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Assessing Societal Benefits and Economic Impacts of earth observation data in the Arctic area

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Abstract

The use of earth observation data and services yields extensive benefits to the society, environment, and economy. Especially actors in the Arctic region are going to be more dependent on earth observation services in the future, as the Arctic is changing rapidly due to climate change. There is a growing need to quantify the benefits from earth observation services to justify investments made into earth observation technologies and to defend research budgets against competing priorities. This study aims to determine the most suitable tools for the assessment of benefits of earth observation data and services in the Arctic area.

A literature study was conducted to review the most essential benefit assessment tools. The applicability of cost-benefit analysis, benefit transfer, value chains, Value Tree Analysis, Weather Service Chain Analysis, and Spatineo Impact were reviewed. Finally, a case study assessing benefits from a lake ice service was performed. The case study applied Spatineo Impact and Value Tree Analysis.

By comparing methods in the literature study, Value Tree Analysis combined with cost-benefit analysis is concluded to be the best approach for assessing the socioeconomic impact of earth observing data in the Arctic. This approach supports the representation of various benefits originating from several earth observing systems. In addition, Spatineo Impact proved to be a useful tool for revealing the realized benefits from the usage of a service. This information is especially valuable to providers of open spatial data.

The case study emphasized that the results of a benefit assessment are highly dependent on the availability of data and on the time frame the study is conducted. Whenever possible, comprehensive interviews and surveys with end-users should be conducted when assessing the socioeconomic impact of an earth observation service.

Keywords socioeconomic impact assessment, benefit assessment, earth observation data, Arctic area, lake ice service

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Tiivistelmä

Ympäristötietojen käytöllä saavutetaan laajasti yhteiskunnallisia, taloudellisia sekä ympäristöllisiä hyötyjä. Varsinkin arktisen alueen toimijat ovat entistä riippuvaisempia ajantasaisista ja tarkoista ympäristötietopalveluista arktisen alueen muuttuessa nopeasti ilmastonmuutoksen seurauksena. Jotta investointeja kaukokartoitusteknologioihin voidaan perustella sekä tutkimusbudjetteja puolustaa kilpailevia prioriteetteja vastaan, tarvitaan menetelmiä ympäristötietojen hyötyjen arvioimiseksi. Tämä tutkimus pyrkii löytämään sopivimmat menetelmät arktisen alueen ympäristötietojen ja ympäristötietopalveluiden vaikuttavuuden arviointiin.

Kirjallisuustutkimuksessa tarkasteltiin oleellisimpia vaikuttavuuden arvioinnin menetelmiä. Nämä olivat kustannus-hyötyanalyysi, hyötyjen siirto, arvoketjut, arvopuuanalyysi, sääpalveluketjuanalyysi ja Spatineo Impact. Spatineo Impactia ja arvopuuanalyysiä sovellettiin ja vertailtiin tarkemmin tapaustutkimuksessa, jossa arvioitiin järvien jääpeiteaineiston vaikuttavuutta.

Menetelmien vertailu kirjallisuustutkimuksessa osoittaa, että arvopuuanalyysi yhdistettynä kustannus-hyötyanalyysiin on paras lähestymistapa arktisten ympäristötietopalveluiden vaikuttavuuden arvioimiseksi, koska sen avulla voidaan esittää moninaisten hyötyjen toteutumista useasta havainnointijärjestelmästä. Tutkimuksessa todettiin myös, että Spatineo Impact on joustava menetelmä etenkin avoimien paikkatietoaineistojen vaikuttavuuden arviointiin.

Tapaustutkimus korostaa arviointityön ajankohdan ja saatavilla olevan tiedon vaikutusta hyötyanalyysin lopputulokseen. Ympäristötietopalveluiden vaikuttavuutta arvioitaessa tulisi mahdollisuuksien mukaan hyödyntää myös haastatteluja ja kyselyitä loppukäyttäjien kokemien hyötyjen selvittämiseksi.

Avainsanat Vaikuttavuusanalyysi, hyötyanalyysi, ympäristötieto, paikkatieto, arktinen alue, järvijääpeite

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Titel Bedömning av samhällelig och ekonomisk nytta av geografiska data i det arktiska området

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Sammandrag

Användningen av geografiska data och geografiska datatjänster ger omfattande fördelar för samhället, miljön och ekonomin. Särskilt aktörer i den arktiska regionen kommer att bli mer beroende av geografiska datatjänster i framtiden, eftersom den arktiska miljön förändras med accelererande fart på grund av klimatförändringen. Det finns ett växande behov för att kvantifiera fördelarna med geografiska datatjänster för att motivera investeringar i teknologi som främjar skapandet av ett bättre geografiskt datasystem. Syftet med denna studie är att fastställa de mest lämpliga verktygen för att bedöma fördelarna med geografiska data och geografiska datatjänster i det arktiska området.

En litteraturstudie genomfördes för att granska de viktigaste metoderna för att bedöma samhälleliga och ekonomiska nyttor. Tillämpligheten av nyttokostnadsanalys, nyttoöverföring, värdekedjor, värdeträdsanalys, väderservice kedjeanalys och Spatineo Impact granskades. Till slut utfördes också en fallstudie, där nyttorna med en geografisk dataprodukt som beskriver istäckets utbredning i sjöar uppskattades. Fallstudien tillämpade och jämförde Spatineo Impact och värdeträdsanalys metoderna.

Genom att jämföra metoderna i litteraturstudien drogs slutsatsen om att värdeträdsanalys kombinerat med nyttokostnadsanalys är den bästa metoden för att bedöma den socioekonomiska nyttan av geografiska data i den arktiska regionen. Denna metod stödjer representationen av mångsidiga nyttor från användningen av flera geografiska datatjänster. Dessutom visade sig Spatineo Impact vara ett användbart verktyg för att avslöja de realiserade nyttorna med att använda en datatjänst. Denna information är särskilt värdefull för leverantörer av öppna geografiska data.

Fallstudiens resultat betonar att en nyttoanalys påverkas starkt av tillgången på data samt av tidsramen studien genomförs i. Då man analyserar nyttorna av geografiska datatjänster borde man i mån av möjlighet också utnyttja intervjuer och frågeformulär med slutanvändarna för att få en möjligast bra uppskattning av de uppfattade fördelarna.

Nyckelord Nyttoanalys, socioekonomisk nytta, geografiska data, geografiska datatjänster, det arktiska området

Contents

Preface

This thesis has been written under Spatineo Inc, where I have had the opportunity to work in collaboration with an international project called Arctic PASSION. The Arctic PASSION project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101003472. The project has made this thesis work possible.

I would like to thank my advisor Jaana Mäkelä for her support and encouragement during the research. Also, I would like to thank my supervisor Henrikki Tenkanen for his help and guidance. I would like to thank Sampo Savolainen for his valuable comments and guidance in technical details. I would also like to thank the colleagues in work package five in the Arctic PASSION project: thank you for many interesting discussions and for a valuable insight to this field. Finally, I would like to thank my partner for the support and ideas he has given during the whole writing process.

Espoo, 17th of February 2022
Isabel Donner

1 Introduction

1.1 Background and motivation

The Arctic area is changing rapidly due to climate change, as it is warming more than two times faster than the global average (IPCC, 2021). To be able to adapt to these changes, people living in and companies operating in the Arctic need accurate and up-to-date information on the condition of the Arctic region.

There is a growing need to monitor the Arctic area in greater detail. The current Arctic observing system is inadequate and does not serve the end-user. The system's components are fragmented and uncoordinated (Starkweather et al., 2020). Moreover, there are gaps in data coverage, data may be difficult to access, and accessible data are often not directly useful to end-users ("Arctic PASSION - Overview," n.d.). To tackle these challenges, there is a need to integrate international observing systems and provide user-friendly applications for the Arctic. An integrated observing system would make it possible to address the challenges caused by climate change.

However, despite recent efforts in estimating the costs and benefits of Arctic observing systems (e.g., Dobricic et al., 2018), there is no in-depth analysis of societal benefits which would be sufficient to justify long-term funding for integrating Arctic observations. To this end, a detailed socioeconomic impact analysis of earth observation data and services in the Arctic would be needed. By quantifying the benefits that new data and services have on local and global societies, further improvements of existing systems and development of new ones can be justified (Adams et al., 2016; PWC, 2016).

The study of this thesis has been done in collaboration with the EU funded project Arctic PASSION, i.e., *Pan-Arctic observing System of Systems: Implementing Observations for societal Needs* ("Arctic PASSION - Overview," n.d.). The key motivation behind the project is to integrate existing and new international observing systems for the Arctic, and to create a pan-Arctic Observing System of Systems (pan-AOSS) that provides accessible high-quality earth observation information that addresses the needs of actors in the Arctic ("Arctic PASSION - Overview," n.d.).

To ensure long-term investments in a pan-AOSS there is a need for a deep understanding of how Arctic observations may benefit different actors. By quantifying the observation system's monetary and non-monetary societal benefits the financial and political sustainability of pan-AOSS can be ensured ("Arctic PASSION - Assessing Societal Benefits and Economic Impacts," n.d.). The assessment work will be carried out on eight pilot services that are developed in the Arctic PASSION project ("Arctic PASSION - Innovating User-Driven Arctic Eurogeo Pilot Services," n.d.). This thesis will support the selection of suitable socioeconomic impact assessment methods for the evaluation of these pilot services.

Socioeconomic impact analysis is an approach that is used to specify and quantify the impacts or value that accumulates in a society resulting from an action (Adams et al., 2016). The impact is an induced social, economic, environmental, or other positive benefit or negative effect for an individual or group of people. The results of a socioeconomic impact assessment can be used as an objective basis to evaluate the impacts of an earth observation project, to communicate the value of earth observation data to key stakeholders, to defend earth observation research budgets against competing priorities and to justify the investments made into projects and programs (Adams et al., 2016).

Literature on socioeconomic impact assessment is extensive and numerous methods have been used to evaluate the benefits of earth observation data. However, the various methods are not always interoperable and the field lacks "best practice" models. The selection of the most suitable assessment methodology can be difficult, as different methodologies are presented in different publications and reports. An overview of existing methods and descriptions on what kind of cases they are suitable for will make the analyst better informed when selecting between available methods. An overview of existing assessment methods and an evaluation of their suitability to assess Arctic earth observation data will support the assessment of an integrated Arctic observing system.

1.2 Aim of the study

The main objective of this thesis is to evaluate and choose the most suitable tools for the assessment of benefits of earth observation data and services in the Arctic area. Based on this objective, this thesis aims to answer three research questions:

1. What methods for assessing societal benefits and economic impact are available and have been used to assess earth observation data and services?
2. Which of the studied methods would be most suitable to assess earth observation pilot services that are developed in projects for the Arctic area?
3. What are the results from testing the methods for chosen existing services?

1.3 Study design

The research was executed as a literature review and a case study. To answer the first research question, a literature review was conducted to study the most essential impact assessment tools that have been used to estimate the benefits originating from earth observation data and services. The studied assessment methods were cost-benefit analysis, benefit transfer, value chains, Value Tree Analysis, Weather Service Chain Analysis, and Spatineo Impact.

Then, to answer the second research question, these methods were compared to find the most suitable tools for assessing earth observation services and data in the Arctic region. Based on the findings of the comparison work, two methods were selected for further analysis. These selected methods are applied in a case study.

The third research question is answered by conducting a case study. In the case study, two socioeconomic impact assessment methods were applied to assess the societal and economic impacts of an existing service. The methods that were applied and compared in the case study were Spatineo Impact and Value Tree Analysis.

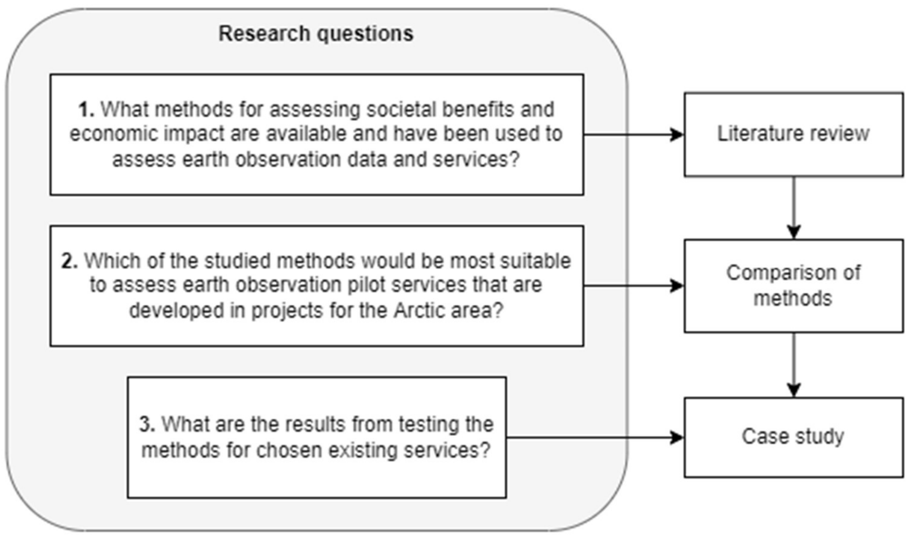

Figure 1 Flowchart of the study design of this work.

1.4 Key concepts

Earth observation is the acquisition of information about the state of the earth through remote-sensing and *in-situ* technologies (Chandra, 2017, p. 3). It includes the assessment of the status of atmospheric, oceanic, and terrestrial environments and the monitoring of changes in them.

An *impact* is a positive or negative change in an individual's or group's life. *Benefits* are impacts that are perceived to be positive. (Adams et al., 2016.) An example of a benefit is a cleaner environment due to better decision-making.

Socioeconomic impact analysis is a collection of methods that are used to assess and measure the societal and economic impacts that accumulate in the society as a result of an action. In an earth observation context, impact assessment generally measures monetary and non-monetary benefits of some earth observation service, project, infrastructure, or investment. (Adams et al., 2016.) There are numerous approaches for conducting a socioeconomic impact analysis. Different methods for assessing societal benefits and economic impact, as well as the general workflow for a socioeconomic impact analysis are discussed in detail in the literature review is section 2.

The *Arctic area* is a geographic region that spreads around the North Pole. The southern boundary of the region varies depending on the definition (see e.g., Manrique et al., 2018), and has been given different definitions in different Arctic Council Working Groups. In this work, the Arctic area is defined as the region north of 60 degrees North (see Figure 2).

Figure 2 The Arctic area. In this work, the Arctic area is defined as the region north of 60 degrees North, marked with red in the figure.

2 Literature review

2.1 General workflow of a socioeconomic impact analysis

A socioeconomic impact analysis can be used to reveal the benefits originating from earth observation data, services or projects. Socioeconomic impact assessments have been used to communicate the value obtained from making investments into the earth observation industry. Often, the aim of the assessment is to show that already made investments have been sensible, or that further investments would induce significant additional value to society.

There are several methods for conducting a socioeconomic impact assessment. The methods have used different approaches and have their own workflows. Nevertheless, a general workflow of a socioeconomic impact analysis can be formulated to give the reader an overview of the different steps that are typically included in the assessment work.

The general workflow of a socioeconomic analysis, according to Adams et al. (2016), can be divided into eight steps: choosing the analytic approach, specifying measurable metrics, identifying impact relationships, collecting and conditioning data, estimating the baseline, quantifying impacts, monetizing impacts, and reporting results. Different authors, (see e.g., World Bank Group et al., 2015) suggest slightly different workflows for conducting a benefit analysis.

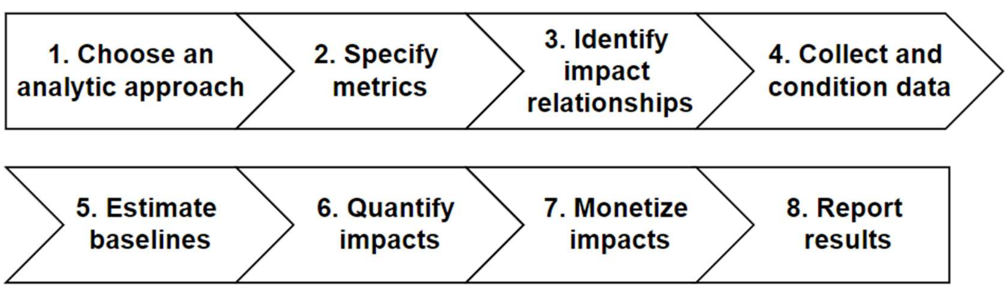

Figure 3 The general workflow of a socioeconomic impact analysis, according to Adams et al. (2016).

The first step in the general workflow is to choose an analytic approach. The choice of a suitable method should be justified carefully as they all have their own advantages and considerations. The choice of approach depends on the maturity of the assessed project, availability of data, the amount of available resources and the need of detailed in-depth analysis. Also, the desired representation of results should be considered. In the last 20 years, various methods have been used for evaluating impacts of earth observation data (Tassa, 2020). The most relevant of these different approaches are discussed in section 2.2.

The second step is to specify the impact metrics to be measured in the analysis. Relevant metrics are concrete, measurable and reflect the ultimate benefit to individuals, groups, or society (Adams et al., 2016). These metrics can be monetary, e.g., net present value and property value, or non-monetary, e.g., biodiversity, mortality, and increased safety.

Next, the analyst needs to identify impact relationships, i.e., how a project's inputs can be linked to the final benefits. In this step the baseline, the resource inputs, project outcomes, and impacts are recognized. The goal is to specify which inputs bring about which impacts. Moreover, key assumptions are identified, and confounding variables are reviewed.

