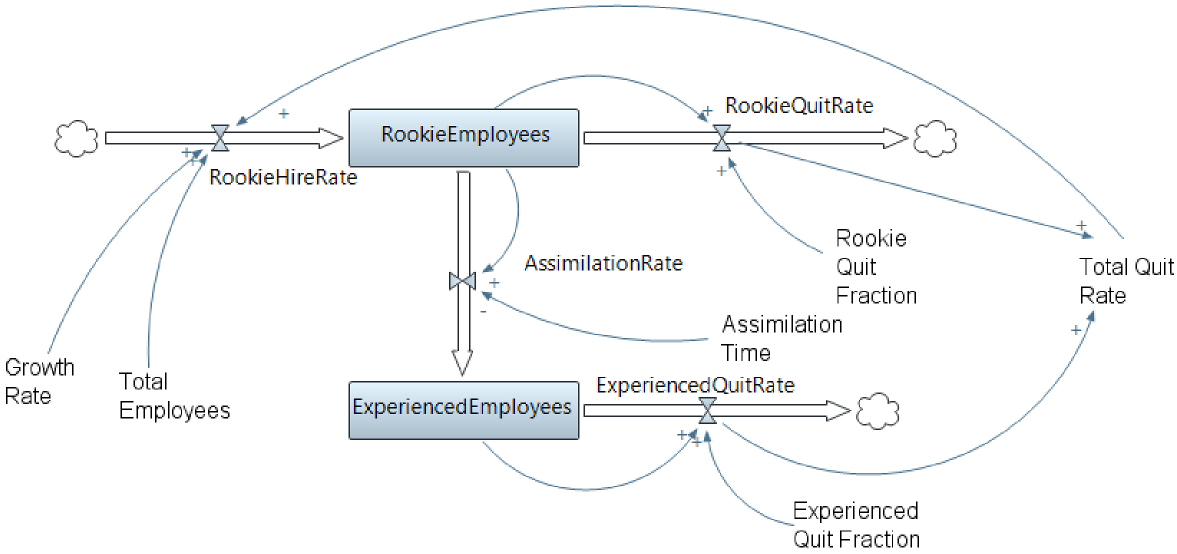


Figure 5.15.: A two-level promotion chain to explore worker training (Sterman, 2000, p.491)

In a first step, the Adopters model (figure 5.14) was mainly adapted. The second model was added continuously in a second step. It was challenging to figure out available data for the SFD. That research on proper values took a lot of time.

Now if both SFD models (figure 5.15 and 5.14) are put together, a qualitative model for the CI sectors water and energy will be created. As in figure 5.17 is shown, the boundaries reach from the water cycle up to the point of energy production and consumption. All other influences were not included in the model, otherwise the complexity would increase too much.

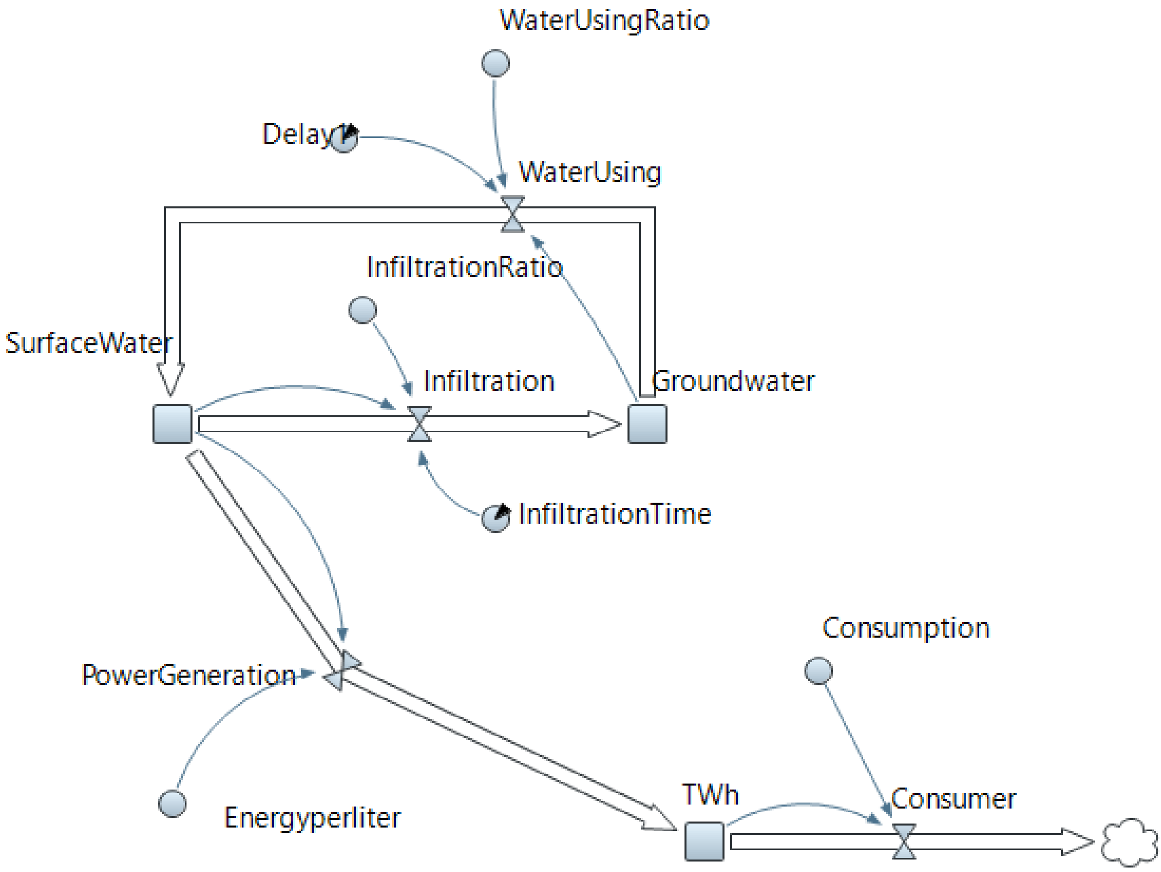


Figure 5.16.: First SFD Water Energy

If the model is considered, the direct dependence of the hydropower generation from the water cycle becomes apparent. Thus, long-lasting dry periods can already lead to a bottleneck. Likewise, with an increase in the population, the security of supply is no longer given. In addition, various assult scenarios on surface water or groundwater would have catastrophic consequences for the population and agriculture. In addition it would directly hit the energy production.
In summary, there are hardly no buffers in the water - energy system. Each reaction is immediately followed by another consequence. Thus, it provides a highly sensitive network. That results in high complex relationships in between the single elements of the system. Even small changes can cause big swings.

