Analysing space dependencies

Methods and factors for method development

THEODOR DE SOUSA | DIVISION OF RISK MANAGEMENT AND SOCIETAL SAFETY | FACULTY OF ENGINEERING | LUND UNIVERSITY, SWEDEN

Analysing space dependencies - Methods and factors for method development

Theodor de Sousa

Lund 2022

Analysing space dependencies - Methods and factors for method development

Theodor de Sousa

Number of pages: 61
Illustrations: 0

Keywords
Vital societal functions, critical infrastructure, interdependency, dependency analysis, space services, space infrastructure, GNSS, PNT, ICT, method development

Abstract
Vital societal functions and critical infrastructure rely to an increasing extent on services from space, such as navigation and positioning systems, timekeeping, and communications. However, understanding of space service dependencies is low among practitioners and society at large, with research on societal space dependency being limited as well. In order to avoid cascading effects from disruptions to these services, societal actors could benefit from conducting space service dependency analyses. The purpose of this thesis is to contribute towards the development of a method for such space dependency analyses, by identifying useful existing methods and important factors.
Two studies have been conducted within the scope of this thesis. An explorative literature study covering twenty-one documents identified eight dependency analysis methods and fourteen factors deemed relevant for performing space service dependency analyses. In a semi-structured interview study with four participants, the findings from the literature study were validated and more perspectives on dependency analyses were provided along the themes of *incentive*, *conduct, results and input data*, as well as *information security.* Based on these studies, a prototype method has been developed, which together with the identified methods and factors are suggested to be implemented in future studies.

Riskhantering och samhällssäkerhet
Lunds tekniska högskola
Lunds universitet
Box 118
221 00 Lund

http://www.risk.lth.se

Telefon: 046 - 222 73 60

Division of Risk Management and Societal Safety
Faculty of Engineering
Lund University
P.O. Box 118
SE-221 00 Lund
Sweden

http://www.risk.lth.se

Telephone: +46 46 222 73 60

Foreword

This thesis is the culmination of a journey which started more than three years ago, with me missing the application date for the master program in risk management and safety engineering. At that time, I made the decision to finish my degree in mechanical engineering, and simply apply again next year. Having some points left to fill up before writing that thesis, I applied to the course *Introduction to Disaster Response Management* just to confirm I was making the right choice in extending my studies.

My choice was not only confirmed. I was thoroughly convinced that my future laid in the risky business. I owe my deepest gratitude to the teachers of that course, Christian Uhr and Tove Frykmer, for lighting an enthusiasm I did not knew I possessed. Furthermore, I am honoured to again being able to thank them. Tove, thank you for being my supervisor during this thesis, and showing what the epitome of academic expertise looks like. Christian, thank you for being my project examiner, my Alpha and Omega of the whole master's degree.

To my supervisor and colleagues at the Swedish Defence Research Agency, who made *me* feel like a colleague, I am also thankful. Your vast humour, kindness, and expertise on everything from [redacted] to [redacted] have brought me constant joy throughout this project.

The individuals participating in my interviews deserve my uttermost appreciation. This was my first interview study ever conducted, I learned a lot from you. Without you, this thesis would be nothing.

I also wish to extend my gratitude to batch six of the DRMCCA program for embracing me as your classmate, widening my perspective on an immense amount of issues, and providing me with a sense of professional agency and ambition to fight them.

Finally, I once again express my deepest love and gratefulness to my parents, Rose and Frederik de Sousa, who have cheered me on and supported me in every way during two rounds of thesis writing. I am looking forward to supporting you when that time comes.

Theodor de Sousa

Lund, 22 September 2022

Summary

Vital societal functions and critical infrastructure rely to an increasing extent on services from space, such as navigation and positioning systems, timekeeping, and communications. However, understanding of space service dependencies is low among practitioners, academia, and society at large. In order to avoid cascading effects from disruptions to space services, societal actors could benefit from conducting space service dependency analyses.

The purpose of this thesis is to contribute towards the development of a method for such space dependency analyses, by identifying useful factors and important methods to address in future research. In order to achieve this objective, the following research questions are answered:

- What methods for dependency analysis found in the literature can be relevant for space service dependency analysis.
- What are important factors to address in a potential method for space service dependency analysis?
- What is a possible design of a method for space service dependency analysis?

Concepts central to this research are presented in Chapter 2. *Vital Societal Functions (VSF) and Critical Infrastructure (CI)* are defined as maintainers of societal functions necessary for ensuring the needs and values of society. *Risk and vulnerability analysis (RVA)* is described within the legal context of Swedish public agencies, highlighting its relevancy to dependency analysis. *Dependencies* and *cascading effects* are presented through the lens of critical infrastructure, followed by a description of *dependency analyses* and current research on the topic. Finally, *space services* as a concept is mapped in relation to the *space value chain*, along with descriptions of some common applications, threats, and characteristics of the space domain.

Following the conceptual framework, the methodology of this thesis is described in Chapter 3. Taking an explorative approach, the research is conducted in part as a literature study and an interview study. The conduct of the literature study was guided by a scoping study framework, dividing the study into five stages. Data was collected from twenty-one documents and analysed using open and axial coding. In the interview study, four participants, from Lund University, the Swedish Civil Contingencies Agency (MSB), the Swedish aviation agency LFV, and the Swedish Defence Research Agency (FOI), were

interviewed using a semi-structured approach with questions revolving around emergent themes developed in the literature study.

The results and related analyses are provided in Chapter 4. In total, the thesis has identified eight dependency analysis methods and fourteen factors which are considered relevant when conducting space service dependency analyses. At sectoral levels, the methods identified are mainly expert based, as these types of methods are deemed to provide benefits relating to overall system robustness, information sharing, data accessibility, and resource efficiency. At an actor level, more technical methods are suggested, which share similarities to conventional risk analysis methods found in industry. The factors which emerged from the literature and interview studies centre on the themes of *incentive*, *conduct*, *results and input data*, and *information security*.

A discussion on the research is presented in Chapter 5, followed by conclusions in Chapter 6. The value of conducting dependency analyses is dissected in a brief discussion on alternative ways of fulfilling the purpose of space service dependency analyses. Additionally, a method prototype incorporating the identified methods and factors is presented in order to contribute towards the development of a method for space dependency analysis. Suggestions for further studies are finally presented. They cover the topics of a connection between ICT and space services, development of a space-related information package for dependency analysts, and adaptation of the existing methods and application of the method prototype for space service dependency analysis.

Sammanfattning

Samhällsviktig verksamhet beror i allt högre utsträckning på rymdtjänster som navigation, positionering, tidshållning, och kommunikation. Förståelsen kring hur dessa rymdberoenden påverkar samhället är dock låg hos såväl yrkesutövare och forskare som samhället i stort. Ett möjligt sätt att begränsa kaskadeffekter från störningar hos rymdtjänster skulle därför kunna vara att utföra beroendeanalyser.

Den här uppsatsen syftar till att bidra till utvecklingen av en metod för rymdberoendeanalyser genom att identifiera lämpliga faktorer och metoder att inkludera i framtida metodutveckling. Som ett led i detta arbete har följande forskningsfrågor besvarats:

- Vilka metoder för beroendeanalys från litteraturen kan vara relevanta för beroendeanalyser av rymdtjänster?
- Vad finns det för viktiga faktorer att beakta i ett potentiellt ramverk för beroendeanalyser av rymdtjänster?
- Hur kan ett ramverk för beroendeanalys av rymdtjänster utformas?

Viktiga koncept presenteras i kapitel 2. *Samhällsviktig verksamhet* definieras som ”verksamhet, tjänst eller infrastruktur som upprätthåller eller säkerställer samhällsfunktioner som är nödvändiga för samhällets grundläggande behov, värden eller säkerhet” (MSB, 2020, p. 1). *Risk- och sårbarhetsanalyser* beskrivs ur ett juridiskt perspektiv och en koppling till beroendeanalyser uppmärksammas. *Beroenden* och *kaskadeffekter* presenteras med hjälp av kritisk infrastruktur, och följs av en redogörelse för *beroendeanalyser* och modern forskning på området. Kapitlet avslutas med en presentation av *rymdtjänster* och dess plats i *rymdvärdekedjan*, samt beskrivningar av vanliga tillämpningar, hot, och typiska karaktärsdrag.

I kapitel 3 skildras uppsatsens metodik. Projektet genomförs med en explorativ ansats i form av dels en litteraturstudie, dels en intervjustudie. Genomförandet av litteraturstudien influeras av ett ramverk för genomförande av en *scoping study,* som delar upp arbetet i fem steg. Data samlades in från tjugoen dokument med öppen och axiell kodning. I intervjustudien intervjuades fyra deltagare från Lunds universitet, Myndigheten för Samhällsskydd och Beredskap (MSB), Luftfartsverket (LFV), och Totalförsvarets Forskningsinstitut (FOI). Intervjuerna var semistrukturerade och frågorna kretsade runt teman som framträtt i litteraturstudien.

Resultat och analys presenteras i kapitel 4. I arbetet identifierades nio beroendeanalysmetoder och fjorton faktorer som bedöms vara relevanta vid genomförandet av rymdberoendeanalyser. På en sektornivå är metoderna överlag expertbaserade, eftersom den typen av metoder är fördelaktiga i fråga om robusthet i systemet, informationsdelning, tillgång till data, och resurseffektivitet. På en aktörsnivå föreslås mer tekniska metoder, som delar likheter med vanliga riskanalysmetoder som återfinns i industrin. Faktorerna som framträdde från litteratur- och intervjustudierna kretsar kring temana *incitament, utförande, resultat och indata,* samt *sekretess.*

Till sist förs en diskussion i kapitel 5, följt av slutsatser i kapitel 6. Värdet av att utföra beroendeanalyser, och alternativa sätt att uppnå samma syften diskuteras. Dessutom presenteras en metodprototyp baserat på de faktorer och metoder som identifierats under studiens gång. Avslutningsvis presenteras förslag på fortsatta studier, vilka kretsar kring en möjlig koppling mellan informations- och kommunikationssystem och rymdtjänster, utveckling av ett informationspaket för beroendeanalytiker, samt anpassning av identifierade metoder och implementering av prototypmetoden för beroendeanalyser av rymdtjänster.

List of Abbreviations

CI	Critical infrastructure.
GNSS	Global navigational satellite system.
ICT	Information and communications technology.
LFV	Luftfartsverket *(Swedish aviation agency).*
LTH	Lunds tekniska högskola *(Faculty of Engineering at Lund University)*
MSB	Myndigheten för samhällsskydd och beredskap *(Swedish civil contingencies agency).*
PNT	Position, navigation, and timing.
RVA *(RSA)*	Risk and vulnerability analysis *(Risk- och sårbarhetsanalys).*
FOI	Totalförsvarets forskningsinstitut *(Swedish defense research agency).*
VSF	Vital societal functions.

Table of Contents

1. Introduction

Vital societal functions (VSF) and critical infrastructures (CI) can be found across all sectors of society. From energy production and telecommunications to healthcare, finance, water and food supply, VSF and CI ensure the continuation of society during crises (MSB, 2014a, p. 12). VSF and CI depend to some extent on each other, resulting in cascading effects in the event of a disruption to one of them, as described by MSB (2009, pp. 31–68). One such example is space infrastructure (Georgescu et al., 2019, p. 79), which according to a report by OECD (2019, p. 67), is considered a CI by Belgium, France, Spain, and Great Britain. While Sweden does not have a government mandated list over what constitutes CI[1], MSB (2021c) also views space infrastructure as a CI. Georgescu et al. (2019, p. 80) present an overview of the reliance of various CI sectors on space CI, where the strongest interdependencies are found in relation to global navigation satellite systems (GNSS) and communication systems. Other interdependencies are found in services such as meteorology or remote sensing, which are used by almost every CI sector. On a societal level, Lindström (2021, p. 7) describes how space dependency has increased to the point where several countries are investing in space defence capabilities, such as anti-satellite weapons as well as protection against them, in order to protect their infrastructure. Most importantly, Lindström notes that neither the nature of these dependencies, nor the potential consequences of a disruption, are clear. Given this lack of understanding, and apparent criticality of societal space dependencies, actors and society at large could benefit from investigating their dependencies on services stemming from space infrastructure.

In order for organisations to manage the risks associated with such dependency on VSF and CI, dependency analyses can be conducted as part of a Risk and Vulnerability Assessment (RVA, *in Swedish: Risk- och Sårbarhetsanalys, RSA*). For the vast majority of public sector agencies in Sweden, conducting RVAs are required as per MSB's regulations (MSBFS 2015:4, 4-5 §§; MSBFS 2015:5, 4-5 §§; MSBFS 2016:7, 4-5 §§), which also specify *identification of critical dependencies* as part of an RVA. Both the RVAs in general, and the

[1] The sectors mentioned for Sweden by OECD are simply examples taken from MSB (2014a, p. 13). Sweden does not currently identify critical sectors. Rather, they state that CI and VSF can be found in all societal sectors (MSB, 2020).

identification of critical dependencies are sometimes perceived as difficult and lacking in method (Eriksson et al., 2020, pp. 32, 57–59; Rönnåker & Wennerbeck, 2020, p. 56). Previous efforts aimed at addressing the issue of performing dependency analyses have been done by Johansson, Svegrup, et al. (2015), who conducted an inventory of available dependency analysis methods useful for supporting the mandated RVAs. They made two conclusions. First of all, they found that few methods lived up to demands specified by MSB in a workshop. Secondly, they suggested efforts aimed at increased development of general method support, as well as research on methods for specific contexts. Such research was later conducted by Rönnåker and Wennerbeck (2020) in a master thesis focusing on dependency analyses on electrical power. Agreeing with Johansson, Svegrup, et al. (2015), found that most methods were developed for general dependencies rather than specific infrastructures such as electrical power, and that practitioners expressed a need for more concrete support with regard to the conduct of dependency analyses. Rönnåker and Wennerbeck suggested several improvements, one such being for methods to include more support on various factors, and to validate the choice of these factors in collaboration with relevant actors. Rydén Sonesson et al. (2021, pp. 6–7) also came to the same conclusion in a combined document and interview study, where they emphasise a lack of consistency in methods among the documents found, and the expressed notion of respondents that dependency analyses are conducted as part of other activities of the RVAs. In summary, dependency analyses seem to lack useful method support, both in general as well as with regard to specific domains.