The fourth step in the general workflow is to identify, collect, and condition relevant data. Depending on the approach used, collected data can consist of existing numerical data, simulated data, findings from a literature review, interviews, or survey results. It is vital that the data collection is done thoroughly and critically. Collected data is then used to establish the baseline. The baseline is a reference case that represents the state of the world in the absence of the earth observation data.

In the sixth step, the analyst attempts to quantify the benefits derived from the use of the earth observation data. Here, the selected socioeconomic impact assessment method or methods are used. To estimate the net impact of the project, the recognized impacts are compared to the baseline established in the previous step. The measurable metrics are referred to again when assessing the impacts.

Once the impacts have been quantified, they can be monetized. The advantage of expressing impacts in a common unit, such as money, is that it enables comparison of impacts against project costs or between different projects (see cost-benefit analysis in section 2.2.1). Also, economic benefits are often of interest to decision-makers. There are various methods for monetizing benefits, e.g., by using existing market values or some standard monetary values for impact quantities, or by using non-market valuation methods. However, it is customary to present some impact metrics in non-monetized form, as monetizing some benefits can be controversial (Adams et al., 2016).

The final step of a socioeconomic impact assessment is to report the results. In the report, the author should state clearly all assumptions made in the analysis as well as the result's uncertainty and sensitivity. The report should be formulated so that it suits its target audience, and thus there can be several reports intended for different audiences. World Bank Group et al. (2015) recommends that to ensure that the results of the analysis are communicated efficiently, a communication strategy for the preparation and execution of a socioeconomic impact assessment should be designed even before the study begins. Good communication can play a key role in maintaining public support for the assessed project or program.

2.2 Methods for socioeconomic impact analysis

2.2.1 Cost-benefit analysis

Cost-benefit analysis is a collection of widely approved economic methods for evaluating the impacts of a project, service, infrastructure, or decision. Cost-benefit analysis can be implemented in different ways, however, in this text the focus is on the common approach. The method systematically identifies, lists, and compares all costs and benefits associated with the evaluated project (PWC, 2016). The underlying idea in cost-benefit analysis is that a project induces positive net benefits if the project's total monetized benefits exceed total costs (Adams et al., 2016).

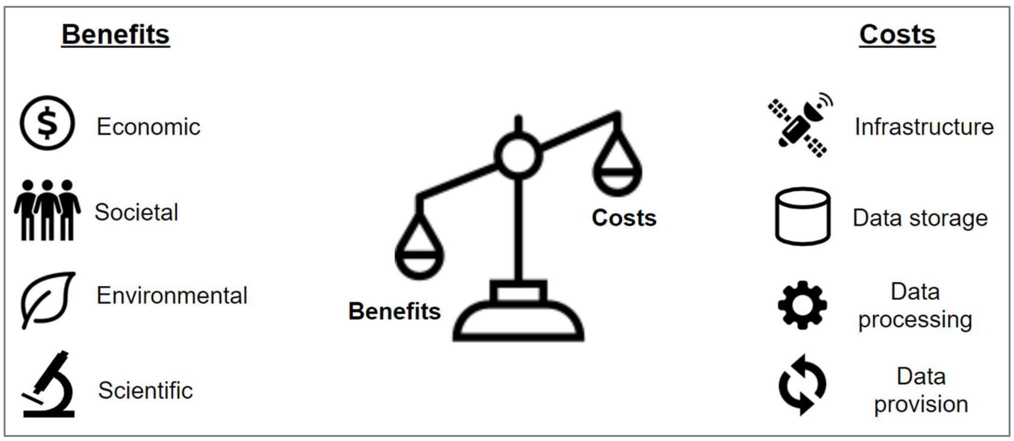

Figure 4 In cost-benefit analysis, the total benefits of the assessed service are compared to its total costs.

Costs that may arise from an earth observation service involve fixed costs and variable costs (PWC, 2016). Fixed costs are costs that are independent of the production output. In earth observation projects the fixed costs include investments made to build the infrastructure (PWC, 2016), e.g., a satellite or other earth observing instrument. Variable costs are costs that vary based on production output. These variable costs are related to the utilisation and maintenance of the existing infrastructure. Typical variable costs are related to data storage, data provision and data pre-processing (PWC, 2016). The total cost of the evaluated project is the sum of fixed and variable costs.

In addition to costs, the analyst attempts to identify and quantify all benefits originating from the evaluated project (Adams et al., 2016). Benefits can be divided into, e.g., economic, societal, environmental, and scientific benefits. To include non-monetary benefits to the cost-benefit calculation, it is possible to use different approaches to estimate an economic value for the benefit. For example, there are several guidelines for calculating the value of a statistical life (see e.g., United States Environmental Protection Agency, 2010). However, as monetizing some benefits can be difficult or even controversial, it is common to report non-quantified benefits outside the cost-benefit calculation (Adams et al., 2016).

The results of a cost-benefit assessment can be expressed using various comparable quantities. These quantities can be used to determine whether a project is worth undertaking. The quantities can also be used for choosing among different projects or project approaches. When reporting the results of a cost-benefit assessment it is advisable to express the result in various quantities, as some quantities may distort the result when presented alone. Examples of typically used quantities are net present value, benefit-cost-ratio, and internal rate of return (for details, see World Bank Group et al., 2015).

Cost-benefit analysis is based on a simple formula (Adams et al., 2016):

$$Net\ Benefits = Benefits - Costs.$$

In other words, positive net benefits can be expected of a project if its benefits exceed its costs. As the cost and benefits of a project may accrue at different time intervals, discounting must be considered when calculating the net benefits. Discounting refers to that most decision-makers would rather receive money sooner than later, which means that the value of an investment decreases over time (Adams et al., 2016). Typically, discounting is considered using a discount rate that is assumed to be constant over time.

Selection of a suitable discount rate is crucial in a cost-benefit analysis, as it affects the result significantly: the selection of discount rate may affect whether the project yields positive net benefits or not. Zhuang et al. (2007) found that the variations in discount policies in different countries are significant. The authors discovered that developed countries typically use as low discount rates as 3–7%, while developing countries use significantly higher rates: 8–15%. The study concludes that because the rate of return for business investments varies in different countries, due to differences in economic structure, stage of financial development, among other things, the countries should independently determine a guideline for an appropriate discount rate and adjust it when required by changes in the domestic economy or international capital markets. However, the discount rate given by national guidelines may not be applicable to all cost-benefit analyses, as there are multiple factors that can affect the expected return of investment of a specific project.

One way to work around the problem of discount rate used in several studies (e.g., Hautala and Leviäkangas, 2007; Leviäkangas et al., 2007) is to analyse the benefits materializing at the current time. With this approach, there is no need to determine a discount rate or to choose the length of the reference period. Moreover, it is usually easier to estimate the benefits that are realizing in the present, rather than evaluating possible future benefits. Naturally, the drawback of this approach is that it does not consider costs or benefits that are generated in the future, which influences the result significantly. Therefore, this workaround is useless when assessing projects where benefits are expected to materialize in the future or over a long period of time, e.g., when assessing the impact of remote sensing projects.

Although the concept of cost-benefit analysis is rather straightforward, it can be extremely difficult to assess the benefits enabled by a project accurately. Tracking the benefits to end-users and quantifying these benefits becomes complex as most end-users may use the earth observation data partially together with other data sources and without knowing what technology the original data is based on (PWC, 2016). Another problem of the approach is that it is often assumed that an investment logically leads to end-user's benefit (PWC, 2016). This assumption does not consider whether the user is capable to fully utilize the improvement made by the investment. End-users might not be able to utilize the available information due to lack of know-how or required technology. Thus, additional investment into infrastructure might not bring additional value to the user.

In addition to benefits being potentially difficult to monetize, obtaining information on observing system costs may be challenging. Comprehensive information about the costs may not be readily available and the available information may not be reported consistently (e.g., Dobricic et al., 2018). Moreover, if the observing system is not specifically designed for the area of interest in the assessment, it might be necessary to determine the share of costs that are attributable to the area of interest. For example, when assessing the societal benefits of Arctic observing systems, Dobricic et al. (2018) determined the share of costs of the remote sensing observing systems that specifically refer to the Arctic by comparing the Arctic area to the total area covered by the satellite system.

Another drawback of cost-benefit analysis methods is that they do not consider whether the benefits of the assessed project are distributed equally or fairly to the society. Benefits achieved may accrue to some specific groups of people or regions. World Bank Group et al. (2015) recommends that equity and distributional considerations should be discussed in the cost-benefit assessment's report, so that decision-makers can take them into account.

Cost-benefit analyses have been widely used in literature when evaluating benefits obtained from the use of earth observations. A cost-benefit analyses provides robust and accurate calculations on net benefits, when markets and models are available (Tassa, 2020). However, Tassa (2020) points out that the cost-benefit analysis method often fails in providing reliable results when established frames are unavailable. She argues that as the techniques used need to be adjusted to the case at hand, and links to final benefits may be scattered and complex, that cost-benefit comparisons may lead to distorted results in the absence of markets and models.

Hautala and Leviäkangas (2007) evaluated the impacts of services provided by the Finnish Meteorological Institute (FMI) using a cost-benefit analysis approach. The study assessed the benefits of the services for different sectors, focusing on weather and road conditions services for transport. The share of benefits to the sector, that was attributable to FMI's services, was estimated using FMI's market share. The benefits were monetized using market prices, statistics, internalised unit cost values and expert estimates. As the total costs, the authors used the FMI's annual costs for 2005. The results indicate that investments into FMI's services pay themselves back by at least 5-fold each year. The good quality, availability, and coverage of statistical data in Finland contributed to accurate results in the assessment work. Estimates for different sectors are detailed and well established. However, differences in the industries, in available source material and in the evaluators' experiences led to that the results obtained from different sectors were inconsistent (Hautala and Leviäkangas, 2007). The authors concluded that their approach had difficulties in outlining the benefits specifically for the sectors, as well as in monetizing benefits. The study focused mostly on economic benefits and limited its time scope to the present.

Leviäkangas et al. (2007) implemented cost-benefit analysis to estimate the net benefits of the everyday services offered by the Meteorological and hydrological service of Croatia, Državni hidrometeorološki zavod (DMHZ). The benefits were assessed by inspecting seven beneficiary sectors separately and the total benefits were obtained by aggregating these results. The studied beneficiary sectors were road transport, rail transport, maritime transport, aviation, building construction, infrastructure and facilities management, energy production and air quality and agricultural production. Data on benefits were collected using literature reviews and statistics, workshops, and expert interviews as well as modelling of expected impacts. For some benefits, there were no statistics available and expert opinions could not be used to estimate the value of the benefits. In these cases, the potential benefits were estimated by using a benefit transfer approach (see chapter 2.2.2 for details about the benefit transfer analysis). The net benefits were obtained by comparing total benefits to the annual budget of DMHZ. The authors recognize that the results are heavily impacted by Finnish benchmarks. As a result, the values on benefits can be viewed only as suggestive estimations. Nevertheless, the study shows that investments into the DMHZ pay themselves back by at least 3-fold each year.

Bouma et al. (2008) used a cost-benefit approach to estimate the additional benefits from investments into satellite observations in a case of water quality management in the North Sea off the Dutch coast. The expected impacts of using satellite-based information on top *in-situ* measurements used at the time were estimated by interviewing stakeholders. The stakeholders were asked how they believe that additional satellite-based information would affect the uncertainty of water quality decision-making and what kind of benefits this would induce. The authors pointed out that the range of answers among respondents varied significantly: the answer depended on the respondent's opinion on the need for a warning system regarding algal blooms and on the foreknowledge of satellite technology. When implementing Bayesian decision theory combined with stakeholder opinions, Bouma et al. (2008) estimated that the rate of return for additional investments into satellite observations would be 48%. However, the result of this estimate is highly dependent of the accuracy of the developed system. Once the probability for certain errors exceeds a critical limit, the value of information for the satellite observations become zero. As a result, it is difficult to access the real net benefits of this yet not implemented observing system. This study emphasized that the benefits from a system are highly dependent on the quality of the produced information as well as the stakeholders' capability and willingness to use the information for decision-making.

2.2.2 Benefit transfer

Benefit transfer is, in a way, the simplest method for conducting a socioeconomic impact analysis, as it does not require an original study to estimate the benefits generated from the assessed project, service, infrastructure, or decision. Instead, the benefit transfer approach applies existing studies to conduct the analysis. Benefit transfer can be defined as the estimation of values in the assessed case using the results obtained in other research, the study cases (United States Environmental Protection Agency, 2010). The benefits are "transferred" from resembling study cases to the assessed case by identifying and accounting for differences between the cases (United States Environmental Protection Agency, 2010).

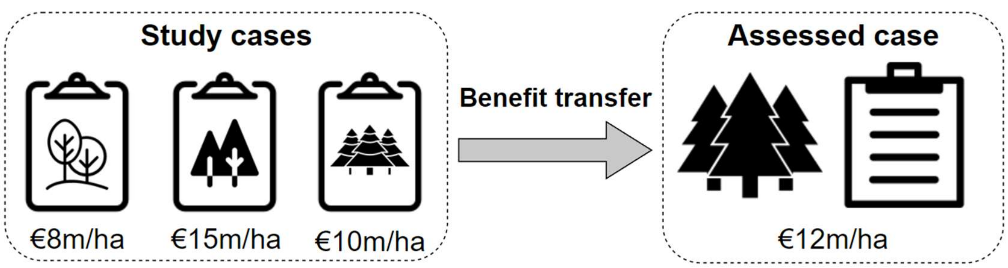

Figure 5 In benefit transfer, the benefits of the assessed case are estimated by transferring benefits from representational study cases.

The process of conducting a benefit transfer can be generalized into a set of steps (United States Environmental Protection Agency, 2010). First, the analyst needs to describe the assessed case in detail to understand its characteristics, consequences, and the beneficiaries. Second, the analyst should select the study case or study cases. This is a crucial step in the process as the selected study cases affects the quality of the result significantly. The potentially relevant studies are identified in an exhaustive literature search. Then, study cases should be selected by reviewing the potential studies for applicability and quality. The study cases should have adequate technical quality and be similar to the assessed case when it comes to locations, populations, cultural and economic differences, and expected changes in site conditions

(World Bank Group et al., 2015). Then, the analyst should transfer the benefit estimates from the study cases to the assessed case. There are several approaches for conducting this step, e.g., value function transfers, unit value transfers, meta-analysis and structural benefit transfer (see United States Environmental Protection Agency, 2010). Generally, the more related the study cases are the more reliable are the results of the benefit transfer. Finally, the analyst must ensure that all key judgements and assumptions are described when presenting the results of the study. The selection of study cases and transfer approach should be justified. When possible, the uncertainty of the results should be quantified and reported.

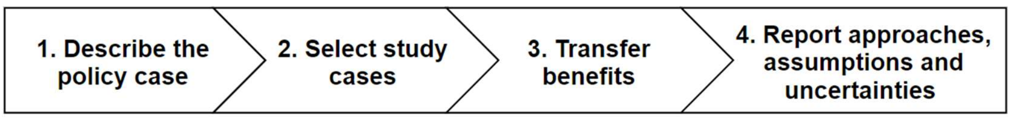

Figure 6 General workflow of the benefit transfer method (according to United States Environmental Protection Agency, 2010).

Benefit transfer is a suitable method for conducting a socioeconomic impact analysis only when other methods are not feasible (United States Environmental Protection Agency, 2010). Often, this happens when time or resources are not sufficient to conduct an original socioeconomic benefit study. The method has been widely used because original studies are time consuming and expensive, while benefit transfer can give cheaper and faster approximate estimates of benefits (United States Environmental Protection Agency, 2010; World Bank Group et al., 2015). Often, the method is used to complement other socioeconomic impact analysis approaches (see e.g., Leviäkangas et al., 2007).

Leviäkangas et al., (2007) conducted a cost-benefit study to estimate the net benefits of meteorological services in Croatia (see chapter 2.2.1. for details about the cost-benefit assessment). For some values, there were no useful statistics or expert opinions available when the authors attempted to assess the benefits for different beneficiary sectors. In these cases, benefit transfer was used to obtain approximations of economic benefits. The study case used was a Finnish case study (Hautala and Leviäkangas, 2007), that estimated the impacts of services provided by the Finnish Meteorological Institute. The analysed services and beneficiary sectors were similar in the study case and the assessed case, making a benefit transfer approach appropriate. Leviäkangas et al., (2007) considered the differences between Croatia and Finland by using a Price Level Coefficient. The Price Level Coefficient represented the difference in purchasing power between the countries and was calculated by dividing the Gross Domestic Product per capita adjusted for purchasing power of Croatia with Finland’s corresponding value. Simplifying, the study assumed that the differences in realized benefits between the countries are dependent on the differences in purchasing power, not considering differences between sectors or inputs. Nevertheless, using this simplified model the authors obtained approximate values for benefits that could not be quantified otherwise within the study's budget.

Hallegatte (2012) used the benefit transfer method to estimate the potential benefits of early warning systems in developing countries. As study case, the author used a study on benefits from early warning systems in Europe and transferred the benefits to developing countries by considering the differences in countries' income levels. The study assumed that richer countries more probably have functioning hydro-meteorological services and therefore realize greater benefits from early warning systems. Consequently, the study defined four groups of countries depending on the income level: low-income, low-middle income, middle-income, and high-income countries. Low-income countries lack basic hydro-meteorological services and were assumed to realize only 10% of European benefits. Low-middle income countries were assumed to realize 20% of European benefits, middle income countries realized 50% and high-income countries were assumed to realize 100% of European benefits. Total benefits were calculated by adding up the results obtained from the four groups. Even as the results obtained from the benefit transfer were coarse and indicative, the results of the study showed that investments into early warning capacity in developing countries would result in significant benefits realized as avoided asset losses and saved lives.