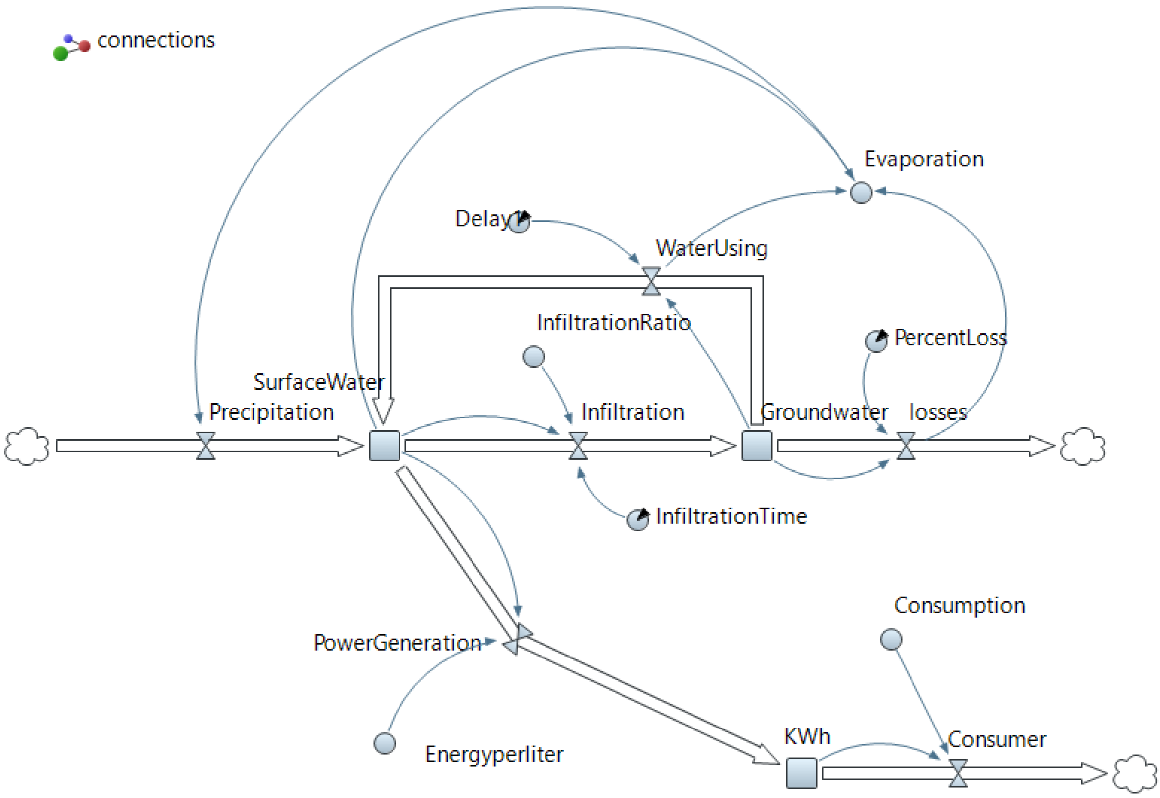


Figure 5.17.: SFD of Energy and Water Sector

5.4. Evaluation and Strategic advice

The SD model illustrates how M&S methods can be used to represent dynamic behaviors of CIs. In the first step, the focus was set on two sectors of the whole CI network to limit the complexity. Based on expert interviews a CLD of the water cycle was developed. In addition, the energy sector was limited to hydropower production. Based on literature, key elements and data on energy production from hydropower could be obtained.

The SFD is based on two already validated and verified models. Even if these are assigned to a different subject area, adaptions to the changed environment could be carried out. The next step will be the transition from a qualitative model to a fully simulated model.

In terms of CI, modeling and simulation methods are necessary to be one step ahead of threats. It is not without reason that many governments invest in such programs. Direct effects of scenarios of any kind can be simulated. Based on the data strategic decisions can be taken to protect CI or to make it more resilient. Precisely, because highly complex and networked systems can be mapped and simulated, M&S paradigms make it predisposed. Simulations can show cascade effects and interdependencies of every individual infrastructure. Especially in Austria, the water network is a very critical area because on the one hand the majority of the energy supply depends on it and on the other hand the essential water supply must be guaranteed.
It is essential to be one step ahead with the efforts in M&S critical infrastructures. For a safe future.

6. Conclusion

The efforts of governments and organizations to invest in modeling and simulating critical infrastructures demonstrate the explosive nature of this issue. Especially in the area of critical infrastructures, not much information is available due to the classified status. This makes it difficult for researchers and organizations to find suitable data sets. Thus, it is difficult to find appropriate models and simulations of critical infrastructures as well. Mainly, these are conceptual models or scientific papers which are explained, but most of the modeling diagrams are not published. Even for very critical infrastructures and their relationships are no data available. Of course, for a good reason, to prevent the misuse of sensitive data.

In order to get an overview of critical infrastructures it is important to know the directives of the countries and organizations. The different definitions of critical infrastructures serve as a framework for the classification of the sectors.

Basically, it is possible to obtain information on dependencies and impacts based on expert interviews of individual disciplines. The literature also contains data on the respective sectors. Accordingly, risk analyzes of critical infrastructures are possible. Optimally, an elaboration within a team of experts with appropriate moderation takes place. The risk analysis of critical infrastructures provides a very good basis to design a model quickly and easily.

The application of Causal Loop Diagrams is very well suited for strategic decision-making which is also helpful for decisions within the expert team. Mental feedback processes and dynamic dependencies can be easily visualized. There are basically

no rules for modeling which simplifies the designing process. Hence, the models do not have to be correct, but they support abstract thinking which is important for very complex system. These are the properties that make Causal Loop Diagrams a powerful tool.
Translating the Causal Loop Diagram into a Stock and Flow Diagram is usually very time-consuming. For this purpose, certain data sets and information are required, but they are not always available. Mostly, adaptations of already known and verified models are used to model a new real-life problem. Especially between qualitative and quantitative models is a very big gap. which is hard to close. Therefore, the ability of the modeler determines whether a model is customizable or can be used for other scenarios. In qualitative System Dynamics models the interdependencies and the resulting dynamic can be displayed very well. Likewise, feedback processes as well as cascade effects and their possible impact in highly complex systems are obvious. However, System Dynamics models offer best conditions for a strategic utilization due to the top-down principle and the possibility to display highly networked systems.

6.1. Interpretation and Discussion

First of all, it is important to know the national critical infrastructure directives in order to get a first overview of possible affected sectors. This is not always easy due to a multitude of directives. But they serve as a foundation for a risk analysis. The risk analysis of critical infrastructures is done with the help of an impact matrix. To clarify the corresponding infrastructures, certain framework conditions and thresholds have to be defined. Only on the basis of the listed infrastructures a risk analysis is possible. With the Impact Matrix, the criticality for each infrastructure can be represented at the current valuation point. But certain infrastructures may become more critical or less critical over time. In order to map this, it is important to include a time variable. This visualizes which infrastructures are particularly critical and therefore particularly worthy of protection. Especially key infrastructures that are strongly connected with others become apparent. Public Safety, Cargo Services, Hospital Healthcare and Transportation Infrastructure are becoming strongly critical over time. In addition to a Macro Impact Matrix, a Micro Impact Matrix was developed. Both show similar positioning of the infrastructures. This can be assumed to be a confirmation of the matrix, since all critical points are logical and comprehensible. Nevertheless, only a trend can be assumed within the Impact Matrix. For a second statement, a cooperation with a team of experts would be necessary. It is not only about, asking how critical an infrastructure is, but also how critical it can become over time.

Recognizing dynamic relationships and feedback structures is not possible within an Impact Matrix. Therefore modeling a Causal Loop Diagram is highly recommended. In the SD Framework only the water and energy sector in Austria is considered. In addition, the energy sector was limited to energy generation. An overall model of critical infrastructures with the same level of detail as the energy-water model shows would only be achieved with a team effort. The Causal Loop Diagram shows direct effects of surface water on energy generation and water supply. Thus, long drought periods can lead to a reduction in water energy generation or affect the water supply of the population. Even attacks or disturbances on one of the elements would have an immediate impact on the security of supply or the population well-being. Through the feedback structures a possible effect can be estimated and shows which other elements can be influenced. Therefore the Causal Loop Diagram is very well suited for strategic advises.