Given this apparent shortage on useful method support, and the increased reliance and dependency on space services across various sectors of society, there seems to be a need for development of a method applicable to dependencies to space services. This thesis investigates current methods, identifies suitable ones for application to space dependencies, proposes important factors to consider for future methods, and presents a prototype of a method.

1.1. Purpose and research questions

The purpose of this thesis is to contribute towards the development of a method for space dependency analysis, in order to address the lack of method support and increase the capability of society to deal with disruptions of space services. A step in this direction is to identify important factors useful for such a method, expanding on the research by Johansson,

Svegrup et al. (2015) and Rönnåker and Wennerbeck (2020). This thesis will therefore aim to answer the following research questions:

- What methods for dependency analysis found in the literature can be relevant for space service dependency analysis?
- What are important factors to address in a potential method for space service dependency analysis?
- What is a possible design of a method for space service dependency analysis?

2. Conceptual framework

In the following section, the relevant context and concepts are briefly described. Initially, *vital societal functions and critical infrastructures* are explained, followed by *risk and vulnerability analyses* and the Swedish regulations governing these analyses. The concept of *dependency* is then introduced in the context of critical infrastructure. In relation to this, *cascading effects* are briefly described, before a contextualisation of *dependency analysis* is provided. Finally, an account is presented on *space services*, their usage in society, possible threats, and unique characteristics of these services in relation to other vital societal functions and critical infrastructures.

2.1. Vital societal functions and critical infrastructure

In the Swedish context, MSB (2020) defines the concept of Vital Societal Functions (VSF) and Critical Infrastructure (CI) (in Swedish *samhällsviktig verksamhet*) as maintainers of societal functions necessary for ensuring the needs and values of society[2]. This definition does not specify which societal functions or infrastructures are vital or critical. Instead, MSB (2021a) provides an extensive list containing examples that are divided into 14 different societal sectors to help practitioners identify them.

2.2. Risk and vulnerability analysis

There are several reasons for conducting a risk and vulnerability analysis (RVA). MSB (2021b) lists three types of reasons relating to support functions: as a decision basis for decision makers, as a basis for risk communication, and as a basis for land use planning. Swedish public actors are furthermore motivated to conduct RVAs because they are required as per regulations on the municipal (MSBFS 2015:5), regional (MSBFS 2015:4), and governmental agency (MSBFS 2016:7) levels risk and vulnerability analyses. According to the above regulations, RVAs should contain method descriptions of the RVA, actor descriptions, identified VSF and CI, critical dependencies, vulnerabilities, as well as threats and risks. They should also contain a description of any need for action due to results found in the RVA.

[2] Due to translational issues, the word function is applied in two different manners: functions (as in *verksamhet*) are necessary for maintaining functions (as in *funktioner*).

2.3. Dependency & cascading effects

In their article on critical infrastructure interdependencies, Rinaldi et al. (2001, pp. 13–14) describe the concepts of *dependency* and *interdependency*. Dependency is "a linkage or connection between two infrastructures, through which the state of one infrastructure influences or is correlated to the state of the other" (Rinaldi et al., 2001, p. 14), and interdependency is a "bidirectional relationship between two infrastructures through which the state of each infrastructure influences or is correlated to the state of the other" (Rinaldi et al., 2001, p. 14). For this thesis, interdependencies are viewed as a subset of dependencies, and will alternate between the two words depending on the context.

Closely related to the concept of dependency is the consequence-focused *cascading effect*, which has gained traction among practitioners and academia (Johansson, Hassel, et al., 2015, p. 2). This concept is often used to describe the serial consequences of a specific failure. One example is Hurricane Sandy, which occurred in the United States in 2012 when a power outage led to fuel pumps not working, subsequently disrupting power generators (OECD, 2019, pp. 30–31). According to the OECD, this interdependency and the realised potential for cascading effects were not anticipated by stakeholders.

2.4. Dependency analysis

Benefits of dependency analysis are described by MSB as: contributing to better continuity planning and aggregated RVAs, a basis for resource allocation, activity priorities, and decision making, as well as facilitating coordination between actors engaged in crisis management (MSB, 2009, p. 17). The same regulation that mandates RVAs to be conducted, also mandates dependency analyses to be conducted as part of the RVAs. For the relevant public actors, there is then an added regulatory requirement to conduct dependency analyses.

Relating back to system perspectives, dependency analyses can be conducted with a plethora of perspectives. In a needs study conducted by Johansson, Svegrup, et al. (2015, pp. 15–18), eight criteria for a suitable dependency analysis method were developed. They provide examples of perspectives which dependency analyses can address. One perspective is the *type of decision* which the analysis is to act as a basis for. These decisions can be either proactive or made during an active crisis. Related to this is the level of detail required for the analysis. The results of the analysis could be purely qualitative, quantitative, or something in-between. Another perspective is *analysis type*, where the analysis can make use of either some specific scenario, no scenario, or a multitude of scenarios in an all-hazard approach. Time is also an

important perspective, which in the context of VSF and CI can be divided into, for example, hours, days and weeks, and years.

Socio-technical systems are found at different levels of society. Dependency analyses can focus on one or several such levels. The workshop identifies four specific levels, the sectoral, functional, organisational, and component levels. Analyses can also utilise various geographical levels. In the Swedish context, they are usually divided into national, regional, or municipal level. Finally, it is important to be clear about what type of knowledge is gathered in the analysis. For VSF and CI, data is described, in the workshop, as available in the form of expert knowledge, historical data, technical data, or economic data.

Dealing with the multitude of perspectives on dependency analysis is complicated. For this reason, analysts and practitioners make use of method support which come in different forms. Johansson, Svegrup, et al. (2015, pp. 7–14) separate these into eight categories. *Frameworks* are barely considered method support. They are instead used to describe important factors to address when conducting the analysis. The paper by Rinaldi et al. (2001) and the dependency wheel by KBM (2008, p. 5) are examples of frameworks. *Empirical methods* make use of historical data to complement expert analyses. *Agent-based methods* apply complex adaptive systems to model infrastructure systems as a network of individual agents. *System-dynamic* methods utilise control theory tools to model system behaviour mathematically. There are also financial models, which apply *input-output methods* to describe the economic interactions between sectors. Using network theory, the *infrastructure-based methods* model technical infrastructure as nodes and arcs connecting the nodes. The methods vary in level of detail, ranging from purely topological dependencies, to functional and geographical dependencies. The relatively novel *flow-based methods* illustrate dependencies implicitly as flows of information, resources, services, populations etc. Finally, *hybrid methods* utilise combinations of the above methods, in order to aggregate the benefits of each.

2.5. Space services

Space services are based solely on flows of information, and can be divided into the general categories of *positioning, navigation, and timing* (PNT), *earth observations*, and *communications* (Acker et al., 2011, p. 5). Different sectors of society make use of these unseen services in different ways, with various levels of dependency (Penent, 2019). Georgescu et al. (2019, pp. 79–120) exemplify space interdependencies within ten CI sectors. GNSS and communication systems are the most important services provided by space

infrastructure, but meteorological and remote sensing services are also important across most sectors. Often, the dependency on space infrastructure is manifested in the form of increased efficiency, such as airports being able to handle larger flows of traffic, but the infrastructure also provides unique services such as handheld long-range communications and surveillance of locations with restricted air space.

The energy sector reduces costs by for example utilising both remote sensing and GNSS to monitor CO_2 emissions globally, and the food sector can increase yield through precision agriculture (Georgescu et al., 2019, pp. 82–88). A similar efficiency increase is seen within aviation, where performance based navigation (PBN) using high precision positioning data allows for flights with less environmental impact (PwC, 2018, p. 104). Whitty & Walport (2018, pp. 34–41) provide estimations of time accuracy required for information and communication infrastructures (ICT), ranging from around 500 nanoseconds for 5G applications to around half a second for ATM transactions and banking, and emphasise the role GNSS can play as a redundant and comparatively cheap alternative to atomic clocks for time synchronisation. At the same time, however, they raise the concern of overreliance on GNSS.

A commonly used description of the space ecosystem is the space industrial value chain (PwC, 2018, p. 21). Within this perspective, value is created through three different segments: Upstream, midstream, and downstream. Which function to put in which segment differ slightly between actors, and the following perspective is deemed most suitable for the context of this thesis. Space infrastructure consist of ground stations, satellites, their daily operation, and the data produced in space, collectively known within the industry as the *midstream* segment of the space-derived value chain (Probst et al., 2016, p. 3). This enables space services, such as positioning, earth observations, and communications, to be utilised by end users, known as the *downstream* segment. However, none of these segments can function without the *upstream* segment, which constitutes research, manufacturing of space infrastructure as well as launch and support services.

Threats to the continuity of downstream space services are seen already at the upstream segment. Having access to space is essential for putting new infrastructure in orbit, and this access can be disrupted in the same manner as regular ground-based infrastructure. For actors without their own upstream infrastructure, space access must be provided by someone else, reducing system transparency and relying on the actor maintaining relations with providers.

The midstream space infrastructures are subjected to various threats. These threats are either natural or antagonistic. Natural threats in space are objects which might collide with important assets, and space weather. The bulk of objects in the near-Earth environment are non-functional artificial objects in space, often denoted as space debris (ESA Space Debris Office, 2021, p. 9). It can be anything from fragments of paint to rocket bodies or complete satellites, and due to their sheer velocity they present a significant danger to space crafts (ESA, 2005). The danger is growing mainly due to the increase in regular space activity, but also due to destructive anti-satellite weapons tests (Weeden & Samson, 2022, p. 05–01). Space weather on the other hand originate from stars, mainly our Sun (ESA, n.d.). Apart from slow-onset hazards such as component degradation from radiation, there is also the threat of sudden-onset large scale *coronal mass ejections* (CMEs) or *solar flares*. Acute consequences from such events include not only the destruction of most satellites, but also of damage to CI on Earth, such as complete destruction of electrical transformer stations (Lindström & Waldenvik, 2004, p. 24). Current antagonistic threats range from kinetic physical attacks, similar in nature to debris collisions, and non-kinetic physical attacks, aimed at blinding sensors, to electronic jamming and cyber-attacks (Harrison et al., 2022, p. 4).

Irrespective of threat origin, one consequence for society can be seen as reduced availability of downstream services. So far, these incidents have been mostly temporary. Kessler and Cour-Palais (1978) expressed concerns that an exponential space debris knock-on effect might render congested orbits unusable for many years. This would present an issue to space services relying on these orbits, as well as any space mission passing through the debris space.

There are other important factors besides the above mentioned threats, which are important to the context of space services. The main difference is the physical domain of space-based infrastructure. Most satellites are not stationary relative to the ground infrastructure, existing instead in an international, three-dimensional dynamic environment where movement rather than location determines threat levels (Slann, 2016, pp. 6–7). Georgescu et al. (2019, pp. 23–24) further describes the context and mention a relatively low number of active satellites (in the lower thousands) collectively providing every single available space service to humanity. These satellites are of mission-specific design, preventing modularity and cross-system compatibility, preventing service redundancy in the event of hardware failure. Despite being mission-specific, these systems often serve a dual use purpose, weaving together civilian and military downstream services. This presents issues relating both to military authority over

availability of service[3], as well as military and national dependency on foreign commercial infrastructure. Such dependencies inhibit clear governance of the infrastructure which, combined with a limited ability to exert physical control and the ever-present threat of collisions, complicates vulnerability analyses conducted by end users not in control of their own space infrastructure.

[3] The American GPS for example utilised reduced resolution for civilian applications until the turn of the millennium, and still maintains capability to prohibit what the US Government considered as hostile usage, according to a statement made by Interagency GPS Executive Board (2003).

3. Methodology

This section describes the methodology applied throughout the thesis. Overall, it maintains a qualitative perspective, due to the explorative purpose and research questions of this thesis. This purpose often requires a need for flexibility with regard to methodology, while not requiring as precise methods as descriptive or explanatory research (Blaikie, 2010, p. 70). Such a flexibility is said to be achievable with qualitative methods (Blaikie, 2010, p. 215).

The choice of conducting purely exploratory research rather than descriptive or explanatory as motivated by the lack of data and low volume of research on space dependency analysis methods. As explained by Blaikie (2010, pp. 70–71), topics or contexts where available knowledge is lacking necessitate an explorative approach as a starting point.