2.2.3 Value chains

Showing the benefits from the usage of earth observation data is a complex task. The end-users of earth observations are diverse and benefit from the information in different ways. In general, the benefits for direct users of the data are fairly simple to assess. However, recognising the impact of made decisions or the value of the earth observations as it is combined with other data becomes more challenging. The benefits from earth observations tend to scatter across the society to different sectors, various end-user groups and to several benefit areas.

To manage this complex task of modelling the flow of benefits originating from earth observation services, several authors have used approaches based on value chains. The studies have mainly been conducted separately and with inconsistent definitions (Tassa, 2020) resulting in that there is no single established way for conducting a value chain analysis. This chapter focuses on a few recent studies that use value chains to assess the socioeconomic benefits accruing from earth observations.

Value chains have been used to model how value flows from one actor to another in the society. Sawyer and Papadakis (2020) define the value chain as the succession of activities that result from the use of an earth observation product or service. PWC (2016) and PwC (2019) use the value chain to describe all socioeconomic benefits enabled from the use of information extracted from earth observations. The value chain approach is useful when analysing the benefits generated from a specific earth observation input to a field or case. Value chains have been used in several studies that assess the benefits generated from the use of remote sensing observations.

Figure 7 The value chain describes how benefits originating from earth observations flow from one actor to another in society. (Amended from Sawyer and Papadakis, 2020, p.20.)

Two comprehensive studies estimating the socioeconomic impact of using Copernicus data in the European Union, by PWC (2016) and PwC (2019), have been conducted using a value chain approach. The studies use value chains to evaluate the benefits for sectors that were recognized as the most common users of Copernicus data: agriculture, forestry, ocean monitoring, air quality monitoring, renewable energies, oil and gas, urban monitoring, insurances (PwC, 2019; PWC, 2016), response to natural disasters, and security (PwC, 2019). In these studies, the value chains represented the downstream domains of each sector, including all the economic and societal impacts inflicted from the use of data from earth observation satellites. The reports discuss in detail how Copernicus data enables numerous applications that bring immense benefits to the sectors. The economic impacts on value chains were assessed by consulting organisations and existing literature, using a microeconomic approach. Societal, environmental and strategic impacts were assessed using quantitative and qualitative approaches (PwC, 2019).

The European Association of Remote Sensing Companies (EARSC) carried out a project with the aim to quantify the benefits resulting from the usage of Copernicus Sentinel data through several case studies. These case studies have used a value chain approach in a structured manner (Sawyer and Papadakis, 2020). The value chain implemented in the case studies begins with the earth observation data product or service, which is used by a primary user organisation. Next, there are the secondary users, who use the services provided by the primary user. Finally, the last link in the value chain are citizens and society. The case studies typically focused on the value chain from a service provider to end-users, but there could be multiple value chains originating from the same service provider. For example, in the case study of ground movement monitoring in Norway, by Sawyer and Boyle (2020), two separate value chains were recognized: one value chain that described the value to construction and related industries as well as road users in general, and one value chain that described how the service provider can make better decisions using their own service.

In these case studies, total benefits were assessed by separately evaluating the value for each appropriate stage in the value chain separately and by adding up these values (see Figure 8 for an example). Benefits derived from the satellite data become more difficult to attribute further down the chain as users become unaware of that the services provided are enabled by remote sensing technologies (Sawyer and Papadakis, 2020). Sawyer et al. (2015) argue that the impact of satellite contribution becomes significantly smaller when moving down the value chain. The authors estimated that the relative value of satellite contribution at the two last stages in their value chain was only 0.1–0.5%. However, the value of the relevant economic activities increases when moving down the value chain, resulting in high absolute benefits (Sawyer et al., 2015).

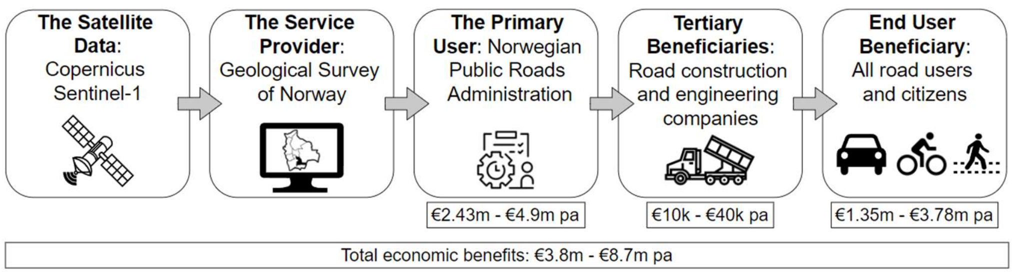

Figure 8 The value chain of ground motion monitoring in Norway. The Geological Survey of Norway produces InSAR Norway, a service for ground motion monitoring, based on Sentinel-1 satellite imagery. The NPRA uses the service for better decision- and policymaking, which results in 2.43–4.9 million euros savings annually. Road construction and engineering companies benefit from better planned and executed projects, which saves 10–40 thousand euros annually. All road users and citizens gain benefits from better roads, generating benefits worth 1.35–3.78 million euros annually. Total economic benefits from Copernicus Sentinel-1 data in this value chain is 3.8–8.7 million euros annually. (Sawyer and Boyle, 2020.) (Figure amended from Sawyer and Boyle, 2020, p. 9.)

The methodology used to assess the case studies defines six dimensions of value: economic, environmental, regulatory, innovation and entrepreneurship, science and technological research, and societal value (Sawyer and Papadakis, 2020). However, only Sawyer and Boyle (2020) attempted to quantify the non-economic benefits. The authors used a scale ranging from zero to five, zero being no perceivable benefits and five being exceptional significance, to describe the magnitude of the importance of Sentinel data to the benefit categories. All three case studies computed estimates of the economic benefits by comparing the current situation to one where the satellite data would not be present. With this approach, savings that can be accounted to the usage of satellite data could be estimated.

2.2.4 Value Tree Analysis

IDA Science and Technology Policy Institute together with Sustaining Arctic Observing Networks (2017) have developed an International Arctic Observations Assessment Framework to support the assessment of the value of earth observation services in the Arctic. The assessment framework introduces a method, the so-called Value Tree Analysis method, for building a value tree that connects earth observations to outcomes and impacts, and finally to societal benefits.

The value tree links observing systems to key products, services, and outcomes, which further link to key objectives. Key objectives are linked to societal benefit sub-areas which form the societal benefit areas. The top of the tree, i.e., the key objectives, societal benefit sub-areas and societal benefit areas, have been recognized for the Arctic area in the International Arctic Observations Assessment Framework. The key objectives have been selected to reflect international Arctic strategies. The framework recognizes 12 societal benefit areas for the Arctic: disaster preparedness, environmental quality, food security, fundamental understanding of Arctic systems, human health, infrastructure and operations, marine and coastal ecosystems and processes, natural resources, resilient communities, sociocultural services, terrestrial and freshwater ecosystem processes, and weather and climate. The societal benefit areas are defined as the social, economic and environmental domains in which operations, services and research result in benefits (IDA Science and Technology Policy Institute and Sustaining Arctic Observing Networks, 2017).

The bottom of the tree, i.e., the observing systems, key products, services and outcomes, and the key product, service, and outcome groups, is to be constructed in a separate assessment work using domain expert knowledge. By following the framework, it can be shown how the usage of earth observation data contribute to the achievement of international objectives in the Arctic region.

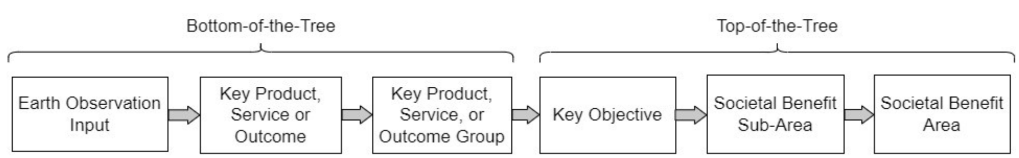

Figure 9 Value tree structure as according to the international Arctic Observations Assessment Framework. (Amended from IDA Science and Technology Policy Institute and Sustaining Arctic Observing Networks, 2017, p. 3.)

The international Arctic Observations Assessment Framework has been applied in a couple of studies. Dobricic et al. (2018) used the framework to form value trees for ten case studies in the Arctic. The selected case studies represent a wide spectrum of observing systems and activities that benefit from earth observations. A value tree for each case study was built using the

Value Tree Analysis approach from the international Arctic Observations Assessment Framework. The relevant observing systems for each case study and the societal benefits the observations generate were identified. Then, a value tree was formed (see figure 8 for an example). To understand the relationship between investments made into the Arctic observing systems and the generated benefits, the costs and monetary benefits were assessed for each case study. The results of the cost-benefit assessment indicated that the economic benefits enabled by the Arctic observing systems outweigh their costs multiplicatively.

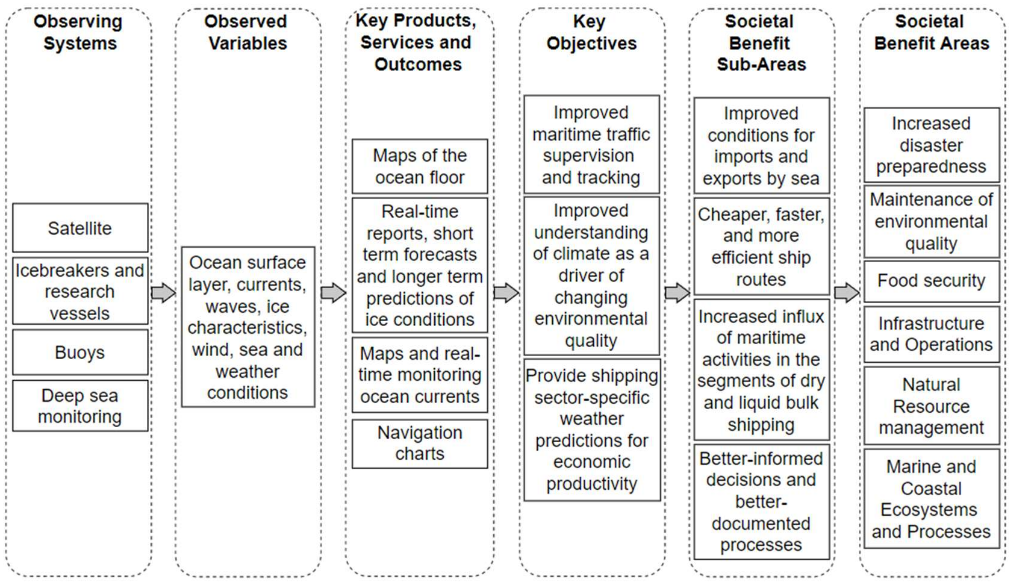

Figure 10 Value tree for a case study in ship management and navigation routes in the Arctic. (Amended from Dobricic et al. 2018, p. 41.)

Strahlendorff et al. (2019) formulated a value tree for physical atmosphere and ocean observation in the Arctic using the International Arctic Observations Assessment Framework. The value tree represents how the investments made into the Arctic observing system of physical atmosphere and ocean flow towards existing services and bring socioeconomic benefits to the Arctic region. The results were visualized using an interactive browser tool developed by Finnish Meteorological Institute and Spatineo Inc. (2019). Using the browser tool, it is possible to visualize how earth observation inputs induce impacts into a specific societal benefit area (see Figure 11). Likewise, it is possible to represent how the outputs of a specific earth observation system provide added value to multiple societal benefit areas (see Figure 12).

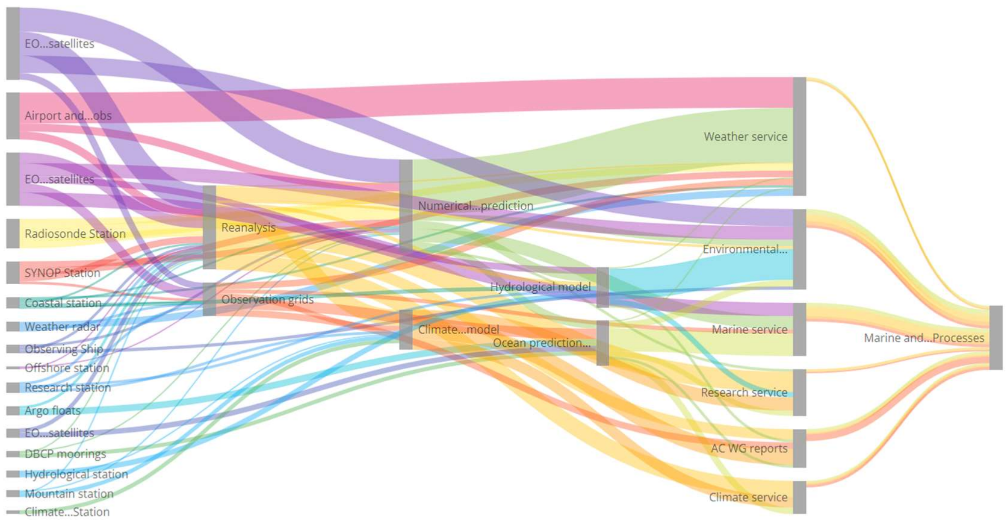

Figure 11 Value tree built by Strahlendorff et al. (2019). This visualization represents how value from different earth observation systems contribute to the societal benefit area Marine and Coastal Ecosystems and Processes. The visualization is made with the browser tool by Finnish Meteorological Institute and Spatineo Inc. (2019). The visualization underlines that multiple earth observation systems are necessary for producing societal benefits.

The interactive web page is a powerful tool for communicating how different earth observation services in the Arctic are interconnected and essential for producing societal benefits. The outcomes of the research can be used to justify the investments made into existing observation systems. However, further research is needed to quantify the benefits that surface from the usage of the observation services.

The Value Tree Analysis method has been used to understand the combination effect from multiple observation systems. The approach is useful when the goal is to model a complex flow of value from observation services to different benefit areas. As the value tree can grow very complex when several earth observation inputs are included, the visualization method is crucial for a successful communication of results. The browser tool developed by the Finnish Meteorological Institute and Spatineo Inc. (2019) is a promising visualization technique for this purpose.

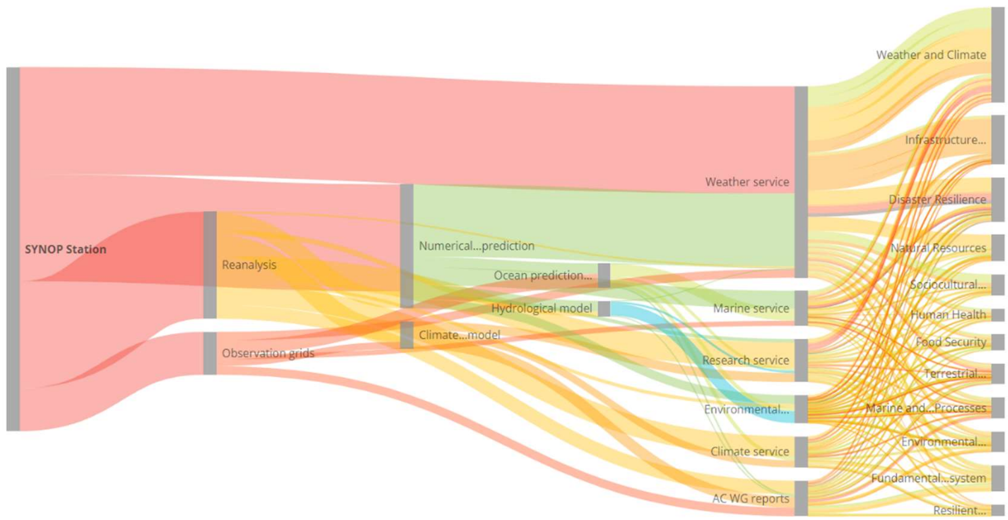

Figure 12 Value Tree built by Strahlendorff et al. (2019). This visualization represents how value from SYNOP stations contribute to the different societal benefit areas in the Arctic. The visualization is made with the web tool by the Finnish Meteorological Institute and Spatineo Inc. (2019). The visualization highlights that the output from SYNOP stations enable many different types of benefits.

2.2.5 Weather Service Chain Analysis

Perrels et al. (2012) introduce a so-called Weather Service Chain Analysis (WSCA) as a method for assessing the value of weather forecast services. The method is presented as an alternative for cost-benefit analysis. One issue of cost-benefit analysis is that it is not suitable in situations where users are non-professionals, as the approach usually assumes that decision-makers are perfectly informed, perfectly aware of different options, and perfectly rational (Perrels et al., 2012). This gives rise to an assumption of that investments that improve the accuracy of data automatically results in increased socioeconomic benefits. However, the benefits generated from a service depend on how the information is delivered, understood, and how decision-makers choose to act upon the information (Perrels et al., 2013).

In WSCA the benefits of a service are assessed by estimating how information decays in the service chain. Information decay refers to that when information is distributed and assimilated, the original value decreases due to e.g., timely access, misinterpretation of the information, or decision-makers unwillingness to change his or her behaviour (Perrels et al., 2013). There are many stages in the service chain where the full potential of the data value might not be reached due to information decay. As a result, the realized benefits at the end of the service chain are typically much lower than in the beginning of the service chain.

Perrels et al. (2012) propose that the degree of realized benefits can be assessed by estimating the information decay at seven different stages in the weather service chain. The degree of value realized at these seven stages compared to a theoretical maximum can be estimated by asking the following questions (Perrels et al., 2012):

Stage 1: To what extent is the information accurate?

Stage 2: To what extent does the information contain appropriate data for a potential user?

Stage 3: To what extent does a decision-maker have timely access to the information?