The transfer into the Stock and Flow Diagram serves primarily as a qualitative model. Basis for the model were two basic models of Sterman. Through an adaptation and adjustments to the water and energy sector, a first model could be developed. Thereby it is difficult to find a suitable data basis for the individual elements due to a very strategic level. Similar to the Causal Loop Diagram, the Surface Water

is also the linchpin in the system. Surface Water and Groundwater represent the main circuit. One of the biggest challenges are the respective delays. It is difficult to estimate how to set the values for a simulation. Basically, a quantitative step with suitable data is possible. It is important for the model to be adaptable for other infrastructures.
Finally, cyberspace should be mentioned as the central link of all critical infrastructures. It is particularly important for critical infrastructures to protect them from any kind of cyberspace threats. Due to highly complex networks and the increasing change between physical and digital systems. Since many critical infrastructures belong to private operators, it is very important to take appropriate protective measures. Ensuring the adherence of the security measures can be done through regular audits or appropriate regulations. Often, businesses still fail doing regular updates, using supported operating systems, or establish cyber-security strategies. Due to that there is a great potential for protection in an area where all critical infrastructures are strongly interconnected. Thus, System Dynamics would offer the possibility to simulate different scenarios and their cascade effects in order to stay one step ahead.

6.2. Future Perception

System Dynamics is ideal for modeling and simulation purposes in a strategic environments. The complexity of critical infrastructures makes the use of System Dynamics attractive. After many governments have launched programs in the field of modeling and simulation of critical infrastructures, this shows the importance of modeling and simulation approaches. A next step to simulate cascade effects of critical infrastructures in Austria would be the development towards a quantitative System Dynamics model. Another step that quantitative model would be developed further from a small model to a large overall model. This would require close cooperation with the authorities, private companies and essential service providers in order to obtain appropriate data sets for a simulation-capable model. Dependencies and feedback processes of infrastructures should be discussed in expert workshops. Only by this collaboration it is possible to create the most realistic System Dynamics models. Because in the future it is important to be optimally prepared, no matter for non-controllable threats such as natural disasters, or for strategic-thinking threats such as terrorism. Ultimately, System Dynamics can help to improve and develop national and international security.

Appendix

Appendix A.

Critical Infrastructure Sectors

Critical Infrastructure

Stand: 15.03.2019

Service	Essential Service	Subsector	Sector
Generating plant Combined heat and power plant Decentralized energy production facility Storage facility Bundling of electric capacity	Electricity production	Electricity supply	Energy
Transmission network Electricity trading	Power transmission		
Power grid Measuring site	Distribution of electricity		
Gas supply system Gas storage	Gas production	Gas supply	
long distance gas pipeline network	Gas transport		
Gas grid	Distribution of gas		
Oil production facility Refinery	Oil production	Oil supply	
long distance oil pipeline network Oil storage Systems for central, multi-site control	Oil transport		
Facilities or system of aggregators for the distribution of fuel and heating oil Petrol station network Systems for central, multi-site control	Distribution of oil		
Heating plant Combined heat and power station	Generation of district heating	Heat supply	
District heating grid	Distribution of district heating		
Airport facility or system for passenger processing	Air transport	Passenger services	
Passenger railway station Shunting and marshalling yard	Rail transport		
Facility or system for disposition of inland waterway vessels	Water transport		
Autonomous driving	Road transport		
Traffic control and management system of public transportation Control center of public transportation	Public transport		
Airport facility or system for cargo handling	Air transport		
Freight yard Shunting and marshalling yard	Rail transport		

Traffic control and management system of seafaring and river transport	Water transport	Cargo Services	Transport
Autonomous driving	Road transport		
Facility or system for operating a logistics center in the segments bulk goods, cargo, general cargo, contract or air freight logistics Facility or IT system for logistics control or administration in the segments bulk goods, cargo, general cargo, contract or air freight logistics	Logistics		
Infrastructure operations within the airport Flight and air traffic control	Air transport	Transportation Infrastructure	
Rail network and interlocking Railway traffic control and control system Railway control center	Rail transport		
Facility or systems for operations of federal waterays Control center of maritime operators and carriers	Water transport		
Traffic control system of federal motorways Traffic control and management system of municipal road traffic Road infrastructure	Road transport		
Facility for weather forecast, tide forecast or water level measurement Satellite navigation System	Satellite		
Rail network and signal boxes of public road passenger transport	Public transport		
Hospital facilities Hospital supply network Emergency treatment Hospital accessibility	Hospitals	In hospital health care	Health sector
Manufacturing facility	Production	Supply of directly life-sustaining medical devices	
Delivery point	Deliver		
Manufacturing facility Facility or system for collecting and processing of blood donations	Production	Supply of prescription medicines and blood and plasma concentrates	

Operating and storage room Facility or system for the distribution of prescription medicines	Distribution		
Pharmacy	Deliver		
Transport system Communication system for order and medical findings transmission	Transportation	Laboratory diagnostics	
Laboratory	Analytics		
Mixed water drainage Sewer Rainwater drainage Pumping station	Municipal drainage	Sewage disposal	Drinking water supply and distribution
Discharge facility Sewage plant Digestion tank for power supply Emergency power	Sewage treatment and water discharge		
Control center Emergency power	Controlling and monitoring Sewage		
Spring Well Transportation network	Water source	Drinking water supply	
Water tower Underground tank Elevated tank	Water reservoir		
Purification plant	Purification		
Transportation network Distriution Network Pumps Emergency power	Distribution		
Control center Sensors Emergency power	Controlling and monitoring Drinking water		
Local access networks providing access to a public telephone service, public data service or internet access service	Access	Voice- and data communication	Digital Infrastructure
Transmission network for publicly available telephone services and data transmission services or Internet access services	Transfer		
IPX for publicly available telephone services and data transmission services or Internet access services	Switchboard		
DNS Resolver which are offered for use publicly available telephone services and data transmission services or Internet access services Authoritative DNS server	Control		
Datacenter	Housing	Data storage and	
Serverfarm	IT-Hosting		

Content delivery network	IT-Hosting	computing	
System for the provision of trust services	Trust services		
Authorization-system System for connection to an authorization system from the point of view of the ATM operator	Authorization of a withdrawal	Cash supply	
System for processing by the ATM operator System for connection to an interbank payment system Clearing system Settlement system	Bring-In the payment transactions		
Account management system	Debit customer account		
Cash center IT system for the cash management	Cash logistics		
Authorization-system System for connection to an authorization system from the point of view of the terminal operator	Authorization	Card-based payment transactions	
System for processing by the POS terminal operator System for acceptance by the POS terminal operator Payment service provider of the payee System for connection to an interbank payment system Clearing system Settlement system	Bring-In the payment transactions		
Account management system	Debit customer account		
System to accept a transfer or direct debit	Acceptance of a transfer or direct debit	Conventional payments	
System for connection to an interbank payment system Clearing system Settlement system	Contribution to payment transactions		
Account management system	Bring-In the payment transactions		
System of a clearing house or central counterparty for settlement of securities and derivative transactions Connection system for the clearing and posting of securities and derivative transactions	Offsetting securities and derivative transactions	Billing and settlement of securities and derivative transactions	Financial services
Securities settlement system Depot management system	Booking securities		