At the onset of the thesis, understanding of the topic and direction of the project was achieved by conducting an initial review of the literary domains of space services and dependency analysis methods. Initial dependency research knowledge was based on the MSB report by Johansson et al. (2015) and the master thesis by Rönnåker and Wennerbeck (2020). Starting points for the topic of space infrastructure dependencies were a book by Georgescu et al. (2019) and an article by Penent (2019). The literature was put to use in the conceptual framework as background knowledge, as well as for informing the direction of the study. Following this initial review, a literature study focusing on research papers and public reports was performed, from which questions for the interviews emerged. Results from the interviews together with the previous document analysis were then combined, forming the basis for the final analysis. These steps are described further below.

3.1. Literature study

The purpose of the literature study was to identify dependency analysis methods relevant for space service dependency analysis, as well as factors useful in the development of a future space dependency analysis method

The overarching literature study was mainly guided by the scoping study framework proposed by Arksey and O'Malley (2005, pp. 21–22), who state that a scoping study is capable of providing both breadth and depth in the mapping of a research area. This type of study is applicable when, for example, assessing and condensing current research activity, as well as relaying these findings to practitioners. Scoping studies can also identify gaps in research, in which case the study has to be more all-encompassing, in order to not produce artificial gaps.

The suggested framework consists of five stages, plus an optional stage called *consultation* which is discussed in the interview subsection of this thesis. The five stages are: *identification of research question*, *identification of relevant studies*, *selection of studies for inclusion*, *charting of data*, and *collating, summarizing, and reporting the results* (Arksey & O'Malley, 2005, p. 22). These stages are performed iteratively as deemed suitable for ensuring sufficient coverage of the literature.

The scoping study framework was suitable for this thesis due to the different stages being descriptive enough to segment the work into suitable pieces, while also being coarse enough to give leeway for the researcher to implement the framework in a manner suitable for the project at hand. Systematic review methods might have provided a more robust descriptions of the workflow, but would not have been as easy to modify or adjust. On the other hand, a limited initial literature review would have allowed for any implementation as seen fit, but would not necessarily have produced the type of documentation needed for a transparent analysis.

Arksey and O'Malley (2005, p. 22) put emphasis on the importance of transparent documentation, for the purpose of replicability. According to Blaikie (2010, pp. 216–217) and Alvehus (2019, pp. 126–127) however, replicability is not necessarily meaningful to strive for in qualitative research, since the qualitative researcher, merely by participating in research, produces an unreplicable outcome. Instead of replicability, Alvehus (2019, pp. 127–134) discusses other types of validity as ways to increase research quality. In this context, transparency is presented by Alvehus as a strict requirement for enabling any sort of quality assessment. At the same time, complete transparency of substantiating qualitative data is said to be difficult to provide, as the analysis to some extent relies on undocumented subjective impressions. The suggested focus is instead on transparency of the process of reasoning and representation, which enable a critical review of the work.

The scoping study framework focuses on academic primary research, implicitly excluding large parts of the *grey literature*[4]. In this thesis however, grey literature is essential as the

[4] Grey literature is defined in this thesis as "that which is produced on all levels of government, academics, business and industry in print and electronic formats, but which is not controlled by commercial publishers." Paez (2017, p. 233)

dependency analyses conducted in practice are not necessarily published in peer-reviewed journals. Rather, this type of literature is published as reports aimed at decision-makers or other practitioners. According to Paez (2017, pp. 234, 236), grey literature is useful in systematic reviews since it provides data which cannot be found in peer-reviewed sources. At the same time, the author presents some challenges relating especially to the systematic review format, such as deviating format of documents, lack of indexing information, and variability of the abstracts. Since this thesis utilised a scoping study approach, with broad qualitative criteria for inclusion and coding, the above mentioned issues were managed by maintaining the open-ended, redefining, reflexive and iterative approach proposed by Arksey and O'Malley (2005, p. 22).

Another issue with grey literature mentioned by (Paez, 2017, p. 236), is the possibility of missing out on wide segments of literature due to not looking in the right place. For this thesis, that issue is further enlarged by the secretive nature of many dependency analyses. Applying an explorative and qualitative approach was in this case beneficial since it did not force the results to be of any certain saturation level, magnitude, recurrence, or format. Finally, the lack of peer-review within grey literature presented the most pressing issue. Without a peer-review process, the level of scrutiny which had to be applied during this thesis was increased. However, as the grey literature used within this thesis mainly consisted of analyses rather than methodology research, and the focus being the method of the analyses rather than their results, the consequences of potentially low quality were deemed to be acceptable given a transparent enough method.

3.1.1. Data collection

Applying the framework proposed by Arksey and O'Malley (2005), the first stage, *identification of research question*, corresponds to the research questions stated in the introduction to this thesis. During the second stage, *identification of relevant studies*, studies were identified in database searches, snowballing from references in already identified literature, and well as from recommendations by researchers at FOI and the Faculty of Engineering at Lund University (LTH). The database searches were performed in the Lund University Libraries database as well as a database provided by FOI library services. For each search, only the first one hundred results were screened, in order to limit the magnitude of documents to process. In both databases, the terms used were *dependency AND analysis* and *beroendeanalys*. The latter search yielded only one result, putting the total number of screened results from the databases at 201 documents. Both reverse and regular snowballing

were applied on the documents found. Reverse snowballing was conducted in Google scholar using the "Cited by" feature, while regular snowballing was done using the reference list of the document.

A three-step reduction process was applied to the literature during the second stage in order to discern relevant documents. Initial screening was performed by evaluating the document title. This evaluation focused on purpose, result, and type of keywords. For example, "dependency analysis" is a common procedure in software development, and such documents were often identified and excluded at this step. 65 documents were selected at this stage from the database searches, snowballing, and recommendations.

The second step consisted of reading the abstracts and conclusion, whereupon the relevancy was further determined depending on factors such as system level, type of result, and context. For example, *Dependency Defence and Dependency Analysis Guidance* by Johanson et al. (2003, p. vii) passed the first step, but was disregarded at the second step due to the context being Common Cause Failures (CCFs) in nuclear power plant safety. Their goals were stated to be identification of failure mechanisms and provision of safety improvement suggestions, as well as specifics on tailoring CCF parameters to specific plants. These topics were deemed to be too domain-specific to be of large use for this thesis, resulting in exclusion of the report at this step in the process.

In the third step, the documents were read in full, with focus on method descriptions. Many of the space dependency-focused documents were excluded at this point, as they provided little substance in terms of how dependencies were identified. One such example is the chapter on critical space infrastructure interdependencies by Georgescu et al. (2019, pp. 79–139), which had a suitable title, relevant abstract, and provided great insights on space infrastructure dependencies, but did not describe how such dependencies were mapped or identified. At this point, the number of documents had been reduced to 26.

In stage three, *selection of studies for inclusion*, a final selection of documents for study was made. This included most of the literature already screened, with few exceptions. Documents removed at this stage had no previous clear reason to be disregarded but did not, in light of an emergent understanding of the literature and direction of the thesis, provide useful information. *Why Satellites Matter* by Acker et al. (2011) was one such study. It was funded by the European Satellite Operator’s Association and claimed to present an "independent, fact-based view on the future of commercial satellites" (Acker et al., 2011, p. 96), but was

deemed speculative, one-sided, and as having an agenda of bolstering commercial space interests. Together these factors led to exclusion despite it conducting some sort of analysis, as the quality of both the method and the results were felt to be subpar. In total, 21 documents were included in the final selection for analysis.

3.1.2. Data analysis

Document analysis was conducted as part of the fourth stage, *charting the data* in combination with the data condensation part of stage five, *collating, summarizing, and reporting the results* of Arksey and O'Malley (2005). This process was based on two types of coding, denoted by Blaikie (2010, pp. 211–212) as *open* and *axial* coding. Open coding was conducted in two rounds. The first round consisted of applying categories derived from the studies of Rönnåker and Wennerbeck (2020) and Johansson et al. (2015), as well as some categories which were identified during the second and third stages of the document analysis. The choice of mixing category origins was made in order to yield a starting point, from which new categories could potentially develop. Literature was then manually coded using the initial categories, in parallel with developing an understanding of how these categories fit within, and were of use to, the context of this thesis. The categories were wide in scope, without strict definitions, in order to fit the different contexts of the documents, as well as to avoid information falling into gaps between the categories. Upon completion of the first coding round, sets of questions related to the categories were developed to aid in the second round of coding, as well as to produce useful input to the interview process. The updated definitions, added categories, and question sets where then implemented during the second round of open coding, presented in Appendix C. After this second round, information gained from the open coding were axially coded into themes by identifying common characteristics among the categories. These themes were then used as foundation for both the subsequent interviews and the final analysis.

3.2. Interview study

The interview study served dual purposes. As suggested by Arksey & O'Malley (2005, pp. 28–29), interviews can improve the applicability of scoping study results. Such consultations were essential in order for this thesis to propose factors which actually aid actors in conducting space service dependency analyses. Furthermore, the interview study also served the standalone purpose of allowing for phenomena and perspectives not found in the literature to emerge. In order to achieve both of these purposes, expert consultations were arranged as

semi-structured interviews. Such interviews consist of a battery of questions around which the researcher adapts the interview to the current situation (Höst et al., 2006, p. 34). The choice of semi-structured interviews was made as it posed a compromise between the openness of a purely explorative interview for the purpose of identifying additional important factors, and the more structured interview suitable for validation of previously identified factors (Kvale & Brinkmann, 2014, p. 148).

3.2.1. Data collection

The interview questions were developed around the themes which emerged during the preceding document analysis. The development process consisted of brainstorming questions related to the categories from the document analysis, sorting them into the overarching themes, identifying overlaps among questions, as well as prioritising which questions to ask. With the ambition to create a valuable and pleasant interview experience, inspiration was taken from a semi-structured example interview by Kvale and Brinkmann (2014, pp. 165–182), which contained information on how to prepare for interviews, write interview manuscripts, as well as how to formulate questions and follow-up questions. The final interview questions were first written thematically, and then dynamically, as per the recommendation of Kvale and Brinkmann (2014, p. 173). The thematical questions were formulated verbose and with purpose. Not for the purpose of being asked to the respondent, but for providing framing and orientation for the researcher. These were then translated into dynamic questions, which were mostly shorter as well as simpler in terms of academic terms, length, and conceptual detail, than their thematic counterparts. Questions were also divided into *initial*, *direct*, *follow-up*, and *structuring questions* according to the description of Kvale and Brinkmann (2014, p. 176). The initial questions on each theme were of a wide and scoping nature, whose purpose was to allow the respondents to discuss the themes without having an impression imposed by more direct questions. Barring any exceptional topics demanding further attention, these questions were then followed by the direct questions. Direct questions were more precise in scope, often relating to one of the categories developed in the document analysis. Follow-up questions acted as either bridges to related topics, or as a possibility for closer scrutiny of certain aspects in the previous question. Finally, once the theme had been sufficiently discussed, or the allocated time had run out, structural questions were posed in order to refocus the discussion to the next theme.

The interviews were documented by note-taking. Transcription of recordings was considered but due to interviews being conducted online, and security concerns, the option of transcribing

was not feasible. Conducting notetaking in parallel with facilitating interviews meant that evaluation and interpretation of information had to be conducted mentally and condensed into a note, while at the same time enabling the continuation of the interview. While intensive, this setup also meant that only impressions and information perceived as being relevant were preserved. Thus, data which might have been useful at a later stage was disregarded. This reduced the magnitude of data to treat in the following analysis. However, by not preserving the whole verbal interview as either text or recording, primary data transparency was reduced leaving only the filtered data. As stated previously, transparency of representation was one of the requirements for allowing proper quality assessments. As the subsequent analysis was solely based on the notetaking, transparency of representation is still preserved, as the notes informing the analysis are available on request from the author. Furthermore, as the thesis was explorative, the downsides of not capturing the whole interview were considered to be offset by the benefits of conducting a mental condensation of the data already at the scene of the interview. This point is also raised by Kvale and Brinkmann (2014, pp. 219–220), who argues that such filtering can act as preservation of key content.

Four interviews were conducted. Seven individuals were contacted in total, out of which three never responded but none declined explicitly. This number is below the usual interval of 15 +/– 10 interviews mentioned by Kvale and Brinkmann (2014, p. 156). Given that space dependencies are seemingly not prioritised to any large extent by many actors, the pool of potential participants was limited from the start, with only a few of these actors known to the author. The low number of participants inhibited generalisations. It also rendered data saturation verification impossible. Nevertheless, as interviews and their analyses are resource intensive, such a small number of interviews were beneficial for maintaining a manageable workload during the thesis, as argued by Kvale and Brinkmann (2014, pp. 156–157). They further argue for the analytical benefits of having the capacity for deeper analyses of a few interviews, as opposed to having to skim a large quantity of interviews. Such an approach was thus suitable for this project, given the explorative purpose and research questions of the thesis. In light of these circumstances, purposive sampling of interviewees was applied. This sampling method is described by Blaikie (2010, p. 178) as a non-probability method where sampling is done by selecting the most relevant cases for a given research purpose. In this case, the aim was to include as diverse a population as possible, featuring both societal actors in positions of sectoral responsibility, space service experts, and practitioners with previous experience of conducting dependency analyses. The final sample included representatives

from LFV, MSB, FOI and LTH. No private actors were interviewed. Including such actors could have provided useful input, but as private actors in Sweden generally do not regard issues outside of business continuity and development and view the state as responsible for enabling participation of private actors (Olsson et al., 2017, p. 39), it was deemed that prioritising public actors would provide more information dense interviews. At the same time, inclusion of private actors could have yielded method factors which could enable these actors to partake more in societal dependency analyses.