Stage 4: To what extent does the decision-maker adequately understand the information?

Stage 5: To what extent can the decision-maker use the information to effectively adapt behaviour?

Stage 6: To what extent do recommended responses help in avoiding damage?

Stage 7: To what extent do benefits from adapted actions or decisions transfer to other economic agents?

The degree of realized value at each stage in the service chain is estimated by "filtering" the estimate with the information decay. The model's linear structure only gives an approximation of each stage's ($S_1 \dots S_7$) value decay. The estimate for realized benefit fraction in the whole chain is (Perrels et al., 2012):

$$Q = \prod_{S=1}^{7} \{S_i\}.$$

Answers to these questions, i.e., estimates of potential reached at each stage, can be obtained from literature or by interviewing experts and end-users. For example, Perrels et al. (2012) estimated the accuracy of a weather service by identifying that 19 out of 21 adverse weather days were correctly predicted.

Estimating the degree of potential reached can be difficult if relevant statistics are lacking. Nurmi et al. (2013) point out that the WSCA should be conducted separately for different sectors and modes, as the availability and usage of information differs between sectors and end-users.

The seven questions can be used for identifying value "bottlenecks" in the weather service chain. By identifying the weakness of the service chain, it is possible to propose targeted improvements to sections in the chain. On the other hand, by inspecting the benefit flow in the whole chain, it is possible to recognize if investments in the infrastructure lead to an increase in value for the whole chain or only for professional users. As Perrels et al. (2012) point out, all but the first stage mostly affect non-professional users. In other words, if the accuracy of information is increased but the other stages of the service chain are left unimproved, the benefit for the non-professional end-user might not increase notably.

Perrels et al. (2012) applied the WSCA method to estimate the value of weather information in avoiding road accidents in Finland. The authors calculated that the costs arising from road accidents due to poor weather conditions every winter were 226 million euros. Next, a literature review was conducted to get estimates for the potential value reached at the first six stages in the weather service chain. The estimates of original potential reached compared to a theoretical maximum value are shown in Table 1. When the degree of realized value at each point is filtered with the information decay it can be seen clearly how the realized value decreases at each stage in the weather service chain (see Figure 13). Finally, the value reached at the sixth stage compared to a hypothetical maximum was only 14%. Having the estimates for the value of road accidents and the estimation of that 14% of the damages were effectively addressed with weather service data, the authors estimated that the value of weather information for avoiding road accidents due to poor weather conditions in Finland is 36 million euros annually (see Perrels et al. 2012 for details). Potential reached at stage seven in the weather service chain was not estimated. The seventh stage in the weather service chain is often less relevant when assessing benefit degradation in a sector level analysis (Nurmi et al., 2013).

Table 1 Estimates of reached potentials per stage in the weather service chain. Values from Nurmi et al. (2013).

Stage	Original potential reached	Filtered potential
1. Information accuracy	92%	92%
2. Information fit to end-user	90%	83%
3. Accessibility	62%	51%
4. Comprehension	85%	44%
5. Ability to respond	40%	17%
6. Effectiveness of response	80%	14%

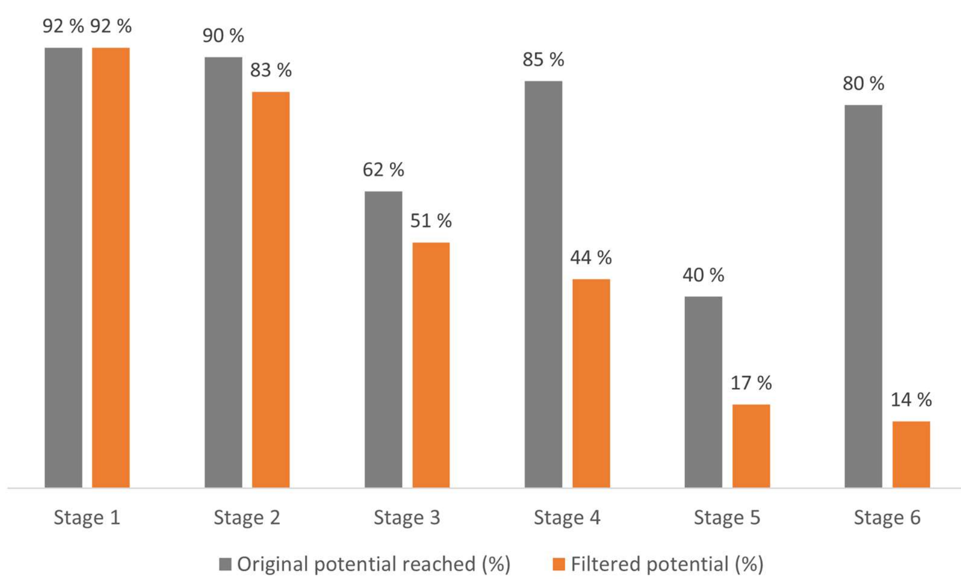

Figure 13 Information decay in the weather service chain in the study of Perrels et al. (2012). (Amended from Perrels et al., 2012, p.6.)

By manipulating the degrees of potential reached, it is possible to make estimations on how much value would come of an improvement in some of the stages in the service chain. In the case of the value of weather information in avoiding road accidents in Finland, improving data accuracy to 100% accurate forecasts would increase the value of weather information for avoiding road accidents with 3 million euros (Perrels et al., 2012). On the other hand, if the bottlenecks of the weather service chain, i.e., accessibility (stage 3) and ability to respond (stage 5), were increased to 80% and 60%, the value reached at the sixth stage would be 27%. This improvement in the weather service chain would correspond to a 35 million euros annual increase in value.

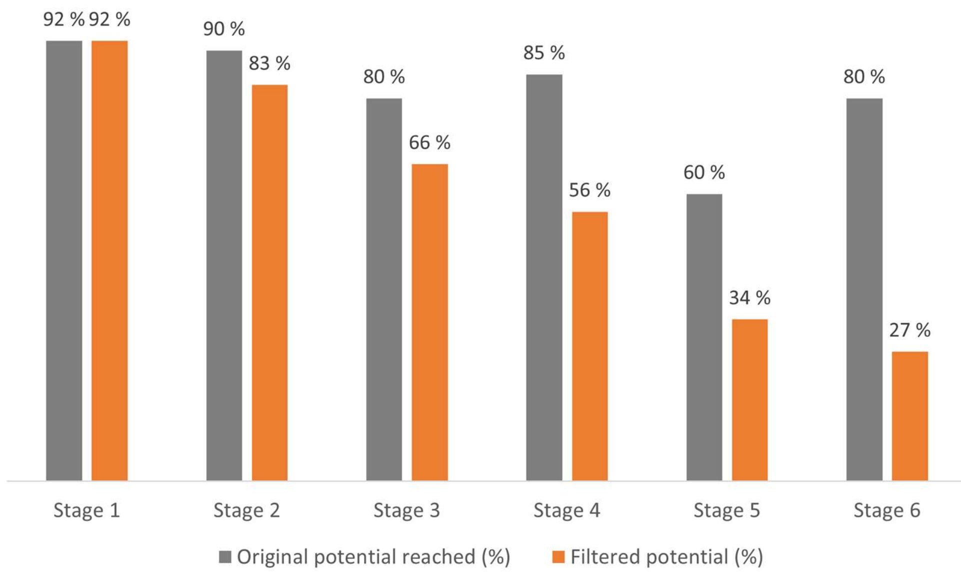

Figure 14 Information decay in the weather service chain by Perrels et al. (2012) with manipulated values for potential reached at stages 3 and 5.

Pilli-Sihvola et al. (2016) used the WSCA method to estimate how negative effects of climate change in the road transport sector could be reduced by investments and innovations in weather services. The first six stages of the weather service chain were used to analyse how end-users' abilities to adapt to poor weather conditions are affected by investments into weather service capabilities. Based on results obtained from literature and interviews, the authors estimated the magnitude of the benefits reached at the time of the study, as well as four years and 14 years in the future. Estimations showed that the expected benefits from investments in the weather services are to grow in the future: by 18–26% in four years and by 26–40% in 14 years. The authors concluded that improvements in the communication technology would give highest proportional benefits, as stage 3 (access) and stage 5 (ability to respond) in the weather service chain had the largest gaps in benefit realization.

2.2.6 Spatineo Impact

One issue related to open data is that no reliable information on the users and applications of the data are collected for the service provider, as the data can be used without registration. Spatineo Impact is a socioeconomic impact assessment method which aims to tackle this issue. This method developed by Spatineo Inc. can be used as a strategic level tool to assess the impact of the open spatial data services that an organization provides ("Spatineo Impact," n.d.).

Spatineo Impact is a commercial solution that enables organizations to get a situational picture of the volume and trends of usage, user groups, purpose of use, and benefits of the services visualized on a dashboard. The assessment work is carried out as a project including experts from Spatineo Inc. and representatives from the customer organisation. Alternatively, Spatineo Impact can be executed as a continuous work, where recommendations based on the assessment work are executed and their impacts are monitored. With the results of the assessment work, the customer organization can improve their services to serve the end-users better and to create greater benefit to their customers and to society ("Spatineo Impact," n.d.).

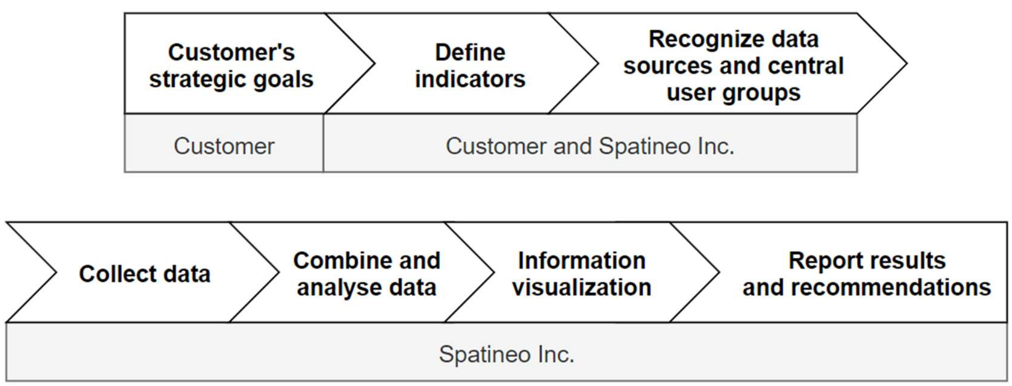

Figure 15 Workflow of the Spatineo Impact project and who is responsible for the progress of the work.

The assessment process starts with defining measurable indicators that show how well the use and benefits of the services support the achievement of the customer's strategic goals (Mäkelä et al., 2020). As an example, one strategic goal of the Finnish Environment Institute was to support cities to decrease their vulnerability to climate change (Mäkelä et al., 2018). In a Spatineo Impact assessment work, the indicator to measure the impact for this goal was whether cities that are of high risk to flooding use the Finnish Environment Institute's data on flood risk (Mäkelä et al., 2018).

Next, data sources for indicators are identified and listed. Also, the most central user groups of the services are identified. This is often an iterative process done together with the customer (Mäkelä et al., 2020). Data sources are selected so that data collection can be conducted as automatically as reasonable. The higher the level of automation, the more time- and cost-efficiently the assessment work can be carried out (Mäkelä et al., 2020). In Spatineo Impact projects, data is collected automatically from access logs of web map services and Google Analytics. In addition, relevant information on the purpose of use and benefits of services are collected from surveys and interviews. Once the most central data sources and user groups have been identified, the data is collected and combined (Mäkelä et al., 2020).

The number of requests to the customer's different data and data services are analysed from anonymized and harmonized access log files. Log access files are collected automatically as the customer sends the files to Spatineo Monitor software (see "Monitoring," n.d.). Other types of log files can also be analysed in the project. The advantage of using log files is that it enables the analysis of user activities from a long period of time, as analysis can be made for any time period where access logs are available. To ensure that the analysis of usage of the services meet the General Data Protection Regulation requirements (European Union, 2016), Spatineo has developed a method to avoid customers having to transmit private IP addresses to Spatineo Monitor. The solution is to anonymize log files before they are sent from a customer to Spatineo. Spatineo provides a free and open-source tool for the technical anonymization procedure.

By analysing the IP addresses behind the requests, it is possible to identify the user groups that have accessed the data. There is some uncertainty related to the analysis of users, as it is not always possible to identify the user group from the anonymized IP address. For example, it is impossible to separate all small and medium-sized companies from citizens, as smaller companies often do not own their own address space but purchase internet bandwidth from telecom and internet service providers similar to private citizens.

Another tool for automatically collecting data is Google Analytics web analytic service. With Google Analytics, useful information on website traffic can be analysed. Pageviews, unique pageviews, average time spent on page and other statistics on user behaviour can be reported using the acquired data. This gives information on what users are interested in and whether web maps published by the organisation are utilized. However, with Google Analytics it is not possible to analyse the usage of interface services, like with log files.

Also interviews and surveys have been used as data collection methods in Spatineo Impact projects. Interviews and surveys have been used to identify the qualitative impact that the customer's data have on internal and external users. By interviewing service developers and maintainers, it is possible to get the big picture of why the service is important, what it is meant to be used for, and what are its main areas for development. From interviews and surveys with stakeholders and end-users the analyst can identify what the services are used for, what are the perceived benefits and the issues that hinder the effective usage of the data. By asking stakeholders and end-users what they use the services for and what actions the usage of the data enables, the analyst can grasp what benefits are realized from the usage of the customer's services. Moreover, use-cases that are of interest to the end-users but for which the service is not currently suitable can be identified.

Based on the findings of the analysis, some suggestions for improvement by which the customer could increase the positive impacts they have on society are formulated. Best results are obtained when the project is repeated after a few years, to see how the suggestions made in the previous project have affected the impact of the customer's services.

Finally, the information is summarized, visualized on a dashboard, and reported to the customer. The up-to-date dashboard is a visual tool for the customer. Using the dashboard, the customer can monitor how the usage of their services supports the organisation's strategic goals. The results of the assessment work can be used by the customer to communicate that their work induces positive impacts to society and that investments into service maintenance and development are justified. Moreover, the information on what the services are used for the most and are perceived as most important to end-users can help the organisation allocate resources and investments. Organisations distributing open access data typically do not have an overview of how much their services are being used, and a numerical analysis of user behaviour can be used to guide decision-making.

3 Materials

3.1 Assessed product: Lake Ice Extent

This work aims to assess the socioeconomic impact of the *Lake Ice Extent for the Northern Europe* (LIE) product. In the Arctic PASSION project, pilot service 8, called *Lake Ice Service for Arctic Climate and Safety* ("Arctic PASSION - Pilot Service -8," n.d.), is based on the LIE product. This pan-European lake ice service is part of the Copernicus Global Land Service.

The LIE product is a three-class lake ice classification product derived using optical satellite sensors. The product is calculated daily and published by the Finnish Environment Institute (the Finnish Environment Institute, n.d.). The product can be viewed through the Finnish Environment Institute's TARKKA service ("TARKKA," n.d.), or accessed through a Web Map Service (WMS) endpoint (the Finnish Environment Institute, n.d.) or through Copernicus Global Land Service portal (Copernicus, 2021).

The LIE product is a raster dataset with 0.0025 degree (about 250 meters) resolution that classifies freshwater pixels as fully snow covered ice, partially snow covered, or snow free ice or open water (Heinilä et al., 2017a). The classification is applied only to cloud-free pixels. The data covers Northern-Europe, more exactly 5 to 45°E and 45 to 71°N (Heinilä et al., 2017a).

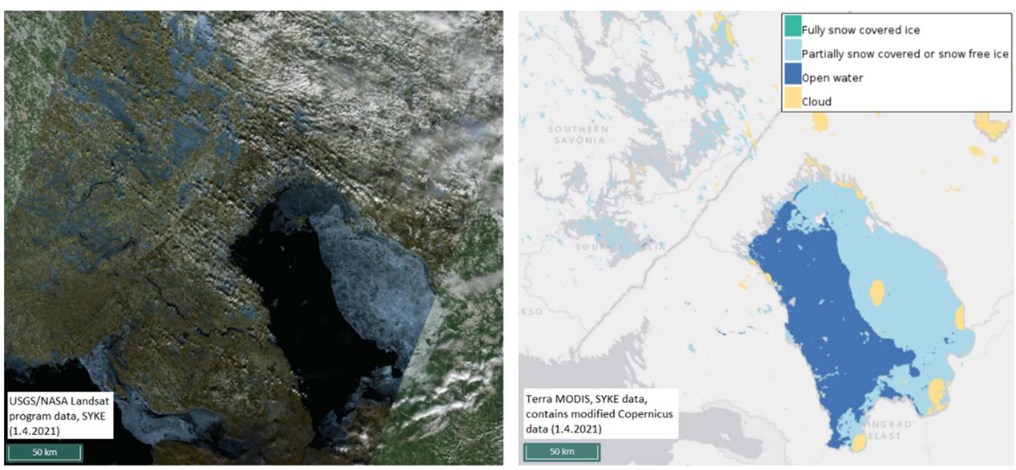

Figure 16 The Lake Ice Extent product classifies freshwater pixels into "fully snow covered ice", "partially snow covered ice or snow free ice", "open water", or "cloud" based on the reflective properties of the optical satellite image. Left: satellite image, contains modified Copernicus data and USGS/NASA Landsat program data. Right: LIE product based on Terra MODIS images, contains modified Copernicus data, lake ice extent algorithm by the Finnish Environment Institute, processed by the Finnish Environment Institute. Both images are screenshots from the Finnish Environment Institute's TARKKA service, presenting the lake ice situation on 1st of April 2021.