System of a CSD			
System for processing the money order	Booking money		
Contract management system (life insurance)	Use of insurance services	Insurance services	
Contract management system (private health insurance)			
Contract management system (composite)			
Incentive system (life insurance)			
Incentive system (Social insurance institution of the statutory pension, accident and unemployment insurance)			
Incentive system (Private health insurance)			
Claims system (composite)			
Payment system (life insurance)			
Payment system (Social insurance institution of the statutory pension, accident and unemployment insurance)			
Payment system (Private health insurance)			
Payment system (Composite)			
Administration and payment system of the statutory health and long-term care insurance			
Facility for the food production	Food production and treatment	Food supply	Agriculture & Food supply
Facility for the treatment of food			
Facility or system for food distriution			
Facility or system for central multi-site control			
Facility for the treatment of food	Food retail		
Facility or system for food distriution			
Facility or system for food ordering			
Facility for placing food on the market			
Facility or system for central multi-site control			
Cultivation area	Crop farming		
Crop protection products			
Facility for harvest stroage			
Greenhouse farming			
Distribution of crops			
Stables			

Slaughterhousess Facility for storage of meat products Distribution of meat products	Livestock farming	Agriculture	
Fish breeding pool Facility for storage of fish and seafood Seafood distribution	Fishing and aquaculture		
Foest clearing for heat supply material	Forestry		
Universities Private/Public research facilities and institutes	Research and Development	Government	Public Administration
Courthouse Detention center Prisoner transport Judge, jury and prosecution	Justice		
Military base and facilities Military staff Military vehicles and aircraft	Armed Forces	Public safety	
Emergency network and communication Police Fire department Ambulance	Emergency Services		
Technical relief agency Disaster prevention Civil defense Civil protection department Technical support facilities	Civil Protection		
Waste disposal service and network Transportation & Logistics Dumps Hazardous substances disposal and storage Waste Combustion	Waste disposal	Community Services	
Schools Kindegarden Sports and clubs	Education & Schools		
Notray service Storage of documents	Notary and document service		
Building and construction agency decision making process	Building and construction		

Appendix B.

Critical Infrastructure Database

Impact	on	k at t0	t	X	Time imp.	C at t5
Electricity supply	Electricity supply			0	0	0,00
Electricity supply	Gas supply	1	1	2,5	0,848284	1,85
Electricity supply	Oil supply	2	1	2,5	0,848284	2,85
Electricity supply	Heat supply	2	2	5	0,986614	2,99
Electricity supply	Passenger services	2	0	0	0	2,00
Electricity supply	Cargo Services	2	1	2,5	0,848284	2,85
Electricity supply	Transportation Infrastructure	3	2	5	0,986614	3,99
Electricity supply	In hospital health care	3	2	5	0,986614	3,99
Electricity supply	Supply of directly life-sustaining medical devices	2	0	0	0	2,00
Electricity supply	Supply of prescription medicines and blood and plasma concentrates	2	0	0	0	2,00
Electricity supply	Laboratory diagnostics	3	0	0	0	3,00
Electricity supply	Sewage disposal	3	1	2,5	0,848284	3,85
Electricity supply	Drinking water supply	2	2	5	0,986614	2,99
Electricity supply	Voice- and data communication	3	2	5	0,986614	3,99
Electricity supply	Data storage and computing	3	1	2,5	0,848284	3,85
Electricity supply	Financial services	2	1	2,5	0,848284	2,85
Electricity supply	Food supply	1	1	2,5	0,848284	1,85
Electricity supply	Agriculture	1	0	0	0	1,00
Electricity supply	Government	1	0	0	0	1,00
Electricity supply	Public safety	2	0	0	0	2,00
Electricity supply	Community Services	1	0	0	0	1,00
Gas supply	Electricity supply	1	1	2,5	0,848284	1,85
Gas supply	Gas supply			0	0	0,00
Gas supply	Oil supply	1	1	2,5	0,848284	1,85
Gas supply	Heat supply	3	2	5	0,986614	3,99
Gas supply	Passenger services	1	0	0	0	1,00
Gas supply	Cargo Services	1	1	2,5	0,848284	1,85
Gas supply	Transportation Infrastructure	1	1	2,5	0,848284	1,85
Gas supply	In hospital health care	2	1	2,5	0,848284	2,85
Gas supply	Supply of directly life-sustaining medica	0	0	0	0	0,00
Gas supply	Supply of prescription medicines and bl	0	0	0	0	0,00
Gas supply	Laboratory diagnostics	2	0	0	0	2,00
Gas supply	Sewage disposal	0	0	0	0	0,00
Gas supply	Drinking water supply	0	0	0	0	0,00
Gas supply	Voice- and data communication	1	0	0	0	1,00
Gas supply	Data storage and computing	1	0	0	0	1,00
Gas supply	Financial services	0	0	0	0	0,00
Gas supply	Food supply	1	0	0	0	1,00
Gas supply	Agriculture	0	0	0	0	0,00
Gas supply	Government	2	0	0	0	2,00
Gas supply	Public safety	1	0	0	0	1,00
Gas supply	Community Services	0	0	0	0	0,00
Oil supply	Electricity supply	1	1	2,5	0,848284	1,85
Oil supply	Gas supply	1	1	2,5	0,848284	1,85
Oil supply	Oil supply			0	0	0,00
Oil supply	Heat supply	3	2	5	0,986614	3,99
Oil supply	Passenger services	3	2	5	0,986614	3,99
Oil supply	Cargo Services	3	2	5	0,986614	3,99
Oil supply	Transportation Infrastructure	1	1	2,5	0,848284	1,85
Oil supply	In hospital health care	2	1	2,5	0,848284	2,85

Oil supply	Supply of directly life-sustaining medica	1	1	2,5	0,848284	1,85
Oil supply	Supply of prescription medicines and bl	1	1	2,5	0,848284	1,85
Oil supply	Laboratory diagnostics	0	0	0	0	0,00
Oil supply	Sewage disposal	0	0	0	0	0,00
Oil supply	Drinking water supply	0	0	0	0	0,00
Oil supply	Voice- and data communication	1	0	0	0	1,00
Oil supply	Data storage and computing	1	0	0	0	1,00
Oil supply	Financial services	0	0	0	0	0,00
Oil supply	Food supply	2	0	0	0	2,00
Oil supply	Agriculture	3	1	2,5	0,848284	3,85
Oil supply	Government	1	1	2,5	0,848284	1,85
Oil supply	Public safety	3	2	5	0,986614	3,99
Oil supply	Community Services	2	0	0	0	2,00
Heat supply	Electricity supply	2	2	5	0,986614	2,99
Heat supply	Gas supply	2	2	5	0,986614	2,99
Heat supply	Oil supply	2	1	2,5	0,848284	2,85
Heat supply	Heat supply			0	0	0,00
Heat supply	Passenger services	1	0	0	0	1,00
Heat supply	Cargo Services	0	0	0	0	0,00
Heat supply	Transportation Infrastructure	1	0	0	0	1,00
Heat supply	In hospital health care	3	1	2,5	0,848284	3,85
Heat supply	Supply of directly life-sustaining medica	0	0	0	0	0,00
Heat supply	Supply of prescription medicines and bl	0	0	0	0	0,00
Heat supply	Laboratory diagnostics	1	0	0	0	1,00
Heat supply	Sewage disposal	0	0	0	0	0,00
Heat supply	Drinking water supply	0	0	0	0	0,00
Heat supply	Voice- and data communication	1	0	0	0	1,00
Heat supply	Data storage and computing	1	0	0	0	1,00
Heat supply	Financial services	0	0	0	0	0,00
Heat supply	Food supply	0	0	0	0	0,00
Heat supply	Agriculture	2	0	0	0	2,00
Heat supply	Government	1	1	2,5	0,848284	1,85
Heat supply	Public safety	1	0	0	0	1,00
Heat supply	Community Services	0	0	0	0	0,00
Passenger services	Electricity supply	2	0	0	0	2,00
Passenger services	Gas supply	3	0	0	0	3,00
Passenger services	Oil supply	3	1	2,5	0,848284	3,85
Passenger services	Heat supply	0	0	0	0	0,00
Passenger services	Passenger services			0	0	0,00
Passenger services	Cargo Services	1	0	0	0	1,00
Passenger services	Transportation Infrastructure	2	1	2,5	0,848284	2,85
Passenger services	In hospital health care	1	0	0	0	1,00
Passenger services	Supply of directly life-sustaining medica	2	1	2,5	0,848284	2,85
Passenger services	Supply of prescription medicines and bl	2	1	2,5	0,848284	2,85
Passenger services	Laboratory diagnostics	0	0	0	0	0,00
Passenger services	Sewage disposal	0	0	0	0	0,00
Passenger services	Drinking water supply	2	0	0	0	2,00
Passenger services	Voice- and data communication	2	0	0	0	2,00
Passenger services	Data storage and computing	1	0	0	0	1,00
Passenger services	Financial services	1	0	0	0	1,00
Passenger services	Food supply	2	0	0	0	2,00
Passenger services	Agriculture	2	0	0	0	2,00
Passenger services	Government	2	1	2,5	0,848284	2,85