3.2.2. Data analysis

A slightly reduced coding process was conducted upon completion of the interviews, as the framing of the interview already was a result of themes derived from coding, as well as due to the filtering which had taken place at the time of the interviews. The notes were sorted into the established themes. Results from the document analysis were then compared with the processed interview notes to identify discrepancies, overlaps, and emergent phenomena between the two. With the knowledge gained from this comparison and preceding analyses, the suggestions regarding factors to address in a future method for space dependency analyses were formulated.

3.3. Delimitations

The focus of this thesis is on dependency analyses of space services. As such, it will not present any concrete results on how societal dependency on space infrastructure actually manifests. The scope is limited to important factors and existing methods and will not seek to develop a complete method support for practitioners. Rather, the ambition is to present a foundation upon which other studies can build further. The thesis will also restrict the scope to public sector agencies on local to national level. The private sector will not actively be included in the thesis.

RVAs showcase vulnerabilities, which make them sought-after by antagonistic actors. For this reason, distribution of RVAs is becoming increasingly restricted. This thesis will only make use of open-access documents, and as a result, provide a limited amount of examples from practice.

4. Results and analysis

Below, the applicable methods found in the literature are presented and analysed, followed by a description of the identified factors. These factors are subsequently analysed in relation to the results from the interview study, together with factors which emerged from the literature, but were discarded following the interviews.

4.1. Literature study

The complete list of literature can be found in Appendix A. The literature exemplifies both methods and factors, as well as provide empirical basis for the relevancy of aforementioned factors and methods.

4.1.1. Methods

Eight methods are determined as relevant for dependency analyses of space services. Their corresponding sources are listed in Table 1, together with a categorisation of the method as well as a short description of the source documents. The vast majority are expert-based methods, but both empirical and input/output methods are present as well.

Table 1: *An overview of the relevant methods found in the literature. Sources can be found in Appendix A*

TYPE	SRC	DESCRIPTION
Empirical	[2]	Report outlining the importance of timekeeping in the electric power sector. Dependencies are formulated as demands placed on timekeeping services for ensuring proper function.
Input/output	[3]	Economic analysis on how space infrastructure contributes to the European economy. Dependencies are derived from potential revenue loss share in the event of a complete disruption of space infrastructure.
Expert based	[4]	Descriptive analysis on how different critical infrastructure sectors in the UK depend on GNSS. Dependencies are derived from the qualitative knowledge of a partaking expert panel.
Empirical	[5]	Experimental research on how GNSS receivers are affected by various types of antagonistic attacks. Component level dependency is discussed with regard to protection against attacks.
Framework, expert based	[12]	A report presenting a method for conducting organisation-level and aggregated dependency analyses. Provides some tools as aid to conduct analyses.
Expert based	[13]	A paper presenting a workshop-based method for eliciting knowledge about infrastructure resilience.
Expert based	[15]	A paper presenting a combined questionnaire-workshop method for critical infrastructure. Dependencies are described from the perspective of both the receiving and providing actor.
Expert based	[16]	A paper implementing the workshop-based *storyline* method for impact analysis of flooding using the graphical *CIrcle* tool

In the framework presented by MSB, (2009), an overarching structure for system and actor level analysis is presented, containing suggestions on which entity to conduct what part of the full analysis. The report does not describe in detail how certain processes, such as dependency identification, should be performed, but presents a three-step process. The steps are (1) *Selection and description of relevant functions*, (2) *Identification and evaluation of external dependencies*, and (3) *Aggregated analysis* (MSB, 2009, pp. 21–27). The first and last steps are preferably conducted by a system-level actor such as municipalities, regions, or public agencies, while the second step is performed by the actor or function investigated. Such a division of labour is suitable for the overall analysis as the different actors will contribute different perspectives and have access to different kinds of information and data. For example, Rydén Sonesson et al. (2021, p. 7) describe how individual actors mainly look at their own dependencies, rather than how others depend on them. Some of these actors also wish for a central actor to coordinate interdependency work. In a workshop by Johansson et al. (2015, pp. 40, 43), various public actors suggest that data collection, as well as dependency analysis should take a bottom-up approach, with the local actors conducting the bottom-level data collection and their own direct dependency analysis. Thus, it seems that the distribution of responsibilities suggested by MSB (2009, p. 22) are in line with the notion presented by actors at different societal levels. Furthermore, by combining this framework with other methods useful at the different steps, a more detailed method can be developed.

Johansson et al. (2015, p. 36) proposed a methodological perspective which was found to be useful when describing the analyses, factors, and methods. This perspective groups analyses into two different approaches: *functional*, and *physical*. Analyses using the functional approach are described as utilising less demanding models, being faster, and more qualitative than analyses with a physical approach. The functional approach is also described as being on an aggregated societal level, addressing dependencies between various functions in a generalised manner using less specific data. Such analyses are said to not possess the same security issues as physical analyses, which require more detailed local data. Johansson et al. (2015, p. 36) exemplify both the methods and types of data which can be applicable using the two approaches. The physical approach is described as using models such as network theory or engineering models, while some models mentioned with regard to the functional approach are the economical input-output model, flow-based models, and workshops. Input data for the physical approach are often technical data such as production capacity, load, and facility data.

Examples of data associated with the functional approach are national economic data, and data from RVAs and continuity management.

The remaining methods presented in Table 1 cater to the two latter steps of the framework presented by MSB (2009). Relating to step 2, dependencies on organisational and component levels are mainly addressed by Hedtjärn Swaling (2015) and Falletti et al. (2019). Falletti et al. (2019, p. 2121) initially demarcates which type of antagonistic threats to treat, by evaluating the relevance of the component to the function it serves and the cost of the potential attacks. Once the choice of attacks to include have been made, the impact on receivers is evaluated and hazardous scenarios identified. The experiment by Falletti et al. (2019, p. 2123) is useful as it only *simulates* an attack on the receivers, by using software and a signal splitter connected to the antennas of the receivers. If the goal of an actor is to evaluate the consequences of jamming devices on receivers and technical systems, this setup could perhaps avoid the issue of possession of jamming devices, which is illegal for most civilian actors in Sweden (SFS 2022:511, 5 §). However, making assumptions on legal feasibility of experimental setups is not within the scope of this thesis, and such discussions should preferably occur in consultation with the Swedish Post and Telecom Authority. Irrespectively, getting primary data on how the physical systems react to disruptions in for example timekeeping, is beneficial for the actors to understand their dependence on space services, as it provides empirical impact data rather than relies on the knowledge of an expert. In line with the suggestion by MSB (2009, p. 23) that the actor itself or a hired external actor conduct the dependency identification and evaluation, there are two possible benefits for the actor conducting this sort of dependency analysis. First of all, it places the technical analysis in the hands of the practitioners, who might possess the detailed technical knowledge to a larger extent than the actors conducting the aggregated analysis. Furthermore, it provides an increased sense of security, as subsequent access to data can be granted as seen fit by the data owner/actor with respect to other conflicting interests.

Hedtjärn Swaling (2015, pp. 8–9) adopts a technical risk-based approach to the analysis of present and future dependencies of the electrical power sector on GNSS-based time keeping. The method corresponds to what is prescribed in step 2 by MSB (2009, pp. 23–25), and features identification of time-dependent functions and their requirements, followed by a consequence assessment and final general discussion. Technical systems often adhere to performance requirements which can be used to identify dependencies (Hedtjärn Swaling, 2015, pp. 18–19, 23–25; Whitty & Walport, 2018, p. 19). In these cases, dependencies are the

direct results of the implementation of a technical requirement. Using for example scenario building, the criticality of these requirements can be understood and identified as dependencies (MSB, 2014b, p. 13). Scenario building is also useful to identify dependencies not stemming from such performance requirements or functional dependencies, as the scenarios might highlight subpar operating conditions and emergent dependencies (Hedtjärn Swaling & Mossberg Sonnek, 2016, p. 42).

The third step of the framework by MSB (2009, pp. 25–28) details the aggregated analysis at inter-actor, sectoral, and societal levels. Methods applicable here differ from analyses at the organisational or component levels, due to increased issues related to information sharing between actors (Guldåker et al., 2019, p. 25; Johansson, Hassel, et al., 2015, pp. 37, 44) and varying incentive levels for participation (Rydén Sonesson et al., 2021, pp. 5–7). Not only should analyses at this level be capable of aggregating information from lower-level actors, but also allow the aggregated information to return to the relevant actors, in order to increase their awareness of themselves and their relation to the whole system (Johansson, Hassel, et al., 2015, p. 43). Information security issues and means of accessing the required data can be managed in different ways. Neither of the two aggregating studies on space service dependencies analyse technical data explicitly. PwC (2018) makes use of sector-level economic and statistical data from databases already treated with regard to information security, decreasing level of detail and avoiding the issue of not being allowed access to technical data from practitioners in the industry. Whitty and Walport (2018) on the other hand conduct a *Blacket review*[5] requested by the UK government, where an expert panel provides the input to the analysis. In this case, information security is dealt with by the expert panel providing general examples of dependencies, without presenting vulnerabilities of concrete actors or other sensitive information. For both of these studies, the result is a broad informative report on the general state of societal space dependency. At such level, however, there is some difficulty in returning useful information to relevant actors. There might be no new insight gained, apart from increased awareness of potential issues, when the level of

[5] A Blacket review is a type of study in the UK, described as: *"an expert-led, independent study, convened by the Government Chief Scientific Adviser to answer specific scientific and/or technological questions, and to inform policy makers"* (Whitty & Walport, 2018, p. 5)

detail in the distributed information is too coarse. Other methods might then be better in this regard.

Several documents apply an expert-based workshop approach to both aggregate and disseminate information. On the topic of critical infrastructure, Chang et al. (2014), Moon et al. (2015), and de Bruijn et al. (2016) conduct various forms of workshops in order to assess resilience, dependency structure, and vulnerability to floods. Chang et al. (2014, p. 422) ask experts to assess disruption and recovery levels at different time scales for a scenario, which after aggregation is presented in a workshop setting. In their specific case, thirteen infrastructure representatives correspond to "*a substantial proportion of major infrastructure organizations in the region*" (Chang et al., 2014, p. 424). Having a strong (yet manageable) representation is suitable as it raises awareness across larger parts of the system, as well as enabling more inter-personal relationships. The latter, together with increased trust between actors are raised as important factors for increased cross-sector resilience by Rydén Sonesson et al. (2021, pp. 5–6). Perhaps, an aggregating dependency analysis method which allows for such connections to form might yield more system resilience compared to methods which only output reports. The workshop is also aimed at creating a forum for feedback and revision, as well as forming a common perspective among the actors, on the current state of the resilience of the system (Chang et al., 2014, p. 424). This iterative approach is meant to improve the validity of the expert judgement process (Chang et al., 2014, pp. 428–429). Forming a common perspective using a consensus round is also done by Moon et al. (2015, pp. 331–332). Instead of conducting it as a group assessment however, the procedure was done individually to avoid certain bias in judgements. Depending on the purpose of the analysis, if it is to achieve the most "true" results, or to raise awareness for relevant actors, either approach might be more applicable. Collectively, these workshop-based methods are suitable for information security reasons as well. The data which is recorded need not to contain detailed information on concrete vulnerabilities, but rather, in the case of Chang et al. (2014) a qualitative ranking of disruption levels, for Moon et al. (2015), a quantitative estimation, or for de Bruijn et al. (2016), a qualitative impact assessment. During a workshop however, classified information can be made available on-site, without data transfer to external actors, by for example subjecting the participants to a security clearance beforehand (Guldåker et al., 2019, p. 49).

In summary, space service dependencies can be analysed through various perspectives, from component to societal level. Different methods are applicable at different system levels, and

conducting analyses at, as well as relaying knowledge between these levels, are beneficial for the overall understanding by the various actors of the system. The framework by MSB (2009) contains a useful structure for encompassing these different methods. Dividing the overall analysis into an actor/component-level analysis and an aggregated analysis, two methods have been identified as useful examples for a single actor to understand its component-level dependencies (Falletti et al., 2019; Hedtjärn Swaling, 2015), and five methods as useful at an aggregated level (Chang et al., 2014, 2014; de Bruijn et al., 2016; Moon et al., 2015; PwC, 2018; Whitty & Walport, 2018).

4.1.2. Factors

While the methods presented above are deemed useful for space service dependency analysis, they have not been designed with the domain of space services in mind. Based on the findings in the literature study, this thesis suggests that the most relevant factors that emerged, listed in Table 2, are to be included or addressed in a potential space dependency analysis method. Several suggestions were made by the literature itself regarding important factors to address during future analysis method development. The most applicable factors for this study are adapted to the space dependency context and presented in Table 3.

The factors identified in this study are expressed in a broad manner and could thus be applicable to other forms of analysis as well. They revolve around the general themes of *incentive*, *conduct*, *results and input data*, and *information security*. While the last theme is condensed into a single factor, it is by no means the least relevant. It is merely expressed as a single umbrella factor due to its many nuances and issues. The factors are analysed in relation to the interviews in the following section, divided into the themes above.