The LIE classification process takes pre-processed top-of-atmosphere reflectance from the Moderate Resolution Imaging Spectroradiometer

(MODIS) sensor and thermal brightness temperature data as input. The LIE classification is based on the differences between the reflective properties of white ice, clear ice, snow, and open water in the visible and near-infrared spectrum. The classification algorithm uses reflectance thresholds that have been selected by comparing time series of MODIS reflectance to *in-situ* observations of snow thickness and ice break-up. Thermal brightness data together with a combination of MODIS channels are used for creating a cloud mask, which is then overlaid on the LIE product. To avoid mixed pixels and to improve visualization, sea and land areas are masked out from the final LIE product. (Heinilä et al., 2017.)

Due to the usage of optical satellite data, the lake ice extent recognition is limited by clouds and by very short daylight conditions. The impact of clouds on the classification is prevented by applying a cloud mask on the LIE product. Misclassification due to poor light conditions are limited by rejecting MODIS data with sun elevation below 25°. (Heinilä et al., 2017.) As a result, the LIE product is not available inside the Arctic Circle during polar night.

3.2 Access log files

A prerequisite for applying the Spatineo Impact method is the availability of access log files of the assessed service. Access logs are files that include information of the requests made to the web server hosting that service. Typically, the log contains a text row for each request made to the server. Access logs from different data providers may be formulated in different formats.

The access logs analysed in this work are logs of the TARKKA service ("TARKKA," n.d.), which is a Web Map Service (WMS) displaying the LIE product. The TARKKA service is a public service published by the Finnish Environment Institute where one can browse and view the Finnish Environment Institute's open satellite data.

The anonymized access logs were sent by the Finnish Environment Institute. These access logs are in custom format. They contain information of the requests, including information of the user, the timestamp of the request, network request parameters, and information of the requested data. Table 3 gives an example of how the log format is used to interpret information of a row in the access log.

Table 2 Example on how access log format is used to interpret information from a row in a log file.

<table>
<tr><th colspan="3">Log row format</th></tr>
<tr><td colspan="3">%h %u %{yyyy-MM-dd'T'HH:mm:ssZ}t "%m %U%q" "%{_UserDefined1_}i" "%{User-Agent}i" "%{Referer}i" %b %s</td></tr>
<tr><th colspan="3">Example log row</th></tr>
<tr><td colspan="3">12.34.56.789 anonymous 2021-01-01T10:55:50Z "GET /geoserver/eo/wms?service=WMS&version=1.1.0&REQUEST=GetLegendGraphic&VERSION=1.0.0&FORMAT=image/png&LAYER=EO_LIE&STYLE=EO_MODIS_LIE_FI&width=20&height=25" "image/png" "Mozilla/5.0 (Windows NT 10.0; Win64; x64) AppleWebKit/537.36 (KHTML, like Gecko) Chrome/95.0.4638.54 Safari/537.36" "https://wwwi4.ymparisto.fi/" 3125 200</td></tr>
<tr><th>Notation in format</th><th>Meaning</th><th>Example</th></tr>
<tr><td>%h</td><td>IP address</td><td>12.34.56.789</td></tr>
<tr><td>%u</td><td>Remote user that was authenticated</td><td>anonymous</td></tr>
<tr><td>%{yyyy-MM-dd-T'HH:mm:ssZ}t</td><td>Timestamp</td><td>2021-01-01T10:55:50Z</td></tr>
<tr><td>%m</td><td>Request method</td><td>GET</td></tr>
<tr><td>%U</td><td>Requested URL path</td><td>/geoserver/eo/wms</td></tr>
<tr><td>%q</td><td>Query string</td><td>?service=WMS&version=1.1.0&REQUEST=GetLegendGraphic&VERSION=1.0.0&FORMAT=image/png&LAYER=EO_LIE&STYLE=EO_MODIS_LIE_FI&width=20&height=25</td></tr>
<tr><td>%{_UserDefined1_}i</td><td>Format information</td><td>image/png</td></tr>
<tr><td>%{User-Agent}i</td><td>Information about the client application (browser, software development tool, etc.) making the request</td><td>Mozilla/5.0 (Windows NT 10.0; Win64; x64) AppleWebKit/537.36 (KHTML, like Gecko) Chrome/95.0.4638.54 Safari/537.36</td></tr>
<tr><td>%{Referer}i</td><td>Address of the web page which is linked to the requested resource</td><td>https://wwwi4.ymparisto.fi/</td></tr>
<tr><td>%b</td><td>Bytes sent, excluding HTTP headers</td><td>3125</td></tr>
<tr><td>%s</td><td>HTTP status code of the response</td><td>200</td></tr>
</table>

As specified in section 2.2.6, the IP addresses in log files should be anonymized according to the General Data Protection Regulation. As a result, the analysed access logs do not contain detailed information on individual users or personal data. Nevertheless, the anonymized logs still enable the estimation of the user's location and the internet service provider (ISP) the user might be using. The estimation of the geolocation of the user on a city-level is not totally accurate. However, the country-level estimation is accurate enough for the purpose of this analysis.

Access logs from 1.1.2019 to 30.11.2021 were collected for analysis. One access log file was produced for each day. These log files were available for analysis, and were not needed to be collected separately, as the Finnish Environment Institute has been using the Spatineo Monitor software. Log files could not be accessed for the time between 24th of January 2021 and 2nd of March 2021 due to an error in the automated transfer of log files to Spatineo Monitor.

3.3 Use and use cases of Lake Ice Extent product

Interviews were conducted to collect information about the usage and main use cases of the Lake Ice Extent product. The interviews were conducted in October and November 2021, and January 2022. The interviewees were six in total, consisting of representatives of the Finnish Environment Institute, developers of the LIE product, developers of the TARKKA service, workers in the Arctic PASSION project, and actors in the Arctic region.

The interviews were held as video meetings and conducted as semi structured interviews. Before the interviews, questions to be answered were determined based on the expertise of the interviewee. In addition to the pre-selected questions, a best possible insight to the topic was attempted to get with free-formed discussion.

The first interviewee was the leader of the development work of pilot service 8 in Arctic PASSION project. Main topics that were discussed were the current contents, the potential benefits from, and the development plans for the TARKKA service and the LIE product. The second interview was with a developer of the TARKKA service. This interview focused on the potential users of the LIE product and the user experiences of the TARKKA service. The third interviewee represented a developer of winter monitoring for the Arctic. The main topics discussed were the user needs for lake ice services. The fourth interview was with a developer of the TARKKA service and discussed prior assessments of the usability and benefits of TARKKA service.

The fifth and sixth interviewees represented important actors in the Arctic region. The interviewees were workers in an energy company focusing on hydropower generation. The interview focused on what benefits the company and the workers obtain by using earth observation data and services in their work.

In addition to the interviews, some additional information was obtained by exchanging emails with the interviewees after the actual meetings. The purpose of these emails was to get more information about details that were not discussed during the interviews.

4 Methods

4.1 The approach of the case study

End-users' interest towards lake ice services has been noted in previous studies. Malnes et al. (2015) conducted a survey to map the extent of interest towards snow and ice products. According to a user requirement survey 28% of respondents were interested in lake ice services. Scandinavian users showed significant interest in the development of lake and river ice products. A majority (84%) of the interested respondents considered that lake and river ice extent products are important. Many (66% of interested respondents) also responded that dates for first and last ice are important. These findings indicate that lake ice products are valuable to Scandinavian users. However, no socioeconomic impact analyses have been conducted for assessing the benefits of lake ice services. This study is a first attempt in estimating the impact of an existing lake ice service.

The impact of an existing lake ice service is assessed in a case study. The case study focuses on assessing the societal and economic impacts of an earth observation product developed for the Arctic area, the *Lake Ice Extent for the Northern Europe* product (see section 3.1 for detailed description of the product). This product was selected due to its relevance to the Arctic PASSION project. One of the pilot services developed in the project is based on improving the existing Lake Ice Extent product.

As the first approach for assessing the socioeconomic impact of the Lake Ice Extent product, Spatineo Impact method was selected. Interviews with the developers of the product pointed out that there was uncertainty in the magnitude the product is used, the end-user groups, and the final use cases. As discussed in section 2.2.6, Spatineo Impact method gives accurate data on usage trends and main user groups.

Prerequisites for the Spatineo Impact method were met, as server access logs of the Web Map Service that displays the Lake Ice Extent data in TARKKA service were available. The log files were anonymized and sent by the Finnish Environment Institute to Spatineo Monitor service (see "Monitoring," n.d.). The format of the access log files is described in section 3.2.

As a second assessment method, the Value Tree Analysis method was selected. Value Tree Analysis was selected because the method reveals how societal benefits are realized from the product. As comprehensive information of end-users' perceived benefits could not be obtained during the time frame of this work, discussions with experts of the assessed product proved to be the best way to gather information of the potential benefits of the assessed product.

The output value tree from assessing the Lake Ice Extent product can be used as input when assessing socioeconomic benefits of an assembly of Arctic earth observation services. A lake ice service is to be developed during the

Arctic PASSION project ("Arctic PASSION - Pilot Service -8," n.d.). The assessment work of the current potential benefits of the Lake Ice Extent can be used as input in the Arctic PASSION project. In the project, eight pilot services will be assessed using the Value Tree Analysis method. The results of these individual assessment works can then be combined to form a value tree showing the impacts of all these pilot services to the Arctic area.

Other assessment methods were not applicable for estimating the benefits of the LIE product due to lack of information. Cost-benefit analysis was not suitable as there was no extensive data available on service costs or on the magnitude of economic benefits. Benefit transfer was not applicable due to that no representative study cases had been made of similar services. Implementation of a Weather Service Chain Analysis was not possible, as sufficient information about end-user experiences of the LIE product could not be obtained during the time frame of this study.

As data collection methods, automatic data collection, semi-structured interviews, discussions with experts, and a literature review were used. Here, automatic data collection refers to the use of access log files, which have been automatically collected by the Finnish Environment Institute. These access log files are analysed using python scripts and by viewing maps visualizing their content in Spatineo Monitor service. Semi-structured interviews were used to obtain more detailed information about the use and use-cases of the assessed product. Discussions with experts involved in the Arctic PASSION project helped in planning the case study and gave some insight to potential use-cases of the product. In the literature review, technical documentation of the Lake Ice Extent product and other relevant studies were reviewed.

4.2 Spatineo Impact

Server access logs were used to analyse the usage of the Lake Ice Extent data layer available in TARKKA service. First, the WMS GetMap requests of the LIE data layer were identified and grouped by session. Here, the defined session is a day. For each session, the set of client IP addresses accessing the data layer were collected. Then, the number of unique IP addresses viewing the product per session were calculated. For visualisation purposes, the total number of unique IP addresses per session were calculated for each month.

To make a more detailed analysis of the socioeconomic impacts from the usage of the data, the locations of the requests and the user groups that have been requesting the data were identified. The IP addresses were enriched using information from geolocation databases and Spatineo's internal database, which maps IP addresses to their corresponding organisations. Using these databases, the locations from where the requests were sent, and the main user groups of the data were identified.

The output of the IP address enriching process was a JavaScript Object Notation (JSON) file. For each IP address the following information was given: the Autonomous System Organisation (ASO), the city and country of the IP address location, the Domain Name Server (DNS), the main user group or category, and some optional note about the IP address domain. A JSON object representing a collection of IP addresses during a session could look like the following example:


```
"2021-11-27": {
  "12.34.56.789": {
   "ASO": "Elisa Oyj",
   "City": "Helsinki",
   "Country": "FI",
   "DNS": "elisa-mobile.fi",
   "Category": "Yleiset",
   "Notes": "Elisa Oyj"
  },
  "98.765.4.321": {
   "ASO": "Nivos Energia Oy",
   "City": "Kellokoski",
   "Country": "FI",
   "DNS": "msoynet.fi",
   "Category": "KansalainenTaiPienyritys",
   "Notes": null
  },
```


The resulting JSON file was then analysed using Python scripts. The number of unique IP addresses per session were calculated for each user group and for each country. The results were visualized with pie charts using Microsoft Excel. Also, the number of unique IP addresses per user group and per country were separated monthly and visualized using a Python script.

When viewing the number of requests originating from different countries, the number of unique IP addresses requesting LIE data from the United States was 24%. This share was surprisingly high, as the assessed product only covers Northern Europe. When analysing the classification output of these IP addresses, it turned out that 98.5% of these unique IP addresses came from Amazon Web Services cloud computing platforms. As it is not possible to determine the location of the user requesting data via an application deployed on cloud computing platforms, the location of the end-users behind these IP addresses were reclassified as *Not Available*.

Spatineo Monitor service was used to make visual interpretation of the access log data. In Spatineo Monitor service, the requested areas were visualized on a map. The requested areas were visualized and compared for different time frames and for different user countries. In this way, patterns in user behaviour were found.

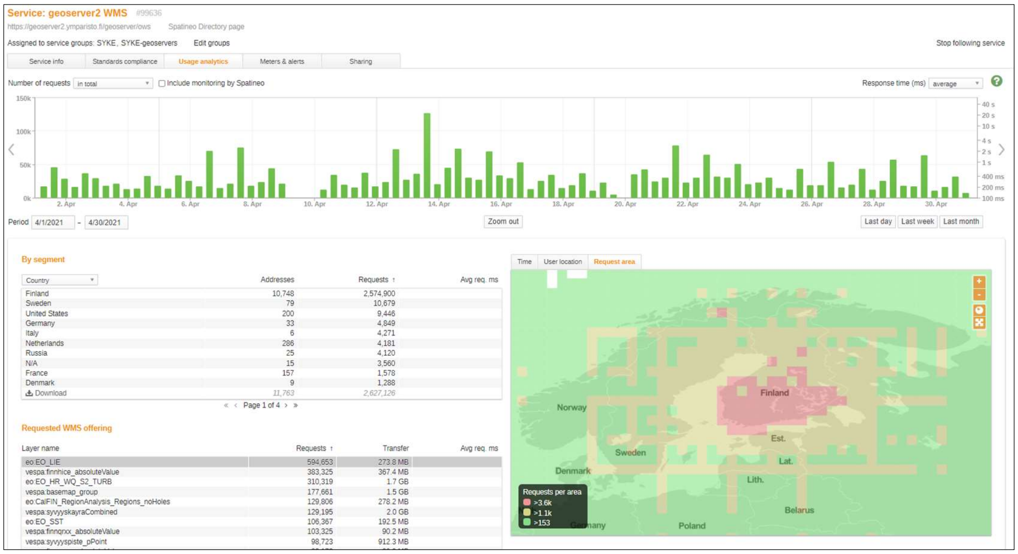

Figure 17 Example view in Spatineo Monitor service, showing usage information of the TARKKA WMS in April 2021. The map in the lower right-hand corner represents the requested areas of the LIE layer during April 2021. Other statistics show the usage of all layers in TARKKA service.

In addition to access log files, interviews were conducted to get information of the usage of the LIE product. The interviews are described in more detail in section 3.3. The interviews provided information on the usage of the LIE product and on the benefits of lake ice services. Also, information on user needs and development plans for the LIE product were obtained.

4.3 Value Tree Analysis

4.3.1 Bottom of the tree

As specified in section 2.2.4, in Value Tree Analysis the bottom of the tree is formed by connecting earth observation inputs to the key products, services, or outcomes, which are connected to the key product, service, or outcome groups. To form the first level in the value tree, earth observation inputs that are needed to form the key product, service, or outcome need to be identified.

For the LIE product, the earth observation inputs were identified using the available technical documents. As specified in section 3.1, the algorithm that calculates the LIE product uses MODIS optical data as input. The MODIS sensor on board the Terra satellite forms the first level in the value tree.

The Lake Ice Extent product uses three intermediate products as input. A Lake Ice Coverage estimate is calculated using MODIS optical data (Heinilä et al., 2017a). MODIS data is also used to compute cloud masks (Heinilä et al., 2017a). As auxiliary data, the process uses four datasets to form the mask for land and sea areas: Finnish national land/water boundaries, Permanent

Water Bodies 2012, GlobCover, and HELCOM Marine area (Heinilä et al., 2017a). Here, these are referred to as land/lake/sea masks. The earth observation inputs to these auxiliary data are not included in the value tree, as they are not relevant for the analysis. The Lake Ice Coverage estimate, cloud masks, and land/lake/sea masks form the second level in the value tree.

The Lake Ice Coverage estimate, cloud masks, and land/lake/sea masks are combined to compute the Lake Ice Extent product. The LIE product is the key product and third level in the value tree.

The fourth level of this value tree is the key product, service, or outcome group. In a research project called CryoLand, funded by the European Union, geospatial products showing lake and river ice extent, temporal variations, and snow burden are defined to be a part of the snow and land ice services assemble (Malnes et al., 2015). Thus, the LIE product is determined to be part of a *Snow and Land Ice services* key service group.

Next, the bottom of the tree is formed by connecting these identified nodes. The MODIS earth observation input is linked to the Lake Ice Coverage estimate and to cloud masks. The Lake Ice Coverage estimate, cloud masks, and land/lake/sea masks are connected to the LIE product, which in turn is connected to Snow and Land Ice services key service group.

4.3.2 Top of the tree

In Value Tree Analysis, the top of the tree is formed by linking key objectives to societal benefit sub-areas which form the societal benefit areas. As the International Arctic Observations Assessment Framework (IDA Science and Technology Policy Institute and Sustaining Arctic Observing Networks, 2017) has already connected the top of the tree for the Arctic area, the remaining work to be done in the analysis is to recognize which key objectives are realized from the usage of the assessed product, service, or outcome. For this end, the applications of the LIE product needed to be identified.