Passenger services	Public safety	3	0	0	0	3,00
Passenger services	Community Services	2	1	2,5	0,848284	2,85
Cargo Services	Electricity supply	1	2	5	0,986614	1,99
Cargo Services	Gas supply	2	2	5	0,986614	2,99
Cargo Services	Oil supply	2	2	5	0,986614	2,99
Cargo Services	Heat supply	1	1	2,5	0,848284	1,85
Cargo Services	Passenger services	1	1	2,5	0,848284	1,85
Cargo Services	Cargo Services			0	0	0,00
Cargo Services	Transportation Infrastructure	1	1	2,5	0,848284	1,85
Cargo Services	In hospital health care	2	2	5	0,986614	2,99
Cargo Services	Supply of directly life-sustaining medica	2	2	5	0,986614	2,99
Cargo Services	Supply of prescription medicines and bl	2	2	5	0,986614	2,99
Cargo Services	Laboratory diagnostics	1	2	5	0,986614	1,99
Cargo Services	Sewage disposal	1	0	0	0	1,00
Cargo Services	Drinking water supply	1	1	2,5	0,848284	1,85
Cargo Services	Voice- and data communication	1	1	2,5	0,848284	1,85
Cargo Services	Data storage and computing	1	1	2,5	0,848284	1,85
Cargo Services	Financial services	1	2	5	0,986614	1,99
Cargo Services	Food supply	3	2	5	0,986614	3,99
Cargo Services	Agriculture	2	1	2,5	0,848284	2,85
Cargo Services	Government	1	0	0	0	1,00
Cargo Services	Public safety	1	1	2,5	0,848284	1,85
Cargo Services	Community Services	1	1	2,5	0,848284	1,85
Transportation Infras	Electricity supply	0	0	0	0	0,00
Transportation Infras	Gas supply	1	0	0	0	1,00
Transportation Infras	Oil supply	1	0	0	0	1,00
Transportation Infras	Heat supply	0	0	0	0	0,00
Transportation Infras	Passenger services	2	2	5	0,986614	2,99
Transportation Infras	Cargo Services	2	2	5	0,986614	2,99
Transportation Infras	Transportation Infrastructure			0	0	0,00
Transportation Infras	In hospital health care	3	2	5	0,986614	3,99
Transportation Infras	Supply of directly life-sustaining medica	2	1	2,5	0,848284	2,85
Transportation Infras	Supply of prescription medicines and bl	2	1	2,5	0,848284	2,85
Transportation Infras	Laboratory diagnostics	1	1	2,5	0,848284	1,85
Transportation Infras	Sewage disposal	0	0	0	0	0,00
Transportation Infras	Drinking water supply	0	0	0	0	0,00
Transportation Infras	Voice- and data communication	1	0	0	0	1,00
Transportation Infras	Data storage and computing	1	0	0	0	1,00
Transportation Infras	Financial services	2	1	2,5	0,848284	2,85
Transportation Infras	Food supply	3	2	5	0,986614	3,99
Transportation Infras	Agriculture	1	1	2,5	0,848284	1,85
Transportation Infras	Government	2	1	2,5	0,848284	2,85
Transportation Infras	Public safety	2	2	5	0,986614	2,99
Transportation Infras	Community Services	2	1	2,5	0,848284	2,85
In hospital health car	Electricity supply	2	1	2,5	0,848284	2,85
In hospital health car	Gas supply	1	0	0	0	1,00
In hospital health car	Oil supply	1	1	2,5	0,848284	1,85
In hospital health car	Heat supply	1	1	2,5	0,848284	1,85
In hospital health car	Passenger services	1	0	0	0	1,00
In hospital health car	Cargo Services	1	1	2,5	0,848284	1,85
In hospital health car	Transportation Infrastructure	1	1	2,5	0,848284	1,85
In hospital health car	In hospital health care			0	0	0,00
In hospital health car	Supply of directly life-sustaining medica	3	1	2,5	0,848284	3,85

In hospital health car	Supply of prescription medicines and bl	3	1	2,5	0,848284	3,85
In hospital health car	Laboratory diagnostics	3	0	0	0	3,00
In hospital health car	Sewage disposal	3	0	0	0	3,00
In hospital health car	Drinking water supply	3	0	0	0	3,00
In hospital health car	Voice- and data communication	3	0	0	0	3,00
In hospital health car	Data storage and computing	3	0	0	0	3,00
In hospital health car	Financial services	2	0	0	0	2,00
In hospital health car	Food supply	2	0	0	0	2,00
In hospital health car	Agriculture	1	0	0	0	1,00
In hospital health car	Government	0	0	0	0	0,00
In hospital health car	Public safety	2	1	2,5	0,848284	2,85
In hospital health car	Community Services	2	0	0	0	2,00
Supply of directly life	Electricity supply	0	0	0	0	0,00
Supply of directly life	Gas supply	0	0	0	0	0,00
Supply of directly life	Oil supply	0	0	0	0	0,00
Supply of directly life	Heat supply	0	0	0	0	0,00
Supply of directly life	Passenger services	3	0	0	0	3,00
Supply of directly life	Cargo Services	1	1	2,5	0,848284	1,85
Supply of directly life	Transportation Infrastructure	1	1	2,5	0,848284	1,85
Supply of directly life	In hospital health care	3	1	2,5	0,848284	3,85
Supply of directly life	Supply of directly life-sustaining medical devices			0	0	0,00
Supply of directly life	Supply of prescription medicines and bl	1	1	2,5	0,848284	1,85
Supply of directly life	Laboratory diagnostics	3	1	2,5	0,848284	3,85
Supply of directly life	Sewage disposal	2	0	0	0	2,00
Supply of directly life	Drinking water supply	1	0	0	0	1,00
Supply of directly life	Voice- and data communication	1	0	0	0	1,00
Supply of directly life	Data storage and computing	1	0	0	0	1,00
Supply of directly life	Financial services	1	0	0	0	1,00
Supply of directly life	Food supply	0	0	0	0	0,00
Supply of directly life	Agriculture	0	0	0	0	0,00
Supply of directly life	Government	0	0	0	0	0,00
Supply of directly life	Public safety	2	1	2,5	0,848284	2,85
Supply of directly life	Community Services	0	0	0	0	0,00
Supply of prescriptio	Electricity supply	0	0	0	0	0,00
Supply of prescriptio	Gas supply	0	0	0	0	0,00
Supply of prescriptio	Oil supply	0	0	0	0	0,00
Supply of prescriptio	Heat supply	0	0	0	0	0,00
Supply of prescriptio	Passenger services	3	0	0	0	3,00
Supply of prescriptio	Cargo Services	1	1	2,5	0,848284	1,85
Supply of prescriptio	Transportation Infrastructure	1	1	2,5	0,848284	1,85
Supply of prescriptio	In hospital health care	3	1	2,5	0,848284	3,85
Supply of prescriptio	Supply of directly life-sustaining medica	1	1	2,5	0,848284	1,85
Supply of prescriptio	Supply of prescription medicines and blood and plasma concer			0	0	0,00
Supply of prescriptio	Laboratory diagnostics	3	1	2,5	0,848284	3,85
Supply of prescriptio	Sewage disposal	2	0	0	0	2,00
Supply of prescriptio	Drinking water supply	1	0	0	0	1,00
Supply of prescriptio	Voice- and data communication	1	0	0	0	1,00
Supply of prescriptio	Data storage and computing	1	0	0	0	1,00
Supply of prescriptio	Financial services	1	0	0	0	1,00
Supply of prescriptio	Food supply	0	0	0	0	0,00
Supply of prescriptio	Agriculture	0	0	0	0	0,00
Supply of prescriptio	Government	0	0	0	0	0,00
Supply of prescriptio	Public safety	2	1	2,5	0,848284	2,85