Table 2: *A list of the most relevant factors which are deemed important for the development of a method on space service dependency analysis.*

FACTOR	MOTIVATION
The method should:	
(1) Accompany expert elicitations with applicable *debiasing* techniques.	Judgement is burdened by cognitive bias. As a tool for increasing process validity and the quality of results, debiasing should be an integral part of the method.
(2) Address a large *range of hazards*.	Full disruptions in space services might have vastly different consequences compared to signal jamming, where the socio-technical system might not detect an erroneous service. Such discrepancies should be emphasised in the analysis, for example by using multiple scenarios.
(3) Be conducted by actors from the *corresponding analysis level*.	Operational level analyses should be conducted by the operational actor itself. This contributes to the actor's understanding of its own system, as well as spreads the burden of data collection for aggregated analyses. In a similar vein, the aggregated analysis should be conducted by an actor possessing a system-level perspective.
(4) Have a *functional approach* to societal and sectoral level analysis.	At these levels, an increase in the number of actors require a decrease in resolution in order to be manageable. These analyses also revolve to a larger extent around non-space-related interdependencies such as general flows of information, goods, or services, which does not require the same technical scrutiny.
(5) Have a *physical approach* to operational and component level analysis.	At these levels, the technological nature of space services is probably best understood using methods that can handle such detail, which corresponds to analyses with a physical approach.
(6) Include lower-level actors as *co-analysts* in aggregated analyses.	Instead of being considered data points for the aggregated analysis, lower-level actors can contribute to a higher-quality analysis by being part of the analysis discourse, as well as gain insights important for their own organisation.
(7) Incorporate *all levels of analysis*.	Understanding of actors' own space service dependencies are limited, reducing the available data for aggregation and higher-level analysis. In order to perform high quality aggregated analyses, space dependency data must manifest at lower levels first and be analysed at all system levels.
(8) Mitigate issues with *information sharing and data security.*	Dependency analyses, by nature, expose vulnerabilities in the object of analysis. For data to be voluntary provided by actors, they must in turn be provided with confidence that the analysis will not imperil them.

Table 3: *A list of the most relevant factors which are adapted from suggestions made in the literature.*

FACTOR	SRC	MOTIVATION
The method should:		
(9) Be *valuable* for analysis types other than for space service dependencies.	[7, pp. 44-46; 12, p. 83]	Space dependency analysis is a very limited domain. Providing value for other common analyses adds incentive for the analyst.
(10) Present various *incentives* for conducting a dependency analysis.	[7, p. 44; 17, p. 43]	Explicitly stating potential incentives can serve as a tool for providing an understanding of why the actor should perform the analysis.
(11) Provide *examples* of past events, common system layouts, common failure modes, and management strategies.	[7, p. 45; 17, p. 43]	Space services manifest in different ways in different systems. Providing information on these manifestations will assist the analyst in understanding their system.
(12) Provide information on how to perform *data collection.*	[7, p. 45; 9, p. 56]	Data collection is a large issue for space dependency analyses and thus something analysts might struggle with. Systematic data collection benefits both the operational and the aggregated analyses.
(13) Provide references and motivation for its own composition to raise *credibility*.	[17, p. 43]	Providing the basis for the method design adds transparency and simplifies validation of the method.
(14) Suggest *visualisation* formats suitable for common target audiences.	[7, p. 46]	Visualisation tools are useful for communication and understanding and are important given the hidden and indirect nature of space dependencies.

4.2. Interview study

Four interviews were conducted as part of the study, with participants representing FOI, LFV, LTH, and MSB, having a combined experience from sectoral coordination, dependency research, the space sector, organisational practice and security. Perspectives emerged from these interviews, which are related in this section to the factors in Tables 2 and 3.

4.2.1. Incentives

One participant had the impression that analyses were being conducted solely because it was mandated, which has a negative effect on the quality of the results. Providing proper purposes, by including the explicit mentioning of such *incentives* in a method support is thus beneficial to the quality, in agreement with factor 10. One participant did however emphasise organisational compliance as a useful incentive. This actor was required by law to maintain understanding of potential internal and external dependencies, risking both economic repercussions and full stop to operations if failing to comply. These incentives are further said to result in yet another incentive, meeting public expectations. When customers or the general public expect compliance, there is a risk of external critique when disruptions occur, and the actor are perceived as not fulfilling their legal responsibilities.

Several participants mentioned system robustness as an incentive for dependency analysis, from both a societal and an operational perspective. The strive towards general robustness, combined with having a method *valuable* for other types of analyses, as suggested by factor 9, might nudge actors toward incorporating explicit dependency analyses into other aspects of their robustness work. Some participants did mention that they do not view dependency analysis as its own process, which might indicate that analyses are already incorporated into other parts of the organisation.

A distinction was noted by the participants between proactive and reactive dependency analyses, with the former employed for avoiding the introduction of critical dependencies into the system all together. This requires intricate knowledge of how the space services are integrated into socio-technical systems, but is also comparatively easy to achieve in the design phase. One participant compared technical system design to “reverse dependency analysis”, as components or sub-systems, by serving a function, introduces a dependency. The comparison highlights the vagueness of what can be considered dependency analysis.

4.2.2. Conduct, input data & results

In general, the participants believed it to be useful to *include information on data collection, common dependencies, analysis errors, solutions, and biases* as suggested by factors 1, 11, and 12. One participant framed it as having the method perform most of the analysis, meaning that analyst should be able to focus on the novel aspects of their system, while the method could provide assistance in more commonly occurring features. The effort required by the analyst was deemed to be significantly larger when dealing with previously unknown dependencies in areas where the actor lacks competence. Relating back to the indirect and unseen nature of space dependencies, this might suggest an increased baseline effort for most actors. One participant raised the issue of having an organisation that trained and consisted mostly of specialists, which had more competence in understanding component and function dependencies rather than dependencies throughout the whole system. In order for a method support to be useful, it has to provide the full picture in different organisational settings without catering only to either generalists or specialists.

One participant highlighted the varying complexity of different space services, and the corresponding competence required to understand them. A suitable method would have to address these different services and their behaviour in full, which could be achieved by including a *range of hazards*, as suggested by factor 2. Having a hazard-oriented approach was further suggested by another participant. Simply studying the 'workflow-as-imagined' would, according to the participant, not contribute to the identification of previously unknown dependencies, as any identified dependencies would be the result of conscious decisions made during the system design.

Aggregated or overarching analyses were by all participants described as relying in some way on lower-level experts. However, unlike the suggestion by factor 6 to include lower-level actors as *co-analysts*, such experts were in general considered solely as data input, with the most relevant actor *corresponding* to that level conducting the analysis, in line with factor 3. For example, at an aggregated sectoral level, it was suggested that the sector responsible agency conduct the analysis. Such an approach risks excluding the lower-level perspectives in the aggregated analysis, which can be detrimental to the overall result and purpose. According to one participant, knowledgeable in the defence domain where operational and strategic perspectives have to collaborate, the operational perspective tends to be neglected and not understood by the strategic level. Gaining operational data without at the same time framing it in an operational perspective will limit the usefulness for actors at this level, who are

managing the sharp end of space dependencies. With this in mind, conducting analyses at *all levels* as stated by factor 7, might be a useful way of capturing these perspectives.

Regarding the choice of applying either a functional or physical approach to the method, the participants believed that both were useful as well as needed. Fast and coarse analyses were suggested as having a preliminary role, to be used as input data for a subsequent detailed analysis at the same level. While perhaps being the most robust way of conduct, it might be hard to motivate resource-wise. If limited to one of the two approaches, one participant considered the *functional approach* as suitable for aggregated analyses, while applying the *physical approach* at the organisational analysis, in line with suggestions by factors 4 and 5. The reasoning, as explained, is that decisions on a sectoral level are usually akin to "how should we allocate resources?" or "where do we need to raise awareness?" where functions rather than physical components or interactions are of interest. It was mentioned, however, that the functional approach, while disengaging from details, still needs to maintain credibility as a basis for decision-making. Such credibility was said to manifest to a larger degree using the physical approach, as the structured documentation and less qualitative nature of such an analysis make for a comprehensible decision-making basis. This potential lack of *credibility* in the functional approach could be addressed by factor 13. The method should then, as previously mentioned, provide arguments, for example in the form of transparent documentation of methods, uncertainties, and data, as to why the analysis is worth acting upon.

4.2.3. Information security

Relating to the topic of transparency, the participants mentioned the issue of opposing incentives between transparency and *information security*. The issue is described in several contexts by the participants who express the same sentiment as factor 8, that information security must be managed explicitly. From the perspective of the analyst, the need for security limits the viable scope of the analysis as well as the later dissemination of the results. The analyst might for example face the choice of getting access to data at the cost of not allowing the data to be included in the final report. Reports can be also become classified. Classifying a report can be perceived as a trust-generating choice allowing actors to provide more data, but can in addition hinder other relevant actors from taking part of the details. Two participants mentioned various requirements which are placed on an organisation dealing with classified reports. Personnel must pass a security clearance check, security agreements must be in place, responsible persons must be assigned within the organisation, secure facilities and rooms must

be constructed, and approved hardware must be obtained. For small or private actors, such requirements will hinder meaningful participation in a dependency analysis, thus reducing incentives for these actors to provide data.

A possible solution to the facility issue, as suggested by a participant, is for a larger actor to provide a venue for secure meetings. Such setups have been utilised previously by for example MSB, who conducted workshops with external actors in secure rooms. An issue mentioned with regard to this approach, which arises in a workshop setting, is the reluctance to share information with other actors, while being positive to sharing it with the analyst. Increasing trust could mitigate such occurrences, but might be hard to achieve if actors have no previous relationships to each other. Another solution suggested to the information sharing issue was to modularise reports, placing sensitive information in classified appendices rather than classifying the full report, the latter being common practice in at least one of the organisations. When choosing between fully obscuring the report or to omit certain data, this approach might be suitable instead.

4.2.4. Rejected factors

A factor which emerged from the literature and subsequently rejected, was experimental stress tests of dependencies using for example GNSS jamming or spoofing. One participant stated that while valuable, such a stress test is illegal to perform as a civilian actor, effectively inhibiting such an analysis strategy as part of a method. Another such factor being dismissed was using preparedness exercises as a tool for gaining dependency data. According to the impression of one participant, exercises are usually constructed in the opposite way, by testing known dependencies. Only limited understanding regarding dependencies would thus stand to be gained from such an exercise. Furthermore, in order for an exercise to generate a larger understanding, it would be too open-ended for other exercise purposes. One possible setup which was discussed were table-top exercises. However, throughout the discussion it became apparent that such a setup would be more similar to a conventional workshop rather than a proper exercise. Finally, the idea of avoiding some security issues by solely employing low-resolution actor data was dismissed by a participant. Even if data consisted of merely yes/no answers, the aggregated data were believed to present security risks.

5. Discussion

This thesis aims to identify relevant methods which might be applicable in the analysis of space service dependencies, as well as factors useful for inclusion in the development of a future dependency analysis method. In the literature study, eight dependency analysis methods are found to be applicable in the space dependency context and fourteen relevant factors are identified. The following discussions touch upon the need for space dependency analyses in the first place, the various methods identified in the study, some suggestions for a method prototype based on the most important factors developed, the conduct of this study, and suggestions for further work and some useful readings.

5.1. On the perceived need for space dependency analysis

Conducting space dependency analyses might not be the best solution in every context. There seems to be differing perspectives both in the literature and the interviews on whether dependency analysis should be considered its own process, or if such analyses exist only implicitly as part of other procedures. For the identified methods and factors to be meaningful to any extent, a discussion is in order regarding the utility of dependency analyses in general. Using the Swedish RVA prescriptions as an example, only the *identification* of critical dependencies is required, compared to the prescribed *identification and analysis* of risks (MSBFS 2015:4; MSBFS 2015:5; MSBFS 2016:7). How does this manifest in practice? Are dependencies therefore not analysed, or are such analyses conducted implicitly in the risk analysis? If dependency *analysis* is not conducted, what is the purpose of requiring the *identification* as part of the RVA?

The findings by Johansson et al. (2015, pp. 9–12) suggest that dependencies appear to serve little purpose, in general being solely mentioned but not evaluated. The RVAs which were studied stem from 2011 and 2013, during which time MSB's older prescriptions stated that critical dependencies as well as threats, risks, and vulnerabilities should be *"identified and evaluated"* (MSBFS 2010:6, 6-7 §§; MSBFS 2010:7, 6-7 §§). It seems that even with the perceived stronger terminology present in these older prescriptions, understanding dependencies were not seen as beneficial enough for conducting the analysis at that time. As participants mention not viewing dependency analysis as its own process, this suggests that dependencies might still not be engaged with in any explicit regard. Of course, these findings originate from the collection of relatively old RVAs, and a very small selection of interview participants, which means that such a notion might not be prevalent among other actors at

present. Relating back to the purpose of this thesis, is there then an actual need of methods for analysing space service dependencies, or could the purpose be served in some other way?

If application of space dependency analysis is limited to solely the identification of dependencies, a simple checklist listing possible dependency sources could surely be compiled from existing material such as Whitty and Walport (2018). The aggregated analysis would perhaps not be able to draw any certain conclusions regarding the reality of societal space dependency, but then again, is there a need for drawing such conclusions? Decisions can be made on the assumption that there are existing dependencies, if care is taken to make the resulting actions beneficial even if such dependencies are non-existent.