The planned main purpose of the LIE product is to determine the timing of some key events in the annual cycle of lake ice (Heinilä et al., 2017a). Long-term changes in the annual cycle of freshwater ice can be used to monitor the effects of climate change in the Northern Hemisphere (Heinilä et al., 2021). Moreover, the influence of changes in duration of ice cover in the water quality and the biological processes in lakes could be analysed using the LIE product (Heinilä et al., 2021).

Some potential use-cases of the LIE product were identified from its technical documents. According to the product user manual, the LIE product can be used for validation of models, for environmental assessment, for biological monitoring, and for flood management (Heinilä et al., 2017b). Also, the LIE product can be used as input in numerical weather predictions and as reference in thermodynamic models, when calculating energy balance of lake ice (Heinilä et al., 2017a).

Additional potential use-cases of the LIE product were identified by interviewing developers of the product and of the TARKKA service. Potential applications for the product were the usage as reference for other similar products, for estimating the accessibility for fishery and boating, and for evaluating the safety of ice roads, ice-skating, and ice-fishing. Moreover, discussions with workers in an energy company confirmed that the LIE product could be used in flood forecasting for hydropower production.

Based on these potential use-cases, the relevant key objectives which materialize from these applications were recognised using the descriptions available in the International Arctic Observations Assessment Framework. In total, 34 key objectives were recognised as relevant to the LIE product. These key objectives are linked to 18 societal benefit sub-areas, which in turn are linked to nine societal benefit areas. As mentioned, the links between key objectives and societal benefit sub-areas, and the links between societal benefit sub-areas and societal benefit areas, are already defined in the International Arctic Observations Assessment Framework.

4.3.3 Final value tree

The final value tree was formed by connecting the bottom of the tree with the top of the tree. In practice, links between the Snow and Land Ice services key service group and the 34 key objectives were formed.

The value tree was visualized using the web tool by Finnish Meteorological Institute and Spatineo Inc. (2019). Using the web tool, nodes, links, and link weights were defined. In this analysis, equal weights were assigned to links due to that the magnitude of costs and benefits were not assessed, as information on costs and monetary benefits were not available. Nevertheless, the weights from key objectives and societal benefit sub-areas were added up to form thicker links to point out how different societal benefit areas are realized depending on how many of its key objectives are met. To make the visualization easier to interpret, the key objectives and societal benefit sub-areas were coloured according to which societal benefit area they were linked to.

The interpretation of the whole value tree is challenging due to the number of key objectives. To make the value tree easier to inspect in detail, the tree was also visualized for each realized societal benefit area separately, as in the study by Strahlendorff et al. (2019). These visualizations were made using a graph drawing software called diagrams.net (“diagrams.net,” n.d.), because the web tool by Finnish Meteorological Institute and Spatineo Inc. (2019) limited the visibility of text which made it impossible to distinguish the individual key objectives and societal benefit sub-areas.

5 Results

5.1 Comparison of socioeconomic impact assessment methods

The results of the literature review show that there are numerous socioeconomic impact analysis methods available for assessing earth observation data and services. All of them have been developed to address different needs and have their own advantages and considerations. Comparison between the analytic approaches is not straight-forward, as they have been used in different use-cases, making different assumptions about the used metrics and about the spatial and temporal scale. Table 3 summarizes some key findings from comparing the analytic approaches reviewed in this work.

Cost-benefit analysis has been widely used to express the economic benefits originating from earth observation services and infrastructures. The method gives robust and accurate results when established markets and models are available (Tassa, 2020). The results of a cost-benefit assessment send a strong message of the profitability of the service, e.g., "1€ of investment gives 4€ worth of benefits every year". However, the method cannot be trusted to give reliable results if established frames are unavailable (Tassa, 2020) or if a suitable discount rate is not selected (Zhuang et al., 2007). Moreover, using the approach to assess a service that generates significant non-monetary benefits might be problematic, as the method relies on evaluating measurable monetary benefits. There are methods available for monetizing non-monetary benefits but using them can be difficult and controversial. A prerequisite for using cost-benefit analysis method is that there must be some information available of the costs of the assessed service.

Benefit transfer is the most recourse efficient socioeconomic impact analysis method. The method has been used in combination with other analytic approaches, especially when estimations on benefits have been otherwise unavailable (e.g., in Leviäkangas et al., 2007). The analyst must be careful when using this method, as it can give inaccurate and misleading results even when it is not intended (United States Environmental Protection Agency, 2010).

Applying benefit transfer to a case taking place in the Arctic can be challenging if there are no study cases from the same area. The Arctic is a complex region due to its distinctive biodiversity, ecological conditions, and large geographic area (Manrique et al., 2018). Arctic data is different compared to data from nearby geographical areas: the *in-situ* observation networks are not as well-established as elsewhere due to harsh environmental conditions, wide area, and remote position of the Arctic (Dobricic et al., 2018). Moreover, many Arctic communities are small, dispersed, and socially and culturally heterogeneous (Manrique et al., 2018). As a result, estimations of benefits for the Arctic people are challenging. Due to the diversity of Arctic communities,

Table 3 Comparison of socioeconomic impact assessment methods.

Method	Suitability	Advantages	Considerations	Results	References
Cost-Benefit Analysis	Gives robust and accurate results on net benefits when markets and models exist. Information on costs must be available.	Widely used and approved. Flexible and can be combined with other methods. Can be applied on different levels of detail.	Possibly distorted results if established markets and models are absent. Sensitive to the selection of discount rate. Benefits should be monetized.	Results emphasize an economic point of view. Economic benefits send a powerful message when justifying investments.	Bouma et al., 2008; PWC, 2016; Hautala and Leviäkangas, 2007; Leviäkangas et al., 2007
Benefit Transfer	Suitable only when time or resources are not sufficient to conduct an original study.	Approach is cheap and fast. Method can be used to complete results from using other approaches.	Results can be inaccurate and misleading if differences between study cases and assessed case are not considered adequately.	How results are presented depends on what methods the benefit transfer is combined with.	Leviäkangas et al., 2007; Hallegatte, 2012
Value Chains	Suitable for showing the manifold benefits originating from one earth observation service or infrastructure.	Impacts are identified in different sectors and beneficiary groups. Indirect value is recognized.	Approach requires deep understanding of the whole value chain. Benefits to end-users can be difficult to quantify.	Emphasizes how the assessed service benefits several actors in society. Benefits are quantified for different stages in the value chain.	PWC, 2016; Sawyer and Boyle, 2020; Sawyer and Oligschläger, 2019
Value Tree Analysis	Suitable for showing a complex flow of value from several observation services to different benefit areas.	The approach allows the assessment of multiple earth observation services in one analysis. Recognised benefits are relevant to the Arctic area.	As the value tree can grow very complex, suitable visualization is crucial for a successful communication of results.	Shows the value of an observing system, rather than of just one service. Value flow is visualized using a value tree.	Dobricic et al., 2018; Strahlendorff et al., 2019
Weather Service Chain Analysis	Suitable for showing how additional investments would improve realized benefits.	Approach identifies weaknesses in the service chain. Applicable when end-user group is heterogenous.	Results are only approximations. Approach can be difficult to use if relevant statistics are lacking. Method has only been applied to weather service chains.	Visualization of information decay in the service chain. Calculations of value and potential value.	Perrels et al., 2013; Nurmi et al., 2013
Spatineo Impact	Suitable when there is little information on how the usage of the service relates to the organisation's strategic goals. Suitable for assessing web map services.	Approach gives detailed information about service usage. Utilizes automatic data collection. Flexible and can be combined with other methods.	User identification from access logs is not fully accurate. Benefit estimates might not be representative if the sample of respondents is small or unevenly distributed.	Report of trends and changes in service usage. Benefits are described qualitatively.	Spatineo Inc., 2021; Mäkelä et al., 2018

it seems inappropriate to expand assessed benefits from one area to the whole Arctic, as it is unlikely that all communities have the same capabilities to benefit from earth observation services.

Value chains are useful when the goal is to show how benefits from a service accrue to different sectors and beneficiaries. The advantage of the approach is that it shows the benefits from the service also for other than primary users. Thus, the results emphasize that the analysed service benefits several actors in society. Value chains have mainly been used to express monetary benefits originating from the assessed service (e.g., Sawyer et al., 2015; Sawyer and Oligschläger, 2019). Generally, non-monetary benefits have been expressed qualitatively. Nevertheless, a few studies have attempted to quantify non-monetary benefits in value chains (e.g., PwC, 2019; Sawyer and Boyle, 2020).

The definition of a value chain is limited as it assumes that value flows only in one direction between actors. Moreover, the approach groups heterogenous beneficiaries into generalizing groups like "primary users" and "secondary users", which makes it difficult to recognize the benefits for a specific user group. If the value chain was allowed to branch into a more tree-like structure, the method would allow a more detailed analysis of how value accrues into distinctive sectors and user groups. PwC (2019) and PWC (2016) partially worked around the problem as they studied the benefits accruing to different sectors separately.

Value Tree Analysis has been used in a different context than the value chain-based approaches. With the value chain the aim has been to justify investments made into a specific observing system. The Value Tree Analysis, on the other hand, has been used to prove that there is value in the network of observing systems (as in Dobricic et al., 2018; Strahlendorff et al., 2019). The approach shows that the synergy of individual observing systems are needed to achieve societal benefits for the Arctic. This highlights the importance of seemingly less significant observing systems, giving them a justification for maintenance and further development. Out of the reviewed assessment methods, Value Tree Analysis is the only method that has been used to represent the benefits originating from an assembly of earth observing systems.

An appropriate visualization method is necessary for presenting the results of a Value Tree Analysis in an understandable way. The International Arctic Observations Assessment Framework specifies 163 key objectives (IDA Science and Technology Policy Institute and Sustaining Arctic Observing Networks, 2017). Even if only a proportion of these key objectives are realized from the assessed service, visualizing all the relevant key objectives may cause difficulties.

Weather Service Chain Analysis method is useful when the goal is to estimate how an additional investment in some of the stages in a service chain would improve benefits for end-users. The method is especially suitable in situations where the end-user group is heterogeneous and includes non-perfectly informed users (Perrels et al., 2012). The method recognises that the final benefits accrued from the information are dependent on the entire service chain (Perrels et al., 2013). WSCA helps in identifying the stages in the service chain for which improvements would have the best socio-economic pay-off. Moreover, when combining WSCA with cost-benefit assessment, it is possible for decision-makers to compare the net benefits resulting from alternative investment strategies (Pilli-Sihvola et al., 2016).

However, the results obtained with WSCA are not accurate and they should be interpreted as estimations of the expected magnitude of benefits resulting from planned investments (Pilli-Sihvola et al., 2016). Moreover, estimation of the original potential reached at different stages in the WSCA can be challenging if comprehensive data on user behaviour is lacking. Especially estimations of the seventh stage, i.e., how benefits transfer to the whole economy, is complex as the analysis would require a combined micro/macro-economic model (Nurmi et al., 2013). Also, improvements in one stage in the service chain can have unexpectedly significant impacts on other stages. For example, improved data accuracy may result in decision-makers being more willing to adapt their behaviour because of the information (Nurmi et al., 2013).

Spatineo Impact is a commercial solution that is tailored for organisations that provide open data via APIs and interface services. The method gives insight to how well the usage of the organisation's services supports the achievement of their strategic goals. Spatineo Impact gives detailed information about usage trends and volume, and main user groups. This information is often unknown for organisations distributing open access data and can help the organisation when prioritizing the distribution of investments. The advantage of the method is that it utilizes automated data collection, which enables continuous monitoring of user activities.

To assess the benefits from the usage of the service, Spatineo Impact relies on surveys and interviews. The validity of results obtained from interviews and surveys highly depends on how many and how diverse users are interviewed or answer the survey. Moreover, the surveys typically reflect the current situation of perceived benefits. The timing of the analysis might affect the results significantly, as some earth observation data is more interesting during different seasons.

So far, Spatineo Impact assessment works have attempted to reveal the benefits for primary users, i.e., the users that access and use the data. Benefits for secondary users, who benefit from the actions of the primary user, have been outside the scope of the study. In previous Spatineo Impact projects, the benefits have mostly been described qualitatively, as determining an unambiguous measure for quantifying benefits has proven to be difficult. This makes the comparison of perceived benefits between different projects or even between analysis made in different years difficult. Nevertheless, it is possible to determine numerical indicators reflecting the realization of the customer's strategic goals based on the qualitative estimations of benefits.

One notable difference between the studied methods is what the results of the assessment work chooses to emphasize. The results of Spatineo Impact and WSCA assessment works emphasize how the assessed service could be improved to serve the end-user better, while the other methods focus on presenting the current or future value from the usage of the service. The analyst should consider the motivation behind the assessment work before selecting a method for the assessment: is the goal to prove that there is value realising from the usage of the service, or is the goal to make the service even more valuable?

The results of the literature review show that it is not meaningful to determine one socioeconomic impact assessment method to be superior to others, as the suitability of a method depends on the assessed service, the availability of data and resources, and the desired representation of results. The methods reviewed in this work all have their own advantages and considerations. Often, best results can be obtained by combining different methods.

Nevertheless, when considering what method would be most suitable for assessing the socioeconomic impacts from earth observation data in the Arctic area, Value Tree Analysis seems to be the most suitable method. Using Value Tree Analysis, it is possible to estimate the total value originating from an assembly of earth observation systems, rather than the value from only one individual service. The method enables the representation of the benefits from investments to several earth observation services important for the Arctic observing network. Moreover, the key objectives that are used to describe the value from services reflect international Arctic strategies.

Best results could be obtained when Value Tree Analysis is combined with a cost-benefit analysis. In practice, this would mean that the analyst estimates the relevant costs of the observing systems, as well as the quantified benefits from the key objectives. Then, appropriate weights would be given to the links in the value tree. The resulting value tree would show an estimate of how the value from the earth observation services compares to the investments made. A visual representation of how value grows when moving towards the societal benefit areas in the value tree sends a strong message to stakeholders and decision-makers.

5.2 Socioeconomic impact assessment using Spatineo Impact

Using the Spatineo Impact method for socioeconomic impact assessment gives detailed information about the usage of the assessed service. Interviews with the service providers revealed that there was little prior knowledge on the usage of the LIE product. With Spatineo Impact method, requests made to the LIE product were analysed and summarised using service access log files. In addition, an interview with important actors in the Arctic region revealed the perceived benefits of lake ice services.

The main user groups behind the IP addresses making requests to the LIE product are presented in Figure 18. As seen from the figure, most of the users are identified as “general” users. This user group consists of those users whose IP addresses are linked to a telecom or internet service provider. These users are generally citizens and smaller companies. Other more accurately identified user groups are companies, public administration, and education and research. Requests have also been made from representatives of the third sector and media.

27% of the IP addresses could not be linked to any user group. Out of these non-classified IP addresses, 87.3% can be linked to Amazon Web Services (AWS) cloud computing platforms. The users behind requests coming from cloud computing platforms cannot be identified. The cloud-based application from which the requests are sent, or the owner of that application cannot be identified either. Nevertheless, it can be assumed that the users of cloud computing platforms have used the LIE product in some application, as AWS is used specifically as an application platform.

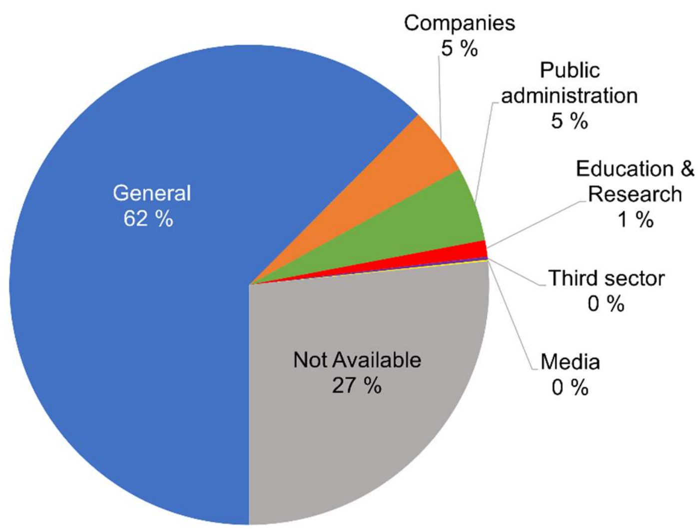

Figure 18 Identified user groups behind the GetMap requests made to the LIE product. The pie chart is based on the total number of unique IP addresses per session 1.1.2019–30.11.2021.

By viewing the identified user groups behind the unique IP addresses separated monthly (see Figure 19), some trends in data usage can be noted. First, the number of unique IP addresses per session for all identified user groups grows during spring months. This indicates that the data is most interesting during the ice break-off season. Fewer users are interested in the data during months with no snow and ice, and during polar night when the product is not available.

Second, the number of unique IP addresses per session representing unidentified users has been exceptional in the time between August 2019 and January 2020. As stated before, most of these requests come from AWS cloud computing platforms. The sudden increase in requests originating from cloud computing platforms could be explained by some application that fetched data during that time from the LIE data layer.