Supply of prescriptio	Community Services	0	0	0	0	0,00
Laboratory diagnosti	Electricity supply	2	0	0	0	2,00
Laboratory diagnosti	Gas supply	1	0	0	0	1,00
Laboratory diagnosti	Oil supply	0	0	0	0	0,00
Laboratory diagnosti	Heat supply	1	0	0	0	1,00
Laboratory diagnosti	Passenger services	0	0	0	0	0,00
Laboratory diagnosti	Cargo Services	2	1	2,5	0,848284	2,85
Laboratory diagnosti	Transportation Infrastructure	2	1	2,5	0,848284	2,85
Laboratory diagnosti	In hospital health care	3	1	2,5	0,848284	3,85
Laboratory diagnosti	Supply of directly life-sustaining medica	3	0	0	0	3,00
Laboratory diagnosti	Supply of prescription medicines and bl	3	1	2,5	0,848284	3,85
Laboratory diagnosti	Laboratory diagnostics			0	0	0,00
Laboratory diagnosti	Sewage disposal	2	0	0	0	2,00
Laboratory diagnosti	Drinking water supply	1	0	0	0	1,00
Laboratory diagnosti	Voice- and data communication	1	0	0	0	1,00
Laboratory diagnosti	Data storage and computing	1	0	0	0	1,00
Laboratory diagnosti	Financial services	1	0	0	0	1,00
Laboratory diagnosti	Food supply	0	0	0	0	0,00
Laboratory diagnosti	Agriculture	0	0	0	0	0,00
Laboratory diagnosti	Government	0	0	0	0	0,00
Laboratory diagnosti	Public safety	1	0	0	0	1,00
Laboratory diagnosti	Community Services	0	0	0	0	0,00
Sewage disposal	Electricity supply	3	1	2,5	0,848284	3,85
Sewage disposal	Gas supply	1	0	0	0	1,00
Sewage disposal	Oil supply	1	0	0	0	1,00
Sewage disposal	Heat supply	2	0	0	0	2,00
Sewage disposal	Passenger services	1	0	0	0	1,00
Sewage disposal	Cargo Services	1	1	2,5	0,848284	1,85
Sewage disposal	Transportation Infrastructure	1	0	0	0	1,00
Sewage disposal	In hospital health care	2	1	2,5	0,848284	2,85
Sewage disposal	Supply of directly life-sustaining medica	0	0	0	0	0,00
Sewage disposal	Supply of prescription medicines and bl	0	0	0	0	0,00
Sewage disposal	Laboratory diagnostics	2	0	0	0	2,00
Sewage disposal	Sewage disposal			0	0	0,00
Sewage disposal	Drinking water supply	3	1	2,5	0,848284	3,85
Sewage disposal	Voice- and data communication	1	0	0	0	1,00
Sewage disposal	Data storage and computing	1	0	0	0	1,00
Sewage disposal	Financial services	1	0	0	0	1,00
Sewage disposal	Food supply	0	0	0	0	0,00
Sewage disposal	Agriculture	2	0	0	0	2,00
Sewage disposal	Government	1	0	0	0	1,00
Sewage disposal	Public safety	1	0	0	0	1,00
Sewage disposal	Community Services	2	0	0	0	2,00
Drinking water suppl	Electricity supply	2	0	0	0	2,00
Drinking water suppl	Gas supply	0	0	0	0	0,00
Drinking water suppl	Oil supply	0	0	0	0	0,00
Drinking water suppl	Heat supply	0	0	0	0	0,00
Drinking water suppl	Passenger services	2	1	2,5	0,848284	2,85
Drinking water suppl	Cargo Services	1	1	2,5	0,848284	1,85
Drinking water suppl	Transportation Infrastructure	1	1	2,5	0,848284	1,85
Drinking water suppl	In hospital health care	3	2	5	0,986614	3,99
Drinking water suppl	Supply of directly life-sustaining medica	2	1	2,5	0,848284	2,85
Drinking water suppl	Supply of prescription medicines and bl	2	0	0	0	2,00

Drinking water suppl	Laboratory diagnostics	3	0	0	0	3,00
Drinking water suppl	Sewage disposal	2	-1	-2,5	-0,84828	1,15
Drinking water suppl	Drinking water supply			0	0	0,00
Drinking water suppl	Voice- and data communication	1	0	0	0	1,00
Drinking water suppl	Data storage and computing	1	0	0	0	1,00
Drinking water suppl	Financial services	1	0	0	0	1,00
Drinking water suppl	Food supply	2	0	0	0	2,00
Drinking water suppl	Agriculture	3	1	2,5	0,848284	3,85
Drinking water suppl	Government	2	1	2,5	0,848284	2,85
Drinking water suppl	Public safety	2	1	2,5	0,848284	2,85
Drinking water suppl	Community Services	2	1	2,5	0,848284	2,85
Voice- and data comı	Electricity supply	2	0	0	0	2,00
Voice- and data comı	Gas supply	2	0	0	0	2,00
Voice- and data comı	Oil supply	2	0	0	0	2,00
Voice- and data comı	Heat supply	2	0	0	0	2,00
Voice- and data comı	Passenger services	3	1	2,5	0,848284	3,85
Voice- and data comı	Cargo Services	2	2	5	0,986614	2,99
Voice- and data comı	Transportation Infrastructure	2	2	5	0,986614	2,99
Voice- and data comı	In hospital health care	3	1	2,5	0,848284	3,85
Voice- and data comı	Supply of directly life-sustaining medica	1	0	0	0	1,00
Voice- and data comı	Supply of prescription medicines and bl	1	0	0	0	1,00
Voice- and data comı	Laboratory diagnostics	2	0	0	0	2,00
Voice- and data comı	Sewage disposal	1	0	0	0	1,00
Voice- and data comı	Drinking water supply	1	0	0	0	1,00
Voice- and data comı	Voice- and data communication			0	0	0,00
Voice- and data comı	Data storage and computing	3	0	0	0	3,00
Voice- and data comı	Financial services	3	2	5	0,986614	3,99
Voice- and data comı	Food supply	2	0	0	0	2,00
Voice- and data comı	Agriculture	1	0	0	0	1,00
Voice- and data comı	Government	3	0	0	0	3,00
Voice- and data comı	Public safety	3	0	0	0	3,00
Voice- and data comı	Community Services	2	0	0	0	2,00
Data storage and cor	Electricity supply	2	0	0	0	2,00
Data storage and cor	Gas supply	1	0	0	0	1,00
Data storage and cor	Oil supply	1	0	0	0	1,00
Data storage and cor	Heat supply	0	0	0	0	0,00
Data storage and cor	Passenger services	3	0	0	0	3,00
Data storage and cor	Cargo Services	2	2	5	0,986614	2,99
Data storage and cor	Transportation Infrastructure	2	2	5	0,986614	2,99
Data storage and cor	In hospital health care	3	0	0	0	3,00
Data storage and cor	Supply of directly life-sustaining medica	1	0	0	0	1,00
Data storage and cor	Supply of prescription medicines and bl	1	0	0	0	1,00
Data storage and cor	Laboratory diagnostics	1	0	0	0	1,00
Data storage and cor	Sewage disposal	0	0	0	0	0,00
Data storage and cor	Drinking water supply	0	0	0	0	0,00
Data storage and cor	Voice- and data communication	3	0	0	0	3,00
Data storage and cor	Data storage and computing			0	0	0,00
Data storage and cor	Financial services	3	0	0	0	3,00
Data storage and cor	Food supply	1	0	0	0	1,00
Data storage and cor	Agriculture	0	0	0	0	0,00
Data storage and cor	Government	3	1	2,5	0,848284	3,85
Data storage and cor	Public safety	3	0	0	0	3,00
Data storage and cor	Community Services	1	0	0	0	1,00