If space dependency analysis is applied for more detailed purposes, knowing the benefits and drawbacks of space dependent technologies and its alternatives might be useful. The technical system, from the perspective of being a reverse dependency analysis as mentioned by a participant, might then provide sufficient information for the decision, as long as the resulting dependencies are consciously accepted. Of course, external technical systems might not allow for scrutiny, but as stated by MSB (2014b, pp. 18–19), system dependency on space services can be addressed during the specification of system functionality or during the procurement of the system. In this case, simply being aware of potential mechanisms might be enough for the actors. Likewise, being able to inform and raise awareness regarding technological adaptation might be sufficient for regulating actors, without having to inform themselves of the grade of societal implementation. If, on the other hand, dependencies should be both identified and analysed, the factors and methods presented in this thesis might be valuable. A transparent and structured method would be especially important for purposes such as identifying and evaluating unknown dependencies which might not be understood from knowledge regarding prescribed system designs, or which emerge from complex socio-technical systems. As a final note, these reflections should not serve to diminish dependency research but, rather, encourage such research to touch upon topics such as relevancy or alternative solutions.

5.2. On the choice of methods

The methods identified as relevant to space dependencies were in general based on expert judgement in some form, with the exception of the empirical and input/output methods. These methods seem to be among the more accessible ones to conduct in practice, given apparent restrictions on data and resources availability for the analyses. Furthermore, they do not require extensive familiarity with the method in order to achieve any meaningful result.

Applying, for example, flow models or other simulation-based models, would possibly require the analyst to quantify and separate data regarding space service information flows from other types of information flows, in order to gain understanding of space dependencies, adding a significant workload. Another limitation of these models is that the tools necessary for data analysis require comparatively advanced mathematical and computational skills, limiting the number of potential analysts. This does not imply that expert-based methods such as interviews, questionnaires, or workshops are easier to perfect. Rather, it implies that the baseline needed for achieving any result whatsoever might be lower for these methods, and thus more accessible for most actors.

5.2.1. Possible connection between space services and ICT

As it appears from Hedtjärn Swaling (2015), Hedtjärn Swaling and Mossberg Sonnek (2016), and Whitty and Walport (2018), space dependencies seem to be closely related to ICT dependencies, implying that there could be benefits to analysing these domains together. The analysis might not require too much modification to be useful for both domains, thereby increasing the incentive for performing the analysis, as it provides a two-for-one result. On its own, methods stemming from ICT analyses might additionally be useful for understanding space dependencies. However, an interesting perspective arises when comparing ICT and space services. In the analysis of space dependencies, the services provided by space infrastructure seem to possess redundant alternatives in earth-based infrastructure. In that case, could an alternative perspective be to consider space service dependencies as dependencies on ICT services with a specific implementation of hardware? Such a perspective might then further argue for the explicit incorporation of ICT methods into the domain of space services.

5.2.2. Perspectives

In both the literature and interview studies, the importance of providing several meaningful perspectives is continuously raised, especially with regard to socio-technical systems and experts. This suggest that the quality of input data, and thus the full analysis, might be influenced by the perspectives involved. When an analysis is made through a single perspective, that perspective might subjugate the whole analysis and limit its quality. Such influence is not necessarily negative, but should perhaps be complemented by other perspectives in order to paint a fuller picture. In practice, incorporating more perspectives means finding more relevant individuals with time to participate in the analysis. The analysis

then becomes more resource demanding and maybe less prioritised by the entity providing said resources.

5.3. On a method prototype

The factors and methods presented in the results do not constitute a method for space service dependency analysis. In order to provide a design example for such a method, a prototype is presented below. Societal-level space dependency analyses seem to be either indirect, as in the economic analysis by PwC (2018), or more exemplifying as in Whitty and Walport (2018). In order to map and understand *which* dependencies exist and *to what extent* they manifest in society, there might be a need for more detailed analyses, as well as data generation at lower levels, as stated in factor 7.

5.3.1. Component and organisational level analysis

With sufficient organisational competence and resources, actors might possibly be able to conduct analyses with a physical approach akin to simulations by Falletti et al. (2019) or following conventional risk management methods as suggested by Hedtjärn Swaling (2015, p. 8), in accordance with factor 5. Technical data from such analyses might provide practical information on potential disruption modes, vulnerabilities, and consequences, which could be used directly by actors to manage these hazards, while also acting as detailed input to the aggregated analysis. The actors should be supported in their analysis by information regarding common dependencies, readily available from for example Whitty and Walport (2018), as well as information where such dependencies manifest. A format suggested in the literature is an Excel template (Guldåker et al., 2019, pp. 40–41; Rönnåker & Wennerbeck, 2020, p. 53), as the spreadsheet program is utilised a lot in practice and relatively easy to use. It can also serve as a structured way of collecting data from different actors.

For actors already familiar with these technical risk analyses, conducting a space service dependency analysis might be as easy as adding some extra focus on space dependency aspects. Lowering the bar for adaptation is important, as a reoccurring issue with both RVAs specifically and dependency analyses in general is the lack of implementation of existing methods (Johansson, Hassel, et al., 2015, pp. 12–14, 44–45). Furthermore, with analyses being required for reasons other than understanding space service dependencies, parallel and inefficient work can be avoided by integrating different kinds of analyses (Guldåker et al., 2019, p. 37).

5.3.2. Sectoral level analysis

Following the component and organisation level analyses, dependency data can then be used as input for scenario building as done by Chang et al. (2014) and de Bruijn et al. (2016), capturing a large range of hazards as specified by factor 2. Using a workshop-based method in a functional approach as per factor 6, the resulting interdependencies and cascading effects in the socio-technical system can be mapped, inter-personal relationships can be formed, dependency knowledge can be shared between actors, and the operational perspective is allowed to solidify in the aggregated analysis. Given the added benefit of personal relationships mentioned in the conceptual framework, the method presented by Chang et al. (2014) might be more suitable when the analysis is used for the purpose of *managing* critical space dependencies. On the other hand, administrative issues can make large workshops inconvenient, in which case the actor segmentation by Moon et al. (2015) might be more efficient.

5.3.3. Addressing potential issues

Simply applying the suggestions above would probably not yield a suitable method. Some issues with these suggestions must be addressed first. The aggregation of detailed data presents a security issue for various stakeholders which should be mitigated in accordance with factor 8, perhaps by some of the suggestions made in the interview study. For example, inter-actor interactions can be regulated by a security agreement between the different actors, covering how data is used, which actors will take part of the information, which information is allowed to aggregate verbally in the workshop, or in writing, etc. The aggregating analyst could also provide a secure venue for the workshop, and put sensitive information in classified appendices in the final report in order to prohibit unwarranted exposure.

It should be noted, however, that keeping information on a need-to-know basis in a public agency context, has to be weighed against the public access to information. If key actors for some reason are not included in the need-to-know selection, the lack of information might possibly result in unmanaged dependency hazards for both actors and the system in general. This approach carries another potential issue as well. Actors might become dependent on specific individuals, both by restricting knowledge of external dependencies to individuals with a relevant security clearance, as well as through the potential loss of informal trust between actors when the individual is replaced. Allowing more representatives from each actor might mitigate these issues, but would of course be subjected to resource limitations.

Resource or knowledge limitations might also result in some actors not having the capacity to conduct simulated tests on their own technical systems, and the aggregating analyst might not be able to provide assistance in any regard necessary for maintaining a high detail level. Barring that a suitable information package is provided as specified by factors 11 and 12, a more functional approach to the actor-level dependency analysis could be utilised. For example, actor dependencies could be mapped as part of an extended expert workshop, where actor representatives, knowledgeable in both their general organisational and technical foundations, contribute and gain understanding of how space services might influence their own practices. This of course could present more security issues, perhaps mostly relating to inter-actor rivalry or competition. The mutually gained knowledge in this alternative approach however, could overcome some of these issues, as Rydén Sonesson et al. (2021, p. 6) indicate the presence of such a phenomenon in their article. Yet another alternative is to conduct individual interviews regarding actor dependencies, similar to the method applied by Chang et al. (2014, p. 423), in combination with subsequent workshops. A possible benefit of this last approach is that the aggregating analyst can provide live expertise in fields where the actor lacks sufficient knowledge, perhaps in a more accessible way than spreadsheet templates.

Apart from Excel, concrete data structuring, analysis, and visualisation tools are not mentioned in the above description as they are deemed to depend on the purpose of the analysis. The analysis might be have a geographical context, in which GIS might be an important tool as described by Guldåker et al. (2019), or a functional context, where the visualisation tool CIrcle by de Bruijn et al. (2016) or dependency and propagation chains as described by MSB (2009) might be more applicable. However, as reasoned earlier, common spreadsheet programs might be the most user-friendly way of providing software assistance.

With expert elicitations being the core of data collection, the workshops must employ sufficient debiasing as stated in factor 1. The workshop format might mitigate some cognitive biases, but also introduce new biases stemming from, for example, group interactions. Montibeller and von Winterfeldt (2015) provide an extensive guide to relevant biases, their behaviour, and useful debiasing techniques relating to decision making and risk analysis. Such information might be useful to incorporate explicitly into both the design of an analysis method, as well as part of a knowledge package for the actor analyses.

In summary, the suggested method prototype consists of the following parts:

1. A knowledge package in the form of an Excel template, which provides information on the nature of space service dependencies and the actor-level method, as well as acting as a standardised data collection tool for the aggregated analysis.

2. Actors conducting component and organisational dependency analyses on their own systems, with the purpose of identifying and managing system behaviour with regard to various disturbances to space service functionality.
   or
   Actors collectively identifying and analysing their dependencies and system behaviours in a workshop. This step could perhaps be further combined with the subsequent workshop.
   or
   Individual interviews with actors mapping their dependencies and system behaviour.

3. Scenario building in preparation for subsequent workshop.

4. A workshop serving as both an aggregated analysis, as well as a value-creating forum for actors to exchange information behind closed doors and as a way of generating inter-actor trust.

5. A modular written report featuring general conclusions in the main body, with classified appendices as necessary to meet information security requirements from sensitive aggregated results or at the request of actors.

5.4. On the quality of the thesis

The quality discussion below is divided into a discussion on the literature and interview studies, followed by a discussion on transparency.

5.4.1. Literature study

During coding, themes emerged organically, in part based on subjective impressions. As a way to improve the quality of this thesis, the literature could have been subjected to a verification coding by another individual. The two coding runs would then have been compared in order to identify divergences. Such coding was not performed, however, due to the amount of literature which would have required significant time from the potential verification coder. The explorative approach implemented in this thesis, while useful as a way to identify interesting emergent phenomena, also resulted in a time-consuming iterative

workflow during the literature study. It inhibited scope delimitation to some extent, as it was hard to know beforehand what kind of literature might be of interest. With more time and resources, a more extensive list would have been preferable, with a stronger focus on reports featuring dependency analyses explicitly or as part of some other process. The analyses chosen in this thesis focus on differing domains, but perhaps an even larger coverage of domains would have provided interesting perspectives.

At the early stages of the literature study, but following the initial selection of documents, emergent documents were included to the study based on the perceived direction of the thesis. This was to be expected given the explorative approach, but it still rendered the study less systematic than maintaining the initial selection only. Furthermore, after a while the decision was made to not include more literature due to time constraints, resulting in a final selection being made during the ongoing analysis.

5.4.2. Interview study

Four participants were interviewed. Three more individuals were contacted but did not respond. This limited number of participants was due to the perception that few organisations have clear critical dependencies on space services, and much less the awareness or available resources to have explicitly investigated these dependencies, limiting the scope of obvious actors to include. The thesis would have been improved by including more participants, as further perspectives and ideas might have emerged. With the explorative approach mentioned previously, there was no obvious way of knowing beforehand how many individuals might be needed for data saturation. The participants did, however, represent several different key perspectives useful for this thesis. LFV provided a strong-regulated practitioner perspective, while MSB had a wide coordinating perspective as well as extensive knowledge regarding space dependencies in general. The representatives from FOI and LTH provided differing research backgrounds relating to dependency analyses. There are of course other perspectives missing, and different individuals from the same domain might have differing opinions. There are various kinds of practitioners for example, of which it would have been interesting to include the perspective of a private practitioner in a comparatively unregulated domain, where concepts such as *business continuity* might be more applicable than *societal resilience*. Another issue relating to perspectives is that two of the participants also authored documents included in the literature study. This might have yielded an artificial alignment of opinions between literature and participants. Given the low number of participants involved, the variation of perspectives shrinks significantly. However, as discussed earlier, the availability

of participants was limited. By selecting other participants, the potential value for validation that interviews could provide would have been stronger. On the other hand, being able to conduct interviews with the authors allows for confirmation of the actuality of information in the related documents, and was done by asking questions regarding concepts and results from their literature.

The interviews were semi-structured, but made use of the questions in Appendix B. In combination with the choice of notetaking rather than transcription, some degree of transparency was lost. Having had to conduct notetaking in parallel with facilitation is one of the larger issues with the interview study. This meant that focus had to be split between the notes and the participant, lowering the quality of each activity. Having a separate person taking notes could have aided in data preserved for analysis.

5.4.3. Transparency

In contrast to the loss of transparency stemming from the interviews, transparency was pursued on several other fronts. In the analytical process, transparency was sought by exemplifying reasoning and choices. Furthermore, the various iterations of data condensation and summarisation were documented in Excel spreadsheets, which acted both as means of providing a somewhat chronological depiction of the process, as well as food for thought for the researcher.

5.5. Further reading

Some reports, which would have been useful in the literature study, were identified too late for inclusion in the project. A source document to Whitty and Walport (2018) was overlooked, regarding the economic impact of GNSS disruptions in the UK, by Sadlier et al. (2017). It could be useful as inspiration for future analysis method choices at sectoral or national levels. One report regarding information system dependency analysis by Bengtsson et al. (2022) would have been useful as input to the actor-level dependency analysis, but was published too late for inclusion. With space services appearing to manifest in systems similar to the implementation of ICT in general, this report as well as Hedtjärn Swaling and

Mossberg Sonnek (2016) and other reports from NCS3[6] might be useful as information on the technical systems closest to space services.