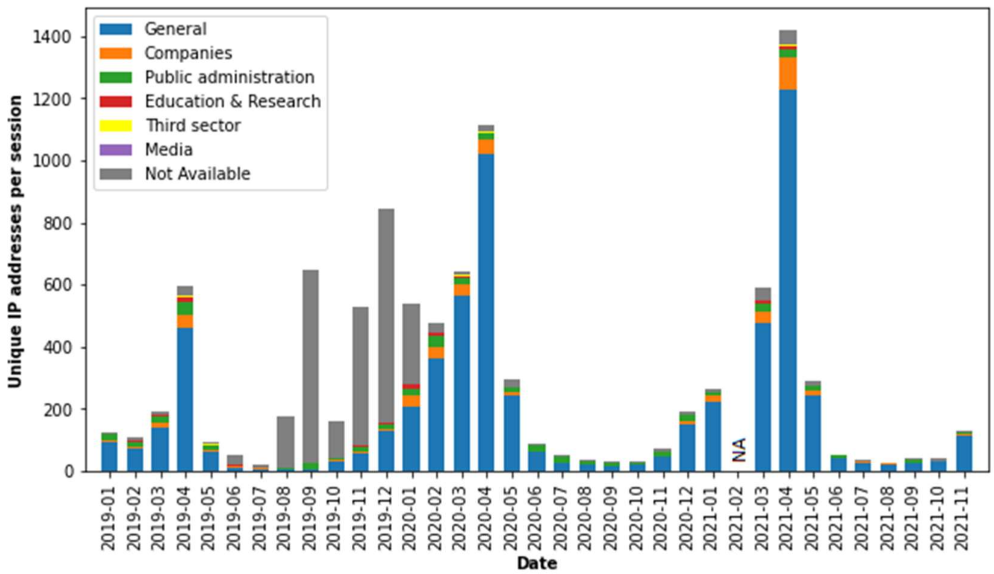

Figure 19 Identified user groups behind the unique IP addresses, separated monthly. No data was available for the time between 24th of January and 2nd of March in 2021.

The requests from the user group "companies" can be refined to a more precise level. Figure 20 shows what sectors identified companies are operating in. According to the analysis, over half of the company requestors represent companies operating in the IT sector.

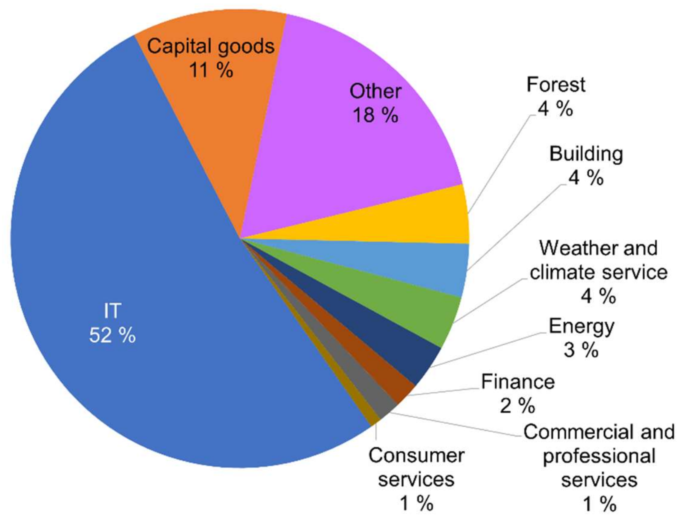

Figure 20 More detailed view of the requests made by companies showing identified sectors the companies operate in. The pie chart is based on the total number of unique IP addresses per session 1.1.2019–30.11.2021 that have been identified to come from companies.

Most of the requests to the LIE product can be identified to come from Finland, as seen in Figure 21. This is not surprising, as the product only covers the Northern Europe and as the LIE product is available at TARKKA service, which is a web map by the Finnish Environment Institute. The proportion of requests coming from other Nordic countries than Finland is low, considering that the LIE product covers all Nordic countries except Iceland. These results indicate that the LIE product provides most value to Finnish users and is unfamiliar to people in other countries.

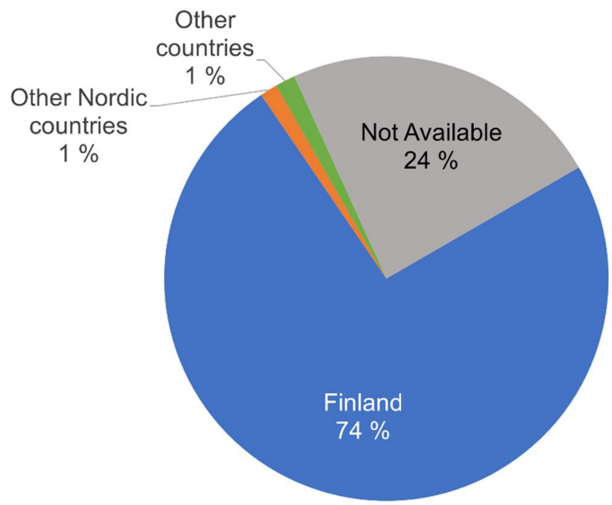

Figure 21 Countries from which requests have been sent to the LIE product in TARKKA service. The pie chart is based on the total number of unique IP addresses per session during 1.1.2019–30.11.2021.

Viewing the requested areas in Spatineo Monitor service shows that there is spatiotemporal variability in the areas that users found interesting. In the beginning of spring, between February and April, the users are most interested in the lake ice extent of southern Finland. In May, however, there is a clear shift of interest as northern parts of Finland become more interesting as well. This pattern in the variability in interest of different areas is repeated annually. This phenomenon is logical, as the ice weakens and breaks off earlier in the southern parts of the country than in the north.

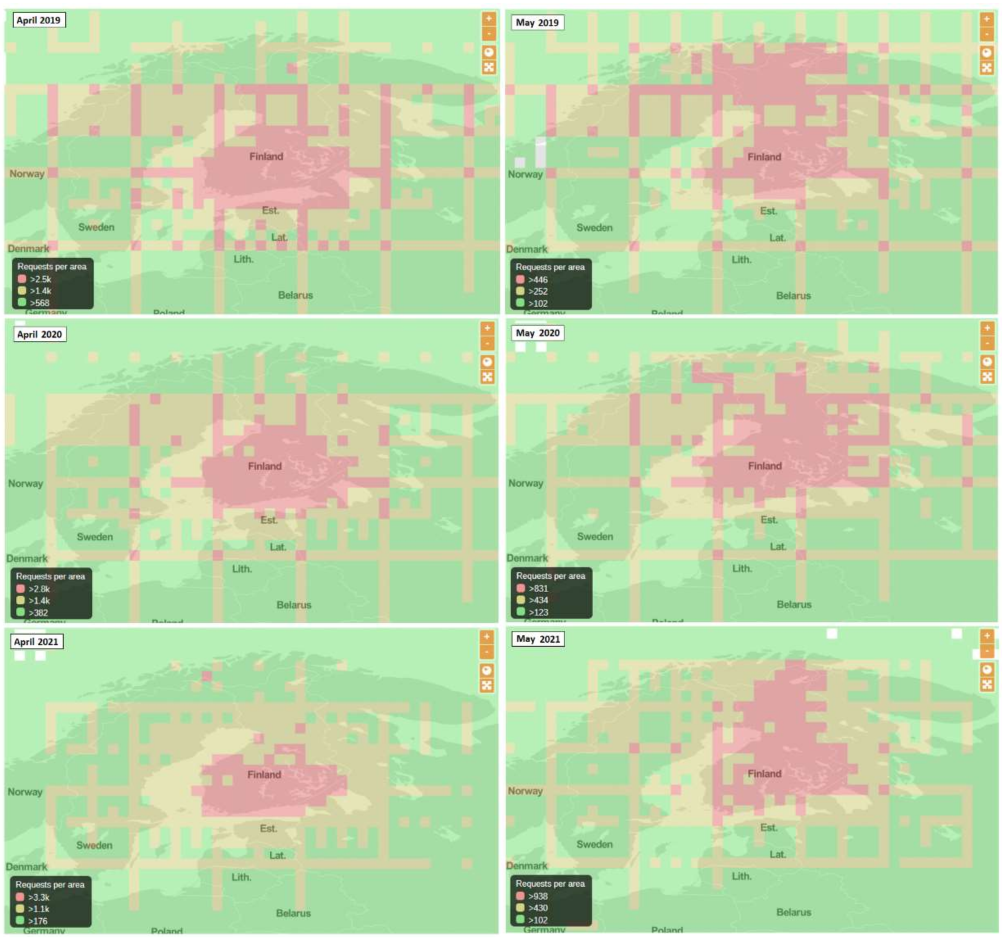

Figure 22 Spatiotemporal variability of the interest in the LIE product. Requested areas of the LIE product in April and May in the years 2019, 2020, and 2021. The red color indicates that most requests have been made to the area.

The interview with two workers in an energy company reveals that data on river and lake ice situation is highly valuable when generating hydropower. The interviewees commented that various datasets from environment and weather services are used in the company daily during winter to get an overview of the river and lake ice situation. Information on the water flow and the extent and the strength of the ice is crucial when optimizing the generation of power. The usage of earth observation data and services saves a substantial amount of working time daily. The workers estimated the benefits from using earth observation services to monitor river and lake ice to be even millions of euros annually. The benefits arise from that the energy company can better control the height of the water surface with up-to-date information, and thus avoid property damage from flooding. On the other hand, it is possible to obtain the greatest possible benefit from hydropower by optimizing water flow.

Other than economic benefits, the used earth observation data and services has improved the safety of workers and the possibilities for recreational use of lake ice. Moreover, the energy company has better possibilities to adapt to climate change when using various earth observation data on river and lake ice to plan their activities. However, when asked about the usage of LIE product, the workers admitted that they have not yet taken the product into daily operational use.

5.3 Socioeconomic impact assessment using Value Tree Analysis

The output of the Value Tree Analysis is a value tree that represents the flow of value between earth observation inputs and societal benefits, resulting from the usage of the Lake Ice Extent product. The final value tree includes one earth observation input, three intermediate products, one key product, one key service group, 34 key objectives, 18 societal benefit sub-areas and nine societal benefit areas.

The value tree represents the potential benefits from the usage of the LIE product. The key objectives that were added to the value tree are based on the potential applications of the LIE product, rather than the actual usage of the product (see section 4.3.2 for details). To what degree these potential benefits are actually realized remains outside of this analysis, as comprehensive information on the use-cases of the product was unavailable.

Below, in Figure 23, the full value tree is presented. The visualization of the value tree shows that numerous societal benefits are potentially realized from the usage of the LIE product. The figure is not as effective in conveying information as the browser tool, as an image does not allow the user to explore the value tree interactively.

Value trees for each societal benefit area are presented in Appendix A. These sub-trees show the realized key objectives and societal benefit sub-areas in greater detail than the visualisation of the full value tree.

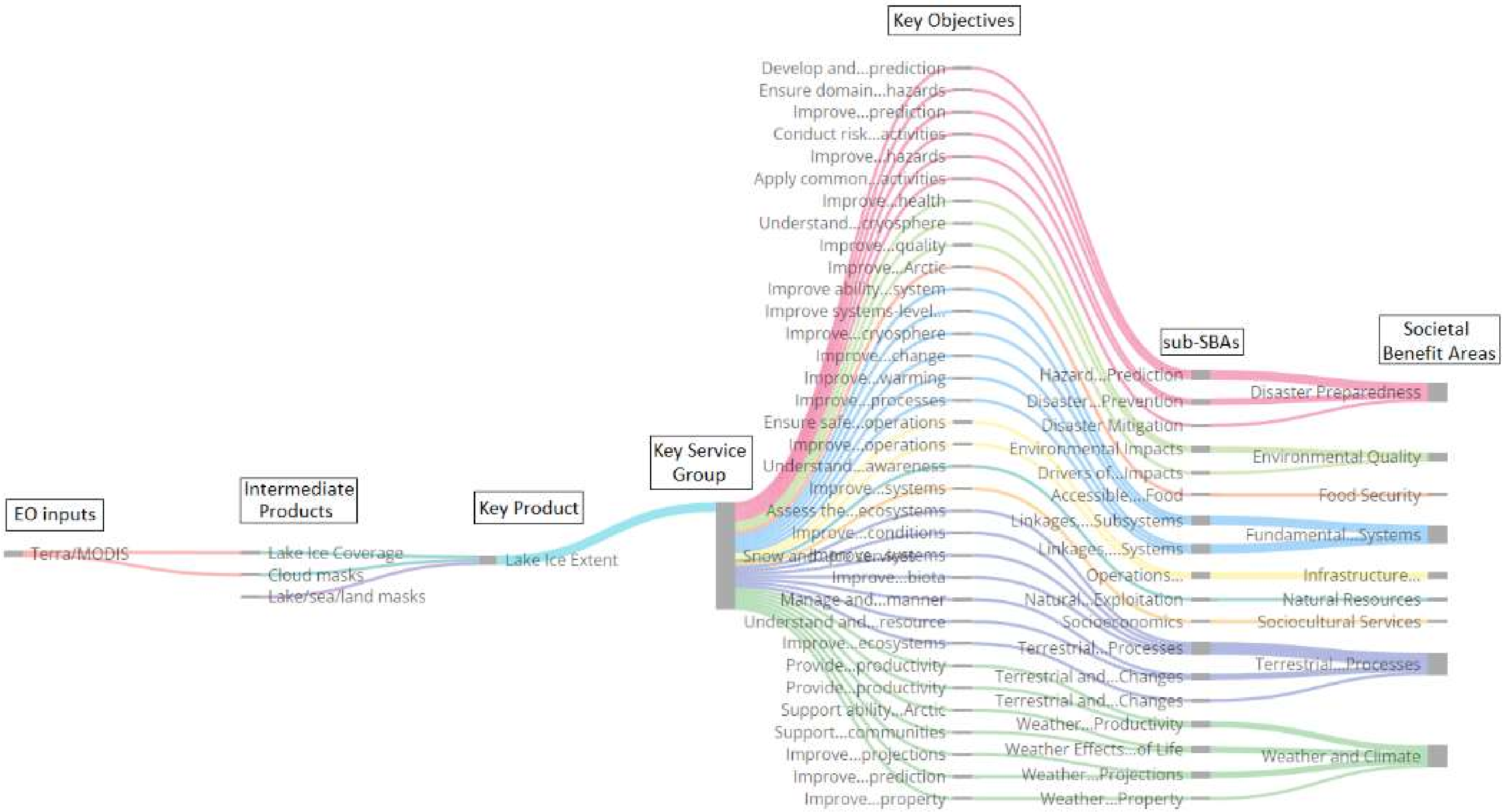

Figure 23 Value Tree Analysis of the Lake Ice Extent product. Full value tree.

6 Discussion

6.1 Literature review

Numerous socioeconomic impact assessment methods have been used to estimate the benefits originating from earth observation data. Some of these methods originate from economics, while others have been developed specifically for assessing earth observation services. Different methods have been used inconsistently and the field lacks best practices. Results of existing benefit assessments of earth observation services are not directly comparable, as studies have made differing assumptions related to the chosen methodology, metrics, and temporal and spatial scale. By reviewing and comparing socioeconomic impact assessment methods, this thesis supports the selection of suitable assessment methods for the evaluation of earth observation services developed for the Arctic.

The main finding of the literature review is that Value Tree Analysis is the most suitable assessment method for estimating the socioeconomic impacts originating from earth observation data in the Arctic area. With Value Tree Analysis, the manifold benefits from several earth observation services can be presented in a powerful way. When combining Value Tree Analysis with cost-benefit assessment, the magnitude of the benefits originating from investments to earth observing systems can be communicated to decision-makers. The key objectives and societal benefit areas represented in the resulting value tree are specifically designed to reflect international Arctic strategies, which strengthens the message of the assessment work's results.

In general, it seems like the results of a socioeconomic impact assessment get more inaccurate the further down the service chain benefits are estimated. Quantifying benefits to primary users of the data is rather reliable if the primary user is an organization or a professional user. However, when estimating the benefits to end-users further down the service chain, the accuracy of the estimate gets poor. Estimating the value from earth observation data becomes highly difficult when the data is combined with other data sources and the users become more unaware of the origin of the data. Moreover, the perceived value from using a service is highly individual and is affected by the user's ability to efficiently use the information for decision-making.

The field of socioeconomic impact assessment of earth observation data and services need more guidelines and best practices to avoid significant differences between assessment works and to make different analysis more comparable. Adams et al. (2016) and World Bank Group et al. (2015) have attempted in providing some general guidelines for conducting a benefit assessment of earth observation data. Still, different analysts make their own choices regarding assumptions and uncertainties, and the reader must be careful when interpreting the results obtained in different assessment works.

It may not be appropriate to compare the results of different impact assessments, as even small changes in the model variables may significantly affect the results.

Nevertheless, the literature study shows that the benefits obtained from using earth observation data are immense and further investments to the sector are justified. It is important to communicate these benefits, as the impacts from earth observation projects are not always evident to decision-makers. Showing the value from earth observation services can be valuable in itself, as information of the current, future, or potential benefits helps better informed decision-making.

6.2 Spatineo Impact

Results of the socioeconomic impact analysis using Spatineo Impact method show that there is a notable interest towards the Lake Ice Extent product among Finnish users. The spatiotemporal variability in the requests to the data and the identified user groups suggest that the product has impact. The product seems to be most valuable to users in the spring during ice break-off season. These outcomes confirm the results of the survey conducted by Malnes et al. (2015), described in section 4.1.

Based on the number of unique IP addresses per session making requests to the data, it seems like the LIE product is most of interest to general users, i.e., citizens and small companies. The benefits of the product to citizens are assumedly associated with better decision-making related to leisure outdoor activities.

Some users are also linked to companies in different sectors and to public administration. This suggests that the product is used in planning or decision-making to obtain economic benefits. The interview with workers in an energy company confirms that daily data on the extent and strength of lake and river ice is essential for the planning of actions related to hydropower generation. The usage of earth observation services to monitor the state of lake and river ice bring the energy company major benefits annually, due to saving in working time, improved optimisation in power generation, and in improved safety. These benefits are however not directly linked to the usage of the LIE product, as these benefits are dependent on the usage of various sources of information. Nevertheless, the interview and the data on service usage confirm that there are potentially economic benefits originating from the usage of the LIE product.