Financial services	Electricity supply	3	1	2,5	0,848284	3,85
Financial services	Gas supply	3	1	2,5	0,848284	3,85
Financial services	Oil supply	3	1	2,5	0,848284	3,85
Financial services	Heat supply	2	0	0	0	2,00
Financial services	Passenger services	3	1	2,5	0,848284	3,85
Financial services	Cargo Services	2	2	5	0,986614	2,99
Financial services	Transportation Infrastructure	2	2	5	0,986614	2,99
Financial services	In hospital health care	1	1	2,5	0,848284	1,85
Financial services	Supply of directly life-sustaining medica	1	1	2,5	0,848284	1,85
Financial services	Supply of prescription medicines and bl	1	1	2,5	0,848284	1,85
Financial services	Laboratory diagnostics	2	0	0	0	2,00
Financial services	Sewage disposal	1	1	2,5	0,848284	1,85
Financial services	Drinking water supply	1	1	2,5	0,848284	1,85
Financial services	Voice- and data communication	1	1	2,5	0,848284	1,85
Financial services	Data storage and computing	1	1	2,5	0,848284	1,85
Financial services	Financial services			0	0	0,00
Financial services	Food supply	2	1	2,5	0,848284	2,85
Financial services	Agriculture	1	1	2,5	0,848284	1,85
Financial services	Government	3	1	2,5	0,848284	3,85
Financial services	Public safety	2	1	2,5	0,848284	2,85
Financial services	Community Services	2	1	2,5	0,848284	2,85
Food supply	Electricity supply	0	0	0	0	0,00
Food supply	Gas supply	0	0	0	0	0,00
Food supply	Oil supply	2	0	0	0	2,00
Food supply	Heat supply	0	0	0	0	0,00
Food supply	Passenger services	2	1	2,5	0,848284	2,85
Food supply	Cargo Services	1	1	2,5	0,848284	1,85
Food supply	Transportation Infrastructure	1	1	2,5	0,848284	1,85
Food supply	In hospital health care	2	1	2,5	0,848284	2,85
Food supply	Supply of directly life-sustaining medica	0	0	0	0	0,00
Food supply	Supply of prescription medicines and bl	0	0	0	0	0,00
Food supply	Laboratory diagnostics	2	0	0	0	2,00
Food supply	Sewage disposal	0	0	0	0	0,00
Food supply	Drinking water supply	2	0	0	0	2,00
Food supply	Voice- and data communication	0	0	0	0	0,00
Food supply	Data storage and computing	0	0	0	0	0,00
Food supply	Financial services	3	0	0	0	3,00
Food supply	Food supply			0	0	0,00
Food supply	Agriculture	3	1	2,5	0,848284	3,85
Food supply	Government	2	1	2,5	0,848284	2,85
Food supply	Public safety	3	1	2,5	0,848284	3,85
Food supply	Community Services	2	0	0	0	2,00
Agriculture	Electricity supply	3	0	0	0	3,00
Agriculture	Gas supply	1	0	0	0	1,00
Agriculture	Oil supply	2	1	2,5	0,848284	2,85
Agriculture	Heat supply	1	0	0	0	1,00
Agriculture	Passenger services	1	0	0	0	1,00
Agriculture	Cargo Services	2	1	2,5	0,848284	2,85
Agriculture	Transportation Infrastructure	1	1	2,5	0,848284	1,85
Agriculture	In hospital health care	0	0	0	0	0,00
Agriculture	Supply of directly life-sustaining medica	0	0	0	0	0,00
Agriculture	Supply of prescription medicines and bl	0	0	0	0	0,00
Agriculture	Laboratory diagnostics	2	0	0	0	2,00

Agriculture	Sewage disposal	2	0	0	0	2,00
Agriculture	Drinking water supply	2	0	0	0	2,00
Agriculture	Voice- and data communication	1	0	0	0	1,00
Agriculture	Data storage and computing	1	0	0	0	1,00
Agriculture	Financial services	3	0	0	0	3,00
Agriculture	Food supply	3	1	2,5	0,848284	3,85
Agriculture	Agriculture			0	0	0,00
Agriculture	Government	2	0	0	0	2,00
Agriculture	Public safety	3	1	2,5	0,848284	3,85
Agriculture	Community Services	2	1	2,5	0,848284	2,85
Government	Electricity supply	2	0	0	0	2,00
Government	Gas supply	2	0	0	0	2,00
Government	Oil supply	2	0	0	0	2,00
Government	Heat supply	2	0	0	0	2,00
Government	Passenger services	2	1	2,5	0,848284	2,85
Government	Cargo Services	1	0	0	0	1,00
Government	Transportation Infrastructure	2	1	2,5	0,848284	2,85
Government	In hospital health care	1	1	2,5	0,848284	1,85
Government	Supply of directly life-sustaining medica	1	0	0	0	1,00
Government	Supply of prescription medicines and bl	1	0	0	0	1,00
Government	Laboratory diagnostics	2	0	0	0	2,00
Government	Sewage disposal	2	0	0	0	2,00
Government	Drinking water supply	3	0	0	0	3,00
Government	Voice- and data communication	3	0	0	0	3,00
Government	Data storage and computing	3	0	0	0	3,00
Government	Financial services	3	1	2,5	0,848284	3,85
Government	Food supply	3	0	0	0	3,00
Government	Agriculture	2	0	0	0	2,00
Government	Government			0	0	0,00
Government	Public safety	3	1	2,5	0,848284	3,85
Government	Community Services	3	1	2,5	0,848284	3,85
Public safety	Electricity supply	3	1	2,5	0,848284	3,85
Public safety	Gas supply	3	1	2,5	0,848284	3,85
Public safety	Oil supply	3	1	2,5	0,848284	3,85
Public safety	Heat supply	1	1	2,5	0,848284	1,85
Public safety	Passenger services	3	1	2,5	0,848284	3,85
Public safety	Cargo Services	1	1	2,5	0,848284	1,85
Public safety	Transportation Infrastructure	2	2	5	0,986614	2,99
Public safety	In hospital health care	3	1	2,5	0,848284	3,85
Public safety	Supply of directly life-sustaining medica	2	1	2,5	0,848284	2,85
Public safety	Supply of prescription medicines and bl	2	1	2,5	0,848284	2,85
Public safety	Laboratory diagnostics	1	0	0	0	1,00
Public safety	Sewage disposal	0	0	0	0	0,00
Public safety	Drinking water supply	3	1	2,5	0,848284	3,85
Public safety	Voice- and data communication	2	1	2,5	0,848284	2,85
Public safety	Data storage and computing	2	1	2,5	0,848284	2,85
Public safety	Financial services	1	1	2,5	0,848284	1,85
Public safety	Food supply	3	1	2,5	0,848284	3,85
Public safety	Agriculture	2	1	2,5	0,848284	2,85
Public safety	Government	3	1	2,5	0,848284	3,85
Public safety	Public safety			0	0	0,00
Public safety	Community Services	1	1	2,5	0,848284	1,85
Community Services	Electricity supply	2	0	0	0	2,00