Knowledge on the nature of space services, common hazards, applications and technical requirements is available in documents such as Acker et al. (2011), Enge et al. (2015), European GNSS Supervisory Authority (2020), Falletti et al. (2019), PwC (2018), Sadlier et al. (2017), Weeden and Samson (2022), and Whitty and Walport (2018).

[6] NCS3 is a joint collaboration between FOI and MSB which is tasked with building competence within cyber security in the field of industrial ICT

6. Conclusion

This thesis has identified eight dependency analysis methods and fourteen factors which are considered relevant when conducting space service dependency analyses. They are based on a literature study of twenty-one documents and an interview study featuring four expert participants. The value of conducting dependency analyses is dissected in a brief discussion on alternative ways of fulfilling the purpose of space service dependency analyses. Additionally, a method prototype incorporating these methods and factors is presented in order to further contribute towards the development of a method for space dependency analysis. Finally, a potential connection between ICT and space services is highlighted as interesting for future research.

The methods identified are in general expert based on aggregated analysis levels, as they are deemed to provide benefits relating to overall system robustness, information sharing, data accessibility, and resource efficiency. On an actor level, more technical methods are suggested, which share similarities to conventional risk management methods found in industry. The factors which emerged from the literature and interview studies centre on the themes of *incentive*, *conduct*, *results and input data*, and *information security*. They are formulated in a general manner and might be applicable for other types of dependency analyses as well.

Together, these results might pave the way for increased awareness of how we, as a society, make ourselves dependent on new technologies, both reaping their benefits, and understanding their costs.

6.1. Further studies

A meaningful next step towards increased societal awareness of space dependencies would be to compile existing knowledge regarding space dependencies into a format useful for both practitioners and agencies with coordinating or governing roles.

Further studies on space dependency method development could investigate the feasibility of understanding these dependencies using existing ICT analysis tools. Interesting questions to answer could be *"what space-related nuances are lost using ICT tools?"* and *"what additions must be made in order to adequately understand space service dependencies using ICT tools?"*

Another related point for further study is the implementation of one of the existing methods suggested in this thesis. In such a case study, it could perhaps be determined if the method need to address any further factors before being beneficial for space service dependency analysis.

Finally, if a completely new dependency method is desired, the factors presented here could be implemented in the design of a new method, with inspiration from the identified methods, and applied in a case study as a proof of concept.

7. References

Acker, O., Pötscher, F., & Lefort, T. (2011). *Why satellites matter*. Booz & Company.

Alvehus, J. (2019). *Skriva uppsats med kvalitativ metod: En handbok* (1st ed.). Liber.

Arksey, H., & O'Malley, L. (2005). Scoping studies: Towards a methodological framework. *International Journal of Social Research Methodology*, *8*(1), 19–32. https://doi.org/10.1080/1364557032000119616

Bengtsson, J., Eriksson, C., & Olsson, M. (2022). *IT-system med externa anslutningar—Metod för analys av verksamheters beroenden* (FOI-R--5306--SE; p. 57). Swedish Defence Research Agency (FOI). https://foi.se/rapportsammanfattning?reportNo=FOI-R--5306--SE

Blaikie, N. W. H. (2010). *Designing social research: The logic of anticipation* (2nd ed). Polity Press.

Chang, S. E., McDaniels, T., Fox, J., Dhariwal, R., & Longstaff, H. (2014). Toward Disaster-Resilient Cities: Characterizing Resilience of Infrastructure Systems with Expert Judgments. *Risk Analysis*, *34*(3), 416–434. https://doi.org/10.1111/risa.12133

de Bruijn, K. M., Cumiskey, L., Dhubhda, R. N., Hounjet, M., & Hynes, W. (2016). *Flood vulnerability of critical infrastructure in Cork, Ireland*. FLOODrisk 2016 - 3rd European Conference on Flood Risk Management. https://doi.org/10.1051/e3sconf/20160707005

Enge, P., Enge, N., Walter, T., & Eldredge, L. (2015). Aviation Benefits from Satellite Navigation. *New Space*, *3*(1), 19–35. https://doi.org/10.1089/space.2014.0011

Eriksson, C., Denward, C., Swaling, V. H., & Mickelsson, L. (2020). *Kunskap för beredskap: Vad har risk- och sårbarhetsanalys gett för effekt hittills och hur kan nyttan öka?* (FOI-R--4804--SE). Swedish Defence Research Agency (FOI). https://foi.se/rapportsammanfattning?reportNo=FOI-R--4804--SE

ESA. (n.d.). *Space weather and its hazards*. ESA. Retrieved 5 April 2022, from https://www.esa.int/Safety_Security/Space_weather_and_its_hazards3

ESA. (2005, March 17). *Space debris: Assessing the risk*. ESA. https://www.esa.int/About_Us/ESOC/Space_debris_assessing_the_risk

ESA Space Debris Office. (2021). *ESA'S ANNUAL SPACE ENVIRONMENT REPORT* (LOG GEN-DB-LOG-00288-OPS-SD). European Space Agency (ESA) European Space Operations Centre (ESOC). https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf

European GNSS Supervisory Authority. (2020). *GNSS user technology report* (No. 3). Publications Office. https://data.europa.eu/doi/10.2878/565013

Falletti, E., Margaria, D., Marucco, G., Motella, B., Nicola, M., & Pini, M. (2019). Synchronization of Critical Infrastructures Dependent Upon GNSS: Current Vulnerabilities and Protection Provided by New Signals. *IEEE Systems Journal*, *13*(3), 2118–2129. https://doi.org/10.1109/JSYST.2018.2883752

Georgescu, A., Gheorghe, A. V., Piso, M.-I., & Katina, P. F. (2019). *Critical Space Infrastructures: Risk, Resilience and Complexity* (Vol. 36). Springer International Publishing. https://doi.org/10.1007/978-3-030-12604-9

Guldåker, N., Johansson, J., Arvidsson, B., & Svegrup, L. (2019). *Utvecklad riskhantering för samhällsviktiga verksamheter avseende översvämningsrisker*. Myndigheten för Samhällsskydd och Beredskap (MSB).

Harrison, T., Johnson, K., Young, M., Wood, N., & Goessler, A. (2022). *Space Threat Assessment 2022*. Center for Strategic and International Studies (CSIS). https://www.csis.org/analysis/space-threat-assessment-2022

Hedtjärn Swaling, V. (2015). *Beroende av korrekt tid i elsystem.* (FOI MEMO 5069). Swedish Defence Research Agency (FOI).

Hedtjärn Swaling, V., & Mossberg Sonnek, K. (2016). *NCS3 Feasibility study—Dependencies to Industrial Information and Control Systems* (FOI-R--4280--SE). Swedish Defence Research Agency (FOI).

Höst, M., Regnell, B., & Runeson, P. (2006). *Att genomföra examensarbete*. Studentlitteratur.

Interagency GPS Executive Board. (2003, March 21). *Special Notices Regarding GPS Selective Availability*. GPS. https://www.gps.gov/systems/gps/modernization/sa/IGEB/

Johanson, G., Hellström, P., Makamo, T., Bento, J.-P., Knockenhauer, M., & Pörn, K. (2003). *Dependency Defence and Dependency Analysis Guidance* (SKI Report 2004:04; Nordic Working group on Common Cause Failure Analysis). Swedish Nuclear Inspectorate (SKI).

Johansson, J., Hassel, H., Petersen, K., & Arvidsson, B. (2015). *Metoder för konsekvensanalys på samhällsnivå* (MSB906). Swedish Civil Contingencies Agency (MSB). https://www.msb.se/sv/publikationer/metoder-for-konsekvensanalys-pa-samhallsniva/

Johansson, J., Svegrup, L., & Hassel, H. (2015). *Översikt över metoder för komplex beroendeanalys på sektoriell & tvärsektoriell nivå* (MSB904). Swedish Civil Contingencies Agency (MSB). https://www.msb.se/sv/publikationer/oversikt-over-metoder-for-komplex-beroendeanalys-pa-sektoriell--tvarsektoriell-niva/

KBM. (2008). *Beroendeanalys—Så gör du! Användarhandledning.* Krisberedskapsmyndigheten (KBM).

Kessler, D. J., & Cour-Palais, B. G. (1978). Collision frequency of artificial satellites: The creation of a debris belt. *Journal of Geophysical Research*, *83*(A6), 2637–2646. https://doi.org/10.1029/JA083iA06p02637

Kvale, S., & Brinkmann, S. (2014). *Den kvalitativa forskningsintervjun* (S.-E. Torhell, Trans.; 3rd ed.). Studentlitteratur.

Lindström, S. (2021). *Utblick—Säkerhetspolitisk utveckling inom rymdområdet* (FOI Memo 7602). Swedish Defence Research Agency (FOI). https://www.foi.se/rapportsammanfattning?reportNo=FOI%20Memo%207602

Lindström, S., & Waldenvik, M. (2004). *Rymdväder—Effekter på militära och civila system.* (FOI-R--1464--SE). Swedish Defence Research Agency (FOI). https://foi.se/rapportsammanfattning?reportNo=FOI-R--1464--SE

Montibeller, G., & von Winterfeldt, D. (2015). Cognitive and Motivational Biases in Decision and Risk Analysis: Biases in Decision and Risk Analysis. *Risk Analysis*, *35*(7), 1230–1251. https://doi.org/10.1111/risa.12360

Moon, J., Lee, D., Lee, T., Ahn, J., Shin, J., Yoon, K., & Choi, D. (2015). Group Decision Procedure to Model the Dependency Structure of Complex Systems: Framework and Case Study for Critical Infrastructures. *Systems Engineering*, *18*(4), 323–338. https://doi.org/10.1002/sys

MSB. (2009). *Faller en – faller då alla?* Swedish Civil Contingencies Agency (MSB). https://www.msb.se/siteassets/dokument/amnesomraden/krisberedskap-och-civilt-forsvar/stod-i-att-analysera-beroenden/faller-en---faller-da-alla.pdf

MSB. (2014a). *Action plan for the protection of vital societal functions & critical infrastructure*. Swedish Civil Contingencies Agency (MSB). https://www.msb.se/siteassets/dokument/publikationer/english-publications/action-plan-for-the-protection-of-vital-societal-functions--critical-infrastructure.pdf

MSB. (2014b). *Vikten av var och när: Samhällets beroende av korrekt tids- och positionsangivelse* (MSB778). Swedish Civil Contingencies Agency (MSB). https://www.msb.se/sv/publikationer/vikten-av-var-och-nar--samhallets-beroende-av-korrekt-tids--och-positionsangivelse/

MSB. (2020, October 27). *Uppdaterad definition samhällsviktig verksamhet* [Memo]. https://www.msb.se/contentassets/75e789d780c741cd9c8621eac846ec21/uppdaterad-definition-samhallsviktig-verksamhet.pdf

MSB. (2021a). *Identifiering av samhällsviktig verksamhet: Lista med viktiga samhällsfunktioner* (MSB1844). Swedish Civil Contingencies Agency (MSB). https://rib.msb.se/filer/pdf/29800.pdf

MSB. (2021b, August 12). *Risk- och sårbarhetsanalyser*. MSB. https://www.msb.se/sv/amnesomraden/krisberedskap--civilt-forsvar/risk--och-sarbarhetsanalyser/

MSB. (2021c, September 12). *Kritisk infrastruktur i rymden*. https://www.msb.se/sv/amnesomraden/informationssakerhet-cybersakerhet-och-sakra-kommunikationer/kritisk-infrastruktur-i-rymden/

MSBFS 2010:6. *Föreskrifter om kommuners risk- och sårbarhetsanalyser*. Retrieved 12 April 2022, from https://www.msb.se/sv/regler/upphavda-regler/krisberedskap-och-informationssakerhet/msbfs-20106/,

MSBFS 2010:7.. *Föreskrifter om statliga myndigheters risk- och sårbarhetsanalyser*. https://www.msb.se/sv/regler/upphavda-regler/krisberedskap-och-informationssakerhet/msbfs-20107/

MSBFS 2015:4. *Föreskrifter om landstings risk- och sårbarhetsanalyser*. Retrieved 12 April 2022, from https://www.msb.se/sv/amnesomraden/krisberedskap--civilt-forsvar/risk--och-sarbarhetsanalyser/

MSBFS 2015:5. *Föreskrifter om kommuners risk- och sårbarhetsanalyser*. Retrieved 12 April 2022, from https://www.msb.se/sv/amnesomraden/krisberedskap--civilt-forsvar/risk--och-sarbarhetsanalyser/

MSBFS 2016:7. *Föreskrifter om statliga myndigheters risk- och sårbarhetsanalyser*. https://www.msb.se/sv/regler/gallande-regler/krisberedskap-och-informationssakerhet/msbfs-20167/

OECD. (2019). *Good Governance for Critical Infrastructure Resilience*. OECD. https://doi.org/10.1787/02f0e5a0-en

Olsson, M., Ryghammar, C., & Lundén, J. (2017). *Näringslivets syn på roller och ansvar i totalförsvaret* (FOI-R--4551--SE). Swedish Defence Research Agency (FOI). https://foi.se/rapportsammanfattning?reportNo=FOI-R--4551--SE