By analysing server access log files, it is not possible to make conclusions of the magnitude of the value of the realized benefits. To estimate the value of the LIE product to end-users, more extensive surveys and interviews with the end-users should be conducted. This is an important part of the customary Spatineo Impact method, as described in section 2.2.6, but could not be executed in this study due to the limited time frame. As it turns out from

Figure 19, users of the LIE product were not active during the time frame this thesis was written, which probably would have caused a low response degree and biased results.

There are some uncertainties related to the results of the Spatineo Impact method. There was a temporal gap in the analysed data, as no access log files were collected in the time between 24th of January and 2nd of March 2021. This, however, does most likely not distort the results significantly, as data was collected from a long period of time. This uncertainty concerns this study specifically.

Other uncertainties concern the Spatineo Impact method in general. First, countries behind user IP addresses cannot be identified with complete certainty. This is due to the uncertainty in the estimation of the geolocation of the user and the fact that the users might use a Virtual Private Network when requesting the data. Also, users that access the data indirectly, typically via a server side application that accesses the data in lieu of the user's computer, cannot be categorized accurately. Same applies to IP addresses originating from cloud computing platforms. Third, the classification into user groups is not perfect. Spatineo Inc. is developing a more accurate classification method which is based on machine learning and the usage of Finnish Business Identity Codes. Fourth, as the analysed IP addresses have been anonymized according to GDPR regulations, it is possible that several users are behind the same IP address. If several users are behind the same anonymized IP address, the method does not recognize the number of individual users and some of the recognised interest towards the assessed product is diminished. Spatineo Impact method will never be perfect due to these limitations, but the objective is to ensure high enough precision for statistically significant results.

The results of a Spatineo Impact analysis can be used as input in most of the reviewed assessment methods. Using Spatineo Impact it is possible to obtain important information of the service usage that cannot be accessed using other methods. Especially, if the service providers or experts do not know exactly what the main user groups and applications of the assessed service are, Spatineo Impact can be used as a reliable method to obtain information of the benefits. With interviews and surveys the perceived value from the usage of the service can be estimated. This information can be used as input to other assessment methods.

The case study showed that the results of a Spatineo Impact analysis give valuable information on the impacts of services especially to providers of open spatial data. The distribution of open access data, i.e., data that can be used without user registration, leads to innovations and economic growth (Huyer and van Knippenberg, 2020). However, distributing fully open data also leads to the problem of that the data provider loses perspective of what the data is being used for and by whom. Spatineo Impact provides an approach for accessing this information.

Unlike the other studied assessment methods, Spatineo Impact gives the data provider an opportunity to track the realization of impacts during a long timeframe. By monitoring indicators, which are based on automatically collected statistics on service usage that reflect socioeconomic impact, and by following up the perceived value to end-users with surveys and interviews, an organisation can get a long-term view of the value development. Using this information, the organisation can improve their services and data so that they serve the end-user better.

6.3 Value Tree Analysis

The results of the Value Tree Analysis assessment show that there are versatile societal benefits potentially realizing from the usage of the Lake Ice Extent product. However, it is uncertain how much of these potential benefits are materialized. Some of the potential applications considered when forming the value tree are more realistic than others. For example, the usage of the LIE product to estimate the safety of ice-skating and ice roads is unlikely due to the rough spatial resolution of the product and the lack of ice thickness information.

The results obtained using Spatineo Impact method confirm that user groups relevant to the societal benefit areas have requested the LIE data. For example, the requests made by IP addresses classified as education and research indicate that the LIE product is used to realize key objectives in the *Fundamental Understanding of Arctic Systems* societal benefit area. Requests from the energy sector on the other hand suggest that the LIE product might have been used when planning measures related to energy production, which would support the *Natural Resources* societal benefit area. The results of the interview conducted in the Spatineo Impact assessment work confirm that lake ice extent information is crucial for companies working with hydropower generation. These findings show that combining results obtained using Spatineo Impact with Value Tree Analysis yields useful additional information to the impact assessment.

The case study showed that connecting the value tree in a Value Tree Analysis can be executed relatively easily. Expert opinions can be used to a large extent when identifying which key objectives are realized from the usage of the assessed service. However, as discussed, interviews and surveys with end-users are necessary to confirm these estimations. The accuracy of the Value Tree Analysis is highly dependent on the input data used for the analysis.

A cost-benefit analysis of the value tree would be a more resource intensive task. Estimating the costs relevant for each earth observation input and the quantitative value realizing from the key objectives would need extensive data collection and evaluation work. Nevertheless, this work would give the Value Tree Analysis credibility and would make the message to stakeholders and decision-makers more powerful. The Value Tree Analysis method does not show its full potential in this work, as the magnitude of costs and benefits could not be assessed. If the results of this analysis were to be combined with a cost-benefit analysis, the visualization of how value grows when moving from earth observation inputs to societal benefits in the value tree could make a strong case for making investments into the earth observation systems and the development of the product.

One advantage of using the Value Tree Analysis method to assess the benefits of earth observation data in the Arctic is that the result reflects the realization of international Arctic strategies. This is also, however, one of the method's limitations. The International Arctic Observations Assessment Framework lists 163 key objectives, 41 societal benefit sub-areas, and 12 societal benefit areas that represent realized benefits for the Arctic region (IDA Science and Technology Policy Institute and Sustaining Arctic Observing Networks, 2017). The Value Tree Analysis according to the International Arctic Observations Assessment Framework does not recognise other benefits than these.

The results of the Value Tree Analysis should be considered as rough estimates of the potential benefits originating from the LIE product. Some of the considered societal benefits are to be realized in the future as a *Lake Ice Service for Arctic Climate and Safety* pilot service is developed in the Arctic PASSION project. For example, estimating the safety of ice-skating and ice-roads could be possible with a lake ice service containing information on ice thickness. In the Arctic PASSION project, *in-situ* measurements of ice thickness will be integrated to the service together with an improved lake ice extent product. The interview with actors in the Arctic confirms that the development plans for the LIE product are in the right direction.

7 Conclusions

The current Arctic observing system is inadequate when facing the challenges of a rapidly changing environment caused by climate change. New earth observation services that are tailored for the end-users are needed for people and actors in the Arctic to be able to adapt to these rapid changes. Socioeconomic impact assessment of earth observation services in the Arctic is an important measure to justify further investment into a pan-Arctic observing system.

This thesis has reviewed different methods for socioeconomic impact analysis that have been used to assess the benefits derived from earth observation data and services. The methods were studied in an extensive literature review. Then, the methods were compared and analyzed in detail. The results of the literature review can be used to make a better-informed choice when selecting between available socioeconomic impact assessment methods.

The literature review shows that combining Value Tree Analysis and cost-benefit analysis is the best approach for assessing earth observation pilot services that are developed in projects for the Arctic region. The advantage of using Value Tree Analysis is that the method enables the representation of diverse benefits from several earth observation services. Cost-benefit analysis, on the other hand, can be used to reveal the value from the usage of the earth observation services, compared to the investments made to them.

Two of the studied methods, Spatineo Impact and Value Tree Analysis, were further examined in a case study. In the case study, the socioeconomic impact originating from an existing earth observation product, a Lake Ice Extent product, was estimated. The case study showed that the selection of suitable assessment methods is highly dependent on the availability of data. Also, the time frame of the conducted study can affect the assessment work significantly. It is advisable to conduct the study at a time when end-users of the assessed service are active, as interviews and surveys with the end-users would give valuable information about the perceived value from using the service. This information is difficult to obtain using other data collection methods.

Nevertheless, the case study showed that Spatineo Impact can be used to estimate some benefits obtained from the usage of the assessed service, as the method provides detailed statistics on the usage of the service. Spatineo Impact proved to be an effective and flexible impact assessment method that can be combined with other methods. The results of a Spatineo Impact assessment are valuable especially to providers of open spatial data. Moreover, the method can be used to effectively improve the service to give greater socioeconomic benefits to end-users.

The results of the case study will be used as input in the ongoing Arctic PASSION project. Although this study could not quantify the value of the benefits originating from the usage of the Lake Ice Extent product in detail, the socioeconomic benefits of the pilot service that is based on this product will be assessed in the Arctic PASSION project. The assessment work to be done in the project will provide complementary information to the results obtained in this thesis, by enriching the results of the Value Tree Analysis with a cost-benefit analysis.

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A. **Value Tree of Lake Ice Extent product (3 pp.)**

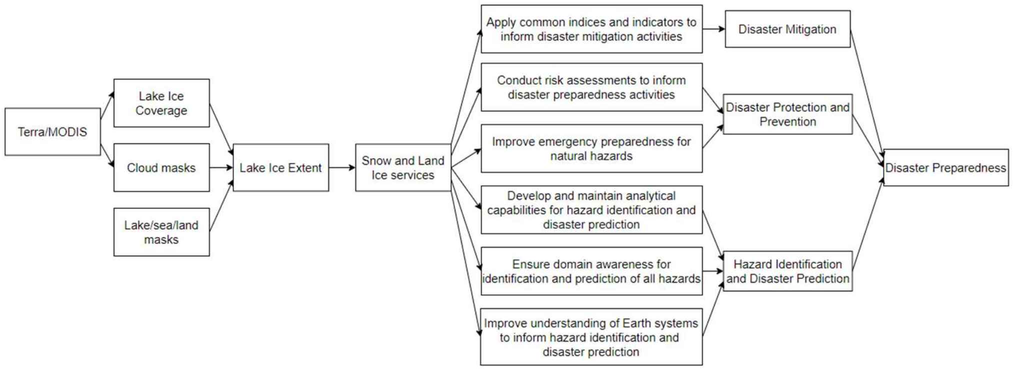

Figure 1 Disaster Preparedness value tree.

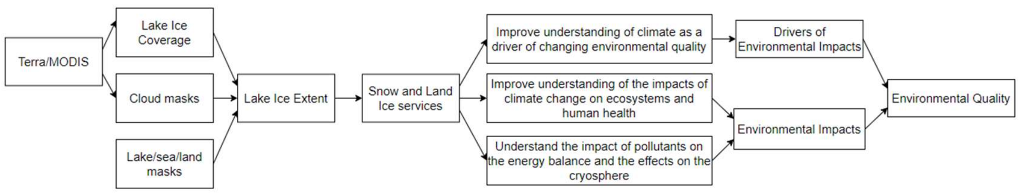

Figure 2 Environmental Quality value tree.

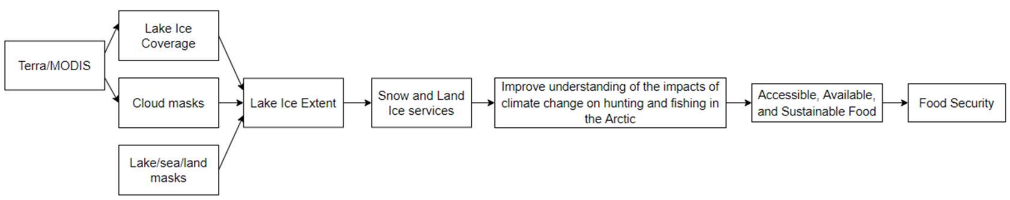

Figure 3 Food Security value tree.

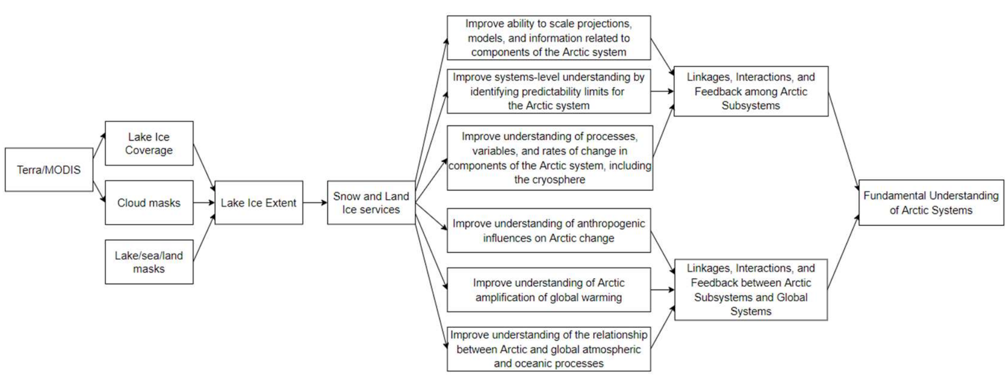

Figure 4 Fundamental Understanding of Arctic Systems value tree.

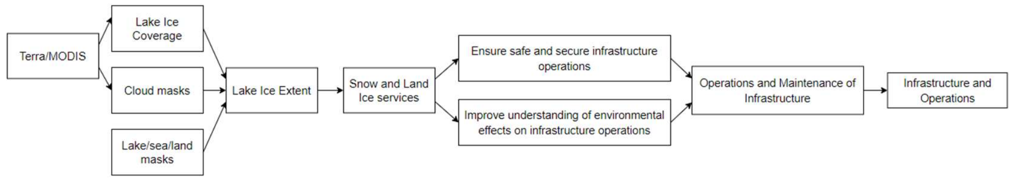

Figure 5 Infrastructure and Operations value tree.

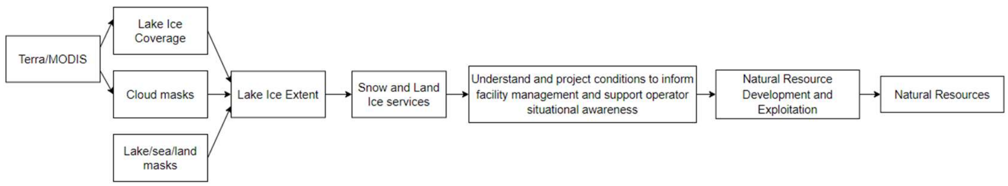

Figure 6 Natural Resources value tree.

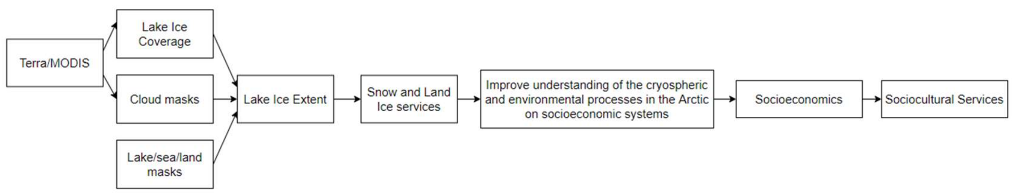

Figure 7 Sociocultural Services value tree.

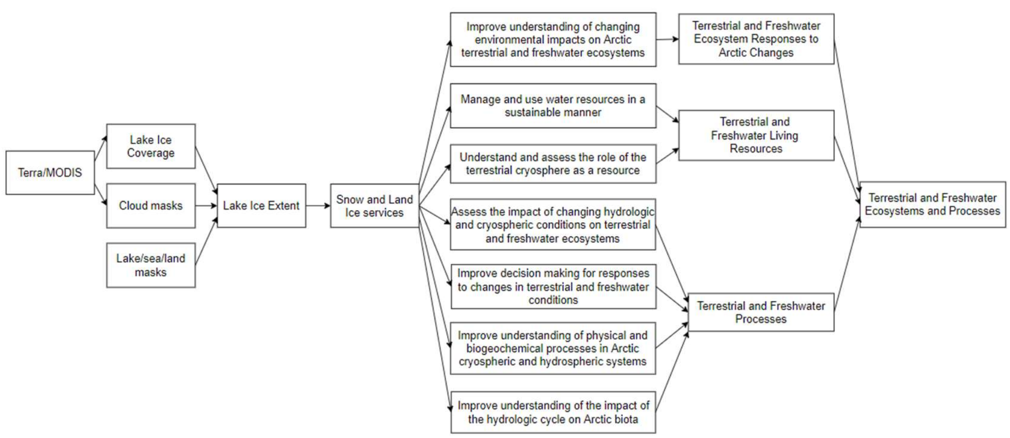

Figure 8 Terrestrial and Freshwater Ecosystems and Processes value tree.

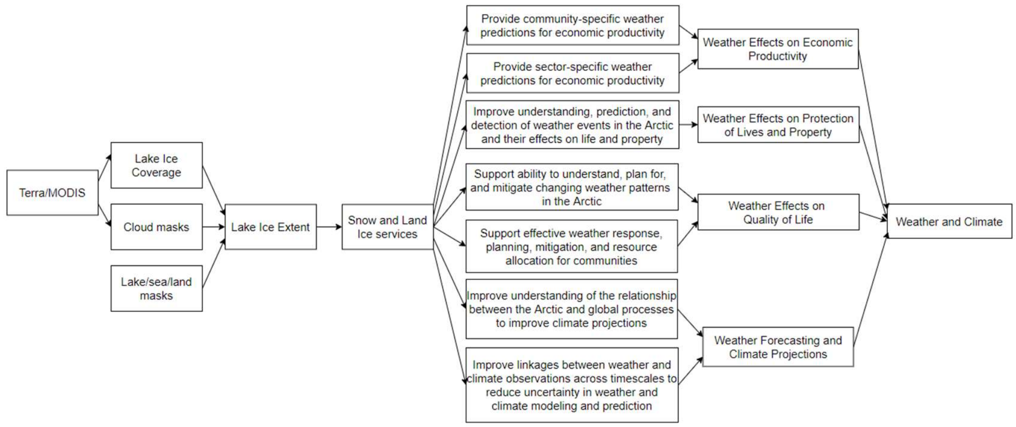

Figure 9 Weather and Climate value tree.