Community Services	Gas supply	2	0	0	0	2,00
Community Services	Oil supply	1	0	0	0	1,00
Community Services	Heat supply	2	0	0	0	2,00
Community Services	Passenger services	1	0	0	0	1,00
Community Services	Cargo Services	2	1	2,5	0,848284	2,85
Community Services	Transportation Infrastructure	2	2	5	0,986614	2,99
Community Services	In hospital health care	2	0	0	0	2,00
Community Services	Supply of directly life-sustaining medica	1	0	0	0	1,00
Community Services	Supply of prescription medicines and bl	1	0	0	0	1,00
Community Services	Laboratory diagnostics	2	0	0	0	2,00
Community Services	Sewage disposal	2	1	2,5	0,848284	2,85
Community Services	Drinking water supply	2	1	2,5	0,848284	2,85
Community Services	Voice- and data communication	0	0	0	0	0,00
Community Services	Data storage and computing	0	0	0	0	0,00
Community Services	Financial services	0	0	0	0	0,00
Community Services	Food supply	1	0	0	0	1,00
Community Services	Agriculture	0	0	0	0	0,00
Community Services	Government	2	1	2,5	0,848284	2,85
Community Services	Public safety	2	1	2,5	0,848284	2,85
Community Services	Community Services			0	0	0,00

Appendix C.

Questionnaire

Maschinenbau- und Betriebsinformatik
mbi

TU Graz
Graz University of Technology

Questionnaire

Business Modeling and Simulation – Critical Infrastructure Water and Energy

Generally			
Field of study?			
Current Studies?	Bachelor O	Master O	PhD O

What was challenging?	Strongly Agree	Agree	Disagree	Strongly Disagree
to understand the task	O	O	O	O
to ascertain the elements	O	O	O	O
to figure out the dependencies	O	O	O	O
to estimate the impact of the elements on the system	O	O	O	O
to think in feedback loops	O	O	O	O
to link the feedback loops	O	O	O	O
to find the proper level of detail	O	O	O	O
to hold the level of detail	O	O	O	O
to set system boundaries	O	O	O	O

1

Sort the question topics according to the perceived difficulty

Feedback to the modeling process

2

Consent

Research Project: Critical Infrastructure - Energy and Water

Name of participant:
Date:

As a part of the research project "Critical Infrastructure - Energy and Water", a Causal Loop Diagram is created to analyze cascade effects.
For the later analysis of the Causal Loop Diagram modeling, the participants' opinions on the modeling process are collected in form of a questionnaire.
For further scientific evaluation, all information about yourself will be removed from the text and / or anonymised. Data from the modeling process in scientific publications are quoted only in excerpts to ensure that nobody is recognizable for third parties also by the sequence of events told in the modeling process.
These data are processed permanently for the purpose of scientific evaluation.

This consent can be revoked at any time. In addition, the right to information, rectification, limitation of processing, deletion and data portability are available. For more information on the exercise of your rights, see:

https://datenschutz.tugraz.at/dsgvo/rechte/

Data protection officer of Graz University of Technology is the x-tention Informationstechnologie GmbH, Römerstraße 80A, 4600 Wels. There is a right to complain to the Data Protection Authority.

I have read the above Privacy Policy, understand and hereby give my consent to this data processing:

___________________	________________________________
Date, Place	*Name/Signature*

Appendix D.

SPSS Analysis

What was challenging?

Descriptive Statistics

	N	Minimum	Maximum	Mean		Std. Deviation
	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic
challenging_1	12	1	3	2,42	,229	,793
challenging_2	12	2	4	2,75	,179	,622
challenging_3	12	1	4	2,33	,225	,778
challenging_4	12	1	4	2,58	,229	,793
challenging_5	12	1	4	2,67	,284	,985
challenging_6	12	1	4	2,58	,229	,793
challenging_7	12	2	4	3,08	,193	,669
challenging_8	12	2	4	2,83	,167	,577
challenging_9	12	1	3	2,25	,218	,754
Valid N (listwise)	12					

It was challenging ..

.. to understand the task (challenging_1)

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	strongly disagree	2	16,7	16,7	16,7
	disagree	3	25,0	25,0	41,7
	agree	7	58,3	58,3	100,0
	Total	12	100,0	100,0	

.. to ascertain the elements (challenging_2)

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	disagree	4	33,3	33,3	33,3
	agree	7	58,3	58,3	91,7
	strongly agree	1	8,3	8,3	100,0
	Total	12	100,0	100,0	

.. to figure out the dependencies (challenging_3)

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	strongly disagree	1	8,3	8,3	8,3
	disagree	7	58,3	58,3	66,7
	agree	3	25,0	25,0	91,7
	strongly agree	1	8,3	8,3	100,0
	Total	12	100,0	100,0	

.. to estimate the impact of the elements on the system (challenging_4)

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	strongly disagree	1	8,3	8,3	8,3
	disagree	4	33,3	33,3	41,7
	agree	6	50,0	50,0	91,7
	strongly agree	1	8,3	8,3	100,0
	Total	12	100,0	100,0	

.. to think in feedback loops (challenging_5)

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	strongly disagree	1	8,3	8,3	8,3
	disagree	5	41,7	41,7	50,0
	agree	3	25,0	25,0	75,0
	strongly agree	3	25,0	25,0	100,0
	Total	12	100,0	100,0	

.. to link the feedback loops (challenging_6)

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	strongly disagree	1	8,3	8,3	8,3
	disagree	4	33,3	33,3	41,7
	agree	6	50,0	50,0	91,7
	strongly agree	1	8,3	8,3	100,0
	Total	12	100,0	100,0	

.. to find the proper level of detail (challenging_7)

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	disagree	2	16,7	16,7	16,7
	agree	7	58,3	58,3	75,0
	strongly agree	3	25,0	25,0	100,0
	Total	12	100,0	100,0	

.. to hold the level of detail (challenging_8)

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	disagree	3	25,0	25,0	25,0
	agree	8	66,7	66,7	91,7
	strongly agree	1	8,3	8,3	100,0
	Total	12	100,0	100,0	

.. to set system boundaries (challenging_9)

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	strongly disagree	2	16,7	16,7	16,7
	disagree	5	41,7	41,7	58,3
	agree	5	41,7	41,7	100,0
	Total	12	100,0	100,0	

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