Paez, A. (2017). Gray literature: An important resource in systematic reviews. *Journal of Evidence-Based Medicine*, *10*(3), 233–240. https://doi.org/10.1111/jebm.12266

Penent, G. (2019). Assessing Europe's Space Dependency and Its Implications. *Éditoriaux de l'Ifri*. https://www.ifri.org/en/publications/editoriaux-de-lifri/assessing-europes-space-dependency-and-its-implications

Probst, L., Frideres, L., Cambier, B., PwC Luxembourg, Duval, J.-P., Roth, M., Lu-Dac, C., & PwC France. (2016). *Big Data in Earth Observation*. Business Innovation

Observatory, European Commission. https://ec.europa.eu/docsroom/documents/16592/attachments/1/translations/en/renditions/native

PwC. (2018). *Dependence of the European economy on space infrastructures: Potential impacts of space assets loss.* European Commision, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs. https://data.europa.eu/doi/10.2873/81127

Rinaldi, S. M., Peerenboom, J. P., & Kelly, T. K. (2001). Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE Control Systems*, *21*(6), 11–25. https://doi.org/10.1109/37.969131

Rönnåker, K., & Wennerbeck, S. (2020). *Vetenskapliga metoder och praktiska tillvägagångssätt för beroendeanalys inom samhällsviktiga verksamheter* [Master thesis, Lund University]. http://lup.lub.lu.se/student-papers/record/9011296

Rydén Sonesson, T., Johansson, J., & Cedergren, A. (2021). Governance and interdependencies of critical infrastructures: Exploring mechanisms for cross-sector resilience. *Safety Science*, *142*. https://doi.org/10.1016/j.ssci.2021.105383

Sadlier, G., Flytkjær, R., Sabri, F., & Herr, D. (2017). *The economic impact on the UK of a disruption to GNSS*. London Economics. https://londoneconomics.co.uk/blog/publication/economic-impact-uk-disruption-gnss/

SFS 2022:511. *Förordning om elektronisk kommunikation*. https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/forordning-2022511-om-elektronisk-kommunikation_sfs-2022-511

Slann, P. A. (2016). Anticipating uncertainty: The security of European critical outer space infrastructures. *Space Policy*, *35*, 6–14. https://doi.org/10.1016/j.spacepol.2015.12.001

Weeden, B., & Samson, V. (Eds.). (2022). *Global Counterspace Capabilities—An Open Source Assessment*. Secure World Foundation (SWF). https://swfound.org/counterspace/

Whitty, C., & Walport, M. (2018). *Satellite-derived Time and Position*. Government Office for Science.

8. Appendix A – Literature list

[1] MSB. (2014). *Vikten av var och när: Samhällets beroende av korrekt tids- och positionsangivelse* (MSB778). Swedish Civil Contingencies Agency (MSB). *https://www.msb.se/sv/publikationer/vikten-av-var-och-nar--samhallets-beroende-av-korrekt-tids--och-positionsangivelse/*

[2] Hedtjärn Swaling, V. (2015). *Beroende av korrekt tid i elsystem.* (FOI MEMO 5069). Swedish Defence Research Agency (FOI).

[3] PwC. (2018). *Dependence of the European economy on space infrastructures: Potential impacts of space assets loss.* European Commision, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs. *https://data.europa.eu/doi/10.2873/81127*

[4] Whitty, C., & Walport, M. (2018). *Satellite-derived Time and Position*. Government Office for Science.

[5] Falletti, E., Margaria, D., Marucco, G., Motella, B., Nicola, M., & Pini, M. (2019). Synchronization of Critical Infrastructures Dependent Upon GNSS: Current Vulnerabilities and Protection Provided by New Signals. *IEEE Systems Journal*, *13*(3), 2118–2129. *https://doi.org/10.1109/JSYST.2018.2883752*

[6] OECD Space Forum. (2020). *Measuring the Economic Impact of the Space Sector: Key Indicators and Options to Improve Data*. G20 Space Economy Leaders' Meeting (Space20), Saudi Arabia. *https://www.oecd.org/sti/inno/space-forum/measuring-economic-impact-space-sector.pdf*

[7] Johansson, J., Hassel, H., Petersen, K., & Arvidsson, B. (2015). *Metoder för konsekvensanalys på samhällsnivå* (MSB906). Swedish Civil Contingencies Agency (MSB). *https://www.msb.se/sv/publikationer/metoder-for-konsekvensanalys-pa-samhallsniva/*

[8] Johansson, J., Svegrup, L., & Hassel, H. (2015). *Översikt över metoder för komplex beroendeanalys på sektoriell & tvärsektoriell nivå* (MSB904). Swedish Civil Contingencies Agency (MSB). *https://www.msb.se/sv/publikationer/oversikt-over-metoder-for-komplex-beroendeanalys-pa-sektoriell--tvarsektoriell-niva/*

[9] Guldåker, N., Johansson, J., Arvidsson, B., & Svegrup, L. (2019). *Utvecklad riskhantering för samhällsviktiga verksamheter avseende översvämningsrisker*. Myndigheten för Samhällsskydd och Beredskap (MSB).

[10] Rönnåker, K., & Wennerbeck, S. (2020). *Vetenskapliga metoder och praktiska tillvägagångssätt för beroendeanalys inom samhällsviktiga verksamheter* [Master thesis, Lund University]. *http://lup.lub.lu.se/student-papers/record/9011296*

[11] Rinaldi, S. M., Peerenboom, J. P., & Kelly, T. K. (2001). Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE Control Systems*, *21*(6), 11–25. *https://doi.org/10.1109/37.969131*

[12] MSB. (2009). *Faller en – faller då alla?* Swedish Civil Contingencies Agency (MSB). *https://www.msb.se/siteassets/dokument/amnesomraden/krisberedskap-och-civilt-forsvar/stod-i-att-analysera-beroenden/faller-en---faller-da-alla.pdf*

[13] Chang, S. E., McDaniels, T., Fox, J., Dhariwal, R., & Longstaff, H. (2014). Toward Disaster-Resilient Cities: Characterizing Resilience of Infrastructure Systems with Expert Judgments. *Risk Analysis*, *34*(3), 416–434. *https://doi.org/10.1111/risa.12133*

[14] Laugé, A., Hernantes, J., & Sarriegi, J. M. (2015). Critical infrastructure dependencies: A holistic, dynamic and quantitative approach. *International Journal of Critical Infrastructure Protection*, *8*, 16–23. *http://dx.doi.org/10.1016/j.ijcip.2014.12.004*

[15] Moon, J., Lee, D., Lee, T., Ahn, J., Shin, J., Yoon, K., & Choi, D. (2015). Group Decision Procedure to Model the Dependency Structure of Complex Systems: Framework and Case Study for Critical Infrastructures. *Systems Engineering*, *18*(4), 323–338. *https://doi.org/10.1002/sys*

[16] de Bruijn, K. M., Cumiskey, L., Dhubhda, R. N., Hounjet, M., & Hynes, W. (2016). *Flood vulnerability of critical infrastructure in Cork, Ireland*. FLOODrisk 2016 - 3rd European Conference on Flood Risk Management. *https://doi.org/10.1051/e3sconf/20160707005*

[17] Hedtjärn Swaling, V., & Mossberg Sonnek, K. (2016). *NCS3 Feasibility study—Dependencies to Industrial Information and Control Systems* (FOI-R--4280--SE). Swedish Defence Research Agency (FOI).

[18] Johansson, J., Hassel, H., & Svegrup, L. (2016). Capturing societal interdependencies from a flow perspective—Part I: Method and model. In *Risk, reliability and safety: Innovating theory and practice* (pp. 2152–2159). Taylor and Francis Group.

[19] Svegrup, L., Johansson, J., & Hassel, H. (2016). Capturing societal interdependencies from a flow perspective—Part II: Application. In *Risk, reliability and safety: Innovating theory and practice* (pp. 2191–2198). Taylor and Francis Group.

[20] Rydén Sonesson, T., Johansson, J., & Cedergren, A. (2021). Governance and interdependencies of critical infrastructures: Exploring mechanisms for cross-sector resilience. *Safety Science*, *142*. *https://doi.org/10.1016/j.ssci.2021.105383*

[21] Tehler, H., Cedergren, A., Hassel, H., & Jonas, J. (2021). *Corona-pandemins kaskadeffekter på lokal och regional nivå med avseende på samhällsviktiga funktioner—Mot ökad motståndskraft* (MSB1895). Swedish Civil Contingencies Agency (MSB).

9. Appendix B – Dynamic questions for interviews

The following interview guide was written in Swedish, as the interviews were conducted in Swedish.

INCITAMENT

- Vad tänker du på när jag säger rymdtjänster och rymdberoenden?
- Ser du något syfte med att förstå beroenden i en verksamhet eller på en samhällsnivå?
- Kan det finnas några externa orsaker till att man gör beroendeanalyser?
- Kan det finnas några interna orsaker till att man gör beroendeanalyser?

UTFÖRANDE

- Om jag säger beroendeanalys, vad tänker du på då?
- Om vi generaliserar och säger att en beroendeanalys kan vara antingen resurssnål, lätt att lära sig, och översiktlig, eller resurskrävande, svår att lära sig, och detaljrik, vilken utformning tror du funkar bäst?
- Är det rimligt att förvänta sig att en beroendeanalys ges tillräckliga resurser?
- Kan ett metodstöd ställa några krav på kompetensen hos utövaren?
- Bör metoden innehålla exempel? Alltså exempel på hur rymdberoenden kan se ut rent tekniskt, vanliga misstag eller bias, och så vidare, eller hade det försämrat metodstödet?
- Finns det något annat som en analytiker kan ha nytta av?
- En aggregerande beroendeanalys kan utformas på lite olika sätt. Vem är bäst lämpad att undersöka indirekta beroenden bakåt och framåt i kedjan?
- Behöver en verksamhet förstå sina egna indirekta beroenden? Behöver den förstå hur den indirekt påverkar andra verksamheter?

INDATA OCH RESULTAT

- Vad för sorts information anser du krävs för att kunna kartlägga och förstå rymdberoenden?
- Ser du några hinder för att få tag på den här typen av information?
- Hade exempelvis beredskapsövningar kunnat användas för att ge empirisk indata åt beroendeanalyser?
- Att medvetet störa ut sin GNSS-utrustning i verksamheten är idag olagligt. Hade data från sådana tester kunnat ge ett mervärde till beroendeanalyser i verksamheter?
- Var anser du att resultat och slutsatser från en beroendeanalys av rymdtjänster kan vara till nytta någonstans?

- Påverkar användningsområdet huruvida informationen behöver vara kvalitativ eller kvantitativ?

SEKRETESS

- Vad ser du för sekretessproblem med att kartlägga och förstå beroenden?
- Vilka lösningar ser du på dessa sekretessproblem?
- Är en möjlig lösning att medvetet minska upplösningen när man gör den aggregerande analysen? Alltså inte beskriva beroendemekanismen utan enbart analysera med hjälp av breda kategorier och typfall, och inte beskriva konsekvenser av störningar på verksamheten?
- Är en möjlig lösning att den aggregerande analysen även fungerar som ett forum mellan verksamhetsutövarna, där de kan förmedla detaljerad information, utan att detaljerna hamnar i den slutgiltiga analysen?

10. Appendix C – Codes and their associated questions

System perspective	Which perspective is used in the document? [Systems, operational, both] What system level is used? [Local, regional, national, international]
Dependency characterisation	Which set of characteristics are used to describe dependencies in the document? [Physical-cyber-logical-geographical/physical-logical-geographical/MSB's dependency wheel/Other] What processes are used to characterise dependencies? [Logical reasoning/feelings/workshop/other]
Input data	Where type of data is used as input? [Empirical/Technical/Economical/Expert] What magnitude of data is required? [Little/Some/Much] What resources are required in order to retrieve data? [People/money/time/others]
Flow chains	What type of flow chain is used to understand dependencies? [Focus/Dependency/Propagation]
Time aspects	What time aspects are found in the document? [Chronological scenarios/endurance/recovery/time resources]
Qualitative/ Quantitative	Is information collected, analysed, and/or presented as qualitative, semi-quantitative or purely quantitative.
Information transmission	How are results conveyed? [Physical report/Manuals/Workshop/Presentation] How are results visualised? [Tables/Figures/Graphs/Longer Text]
Downstream consequences	Are propagated consequences of disruptions regarded? [Higher order dependencies, risks associated with dependencies]
Threat type	What kind of threats are regarded? [Antagonistic/Natural]
Decision-making purpose	What purpose is the analysis serving? [Strategic, operational, tactical decision making/proactive/reactive/explorative]
Type of analysis	How is the analysis delimited? [Scenario/All-hazard]
Complexity	How much prior knowledge is demanded by the analyst in order to conduct the dependency analysis? [little, some, much] Is the analysis complex or simple in conduct/data collection/analysis/presentation? [Complex/simple] How detailed are the results? In what way are uncertainties regarded?
Degree of maturity	How mature is the method? [Framework/described method/exemplified/applied/used in practice] What quality of results is the method capable of achieving?
Type of method	What type of method is applied in the document? [I/O, frameworks, empirical, agent based, system-dynamic, infrastructure, flow, hybrid]
Debiasing	What techniques are used in the document to mitigate biases in for example expert elicitations? [EXAMPLES]
Information security	How does the document regard secrecy issues associated with data retrieval and presentation?
Approach	What approach characterises the document? [Functional/physical/risk-based]
Dependency management	How is the output of the dependency analysis managed in the document?