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Compensation of adverse effects of wind farms on air surveillance capability using spatial decision analysis

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ABSTRACT OF MASTER'S THESIS

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Wind farms interfere with air surveillance systems by causing adverse effects. In this thesis, a new approach for planning compensation of adverse effects and assessing cost-efficiency of compensation alternatives, i.e., alternative air surveillance systems, is introduced. In the approach, a spatial multi-criteria decision analysis model is applied for supporting the analysis of the coexistence of air surveillance systems and wind farms. Utilizing this model, one can determine the air surveillance capability of alternative air surveillance systems by taking also into account adverse effects. The spatial decision analysis model utilizes an existing computational tool for calculating performance metrics that describe the air surveillance capability. Additionally, this thesis introduces a novel procedure for comparing compensation alternatives. With the procedure, an alternative that compensates adverse effects and provides the best possible air surveillance capability in a cost-efficient way can be identified. The application of the comparison procedure and the spatial decision analysis model is demonstrated by solving an example compensation problem. Based on this example, the new approach provides viable compensation solutions. Hence, it enables the analysis of the coexistence of air surveillance systems and wind farms. Such an approach for planning the compensation of adverse effects based on spatial decision analysis has not been presented earlier in the literature. Overall, the approach allows the comparison of compensation alternatives in a transparent manner as well as the communication of compensation recommendations to stakeholders in a well-argued way.

Keywords: air surveillance, compensation of adverse effects, multi-criteria decision analysis, spatial decision analysis, wind power

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Tuulivoimalat aiheuttavat haittavaikutuksia ilmavalvontajärjestelmille. Tässä työssä esitellään uusi lähestymistapa haittavaikutuksien kompensoinnin suunnitteluun, joka mahdollistaa tuulivoimaloiden sijoittamisen ilmavalvontajärjestelmien lähialueille. Ilmavalvontajärjestelmien ja tuulivoimaloiden yhteensovittamisen tarkastelun tueksi kehitetään spatiaalinen monikriteerinen päätösanalyysimalli. Tämän mallin avulla voidaan määrittää vaihtoehtoisten ilmavalvontajärjestelmien ilmavalvontakyky huomioiden tuulivoimaloiden aiheuttamat haittavaikutukset. Päätösanalyysimalli hyödyntää olemassa olevaa työkalua ilmavalvontakykyä kuvaavien suorituskykymittareiden laskentaan. Lisäksi tässä työssä kehitetään päätösanalyysimallin käyttöön menettelytapa, jonka avulla voidaan vertailla kompensaatiovaihtoehtoehtoja eli vaihtoehtoisia ilmavalvontajärjestelmiä. Menettelytapa tunnistaa vaihtoehtojen joukosta järjestelmän, joka kompensoi haittavaikutukset ja tuottaa parhaan mahdollisen ilmavalvontakyvyn kustannustehokkaasti. Menettelytavan käyttö demonstroidaan ratkaisemalla esimerkkikompensaatio-ongelma. Esimerkin perusteella spatiaaliseen päätösanalyysiin perustuva lähestymistapa tuottaa uskottavia kompensaatioratkaisuja. Näin se mahdollistaa ilmavalvonnan ja tuulivoimaloiden yhteensovittamisen tarkastelun. Olemassa olevassa kirjallisuudessa ei ole aiemmin esitetty tämän tyyppistä spatiaaliseen päätösanalyysiin perustuvaa ratkaisua haittavaikutusten kompensoinnin suunnitteluun. Esitetyllä lähestymistavalla kompensaatioratkaisuiden vertailu voidaan toteuttaa läpinäkyvästi ja valitut ratkaisut kyetään kommunikoimaan perustellusti eri sidosryhmille.

Asiasanat:	ilmavalvonta, haittavaikutusten kompensointi, monikriteerinen päätösanalyysi, spatiaalinen päätösanalyysi, tuulivoima
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Patrik Lahti

Abbreviations and Acronyms

AAGL	Above average ground level
AEM	Adverse effect metric
AHP	Analytic hierarchy process
AOI	Area-of-interest
ATV	Areawise total value
CEF	Cost-efficiency figure
CVF	Consequence value function
DM	Decision maker
GIS	Geographical information system
ICT	Information and communication technology
LOS	Line-of-sight
NATO	North Atlantic Treaty Organization
PTV	Pointwise total value
RCS	Radar cross section
RF	Radio-frequency
SMCDA	Spatial multi-criteria decision analysis
TCV	Total criterion value
VFF	Visual feasibility figure

Contents

Chapter 1

Introduction

Energy production is a cornerstone of a modern society. The ongoing electrification increases the energy demand further. However, fossil fuel based energy production is not a sustainable alternative due to, e.g., extensive greenhouse gas emissions. Therefore, to respond to the increasing demand, substantial investments in sustainable energy production are required. The sustainable alternatives consist mainly of renewable energy sources such as wind, solar and water power. They are lucrative due to low production costs and emissions. However, e.g., in Finland, available water power resources have already been harnessed into production. Furthermore, solar power is not yet profitable due to the low availability of solar radiation in the Nordics. Wind power anyhow is a favorable choice. Due to high wind availability, increased profitability and low emissions, there has been a significant increase in investments in wind power in Finland during the last 20 years. According to Finnish Wind Power Association (2022b), the cumulative capacity of installed wind power has increased from about 100 MW to over 3000 MW in the course of last ten years. Moreover, the Finnish Wind Power Association (2022a) estimates that wind power production in Finland reaches 30 TWh by 2030. To implement so called green transition, the Finnish Government has also actively enforced renewable energy and especially wind power production (Prime Minister's Office, 2019).

Even though wind power is a lucrative alternative for sustainable energy production, it is not a silver bullet. Wind power production has been opposed due to several factors. First, the size and look of wind turbines and their effect on scenery cause opposition in nearby residents (see, e.g., Bishop and Miller, 2007; Haggett, 2011; Zerrahn, 2017). Second, wind farms have been claimed to have environmental effects on both human and animal populations. For example, birds and bats may be distracted by ultrasound caused by the spinning blades of the turbines (see, e.g., Meller, 2017; Miller, 2008). Similarly, the human population is offended by the sound and light effects of wind turbines (Bakker et al., 2012; Knopper and Ollson, 2011). For example, the spinning blades cause flicker distracting nearby residents (Bishop and Miller, 2007). Yet, one of the greatest challenges is related to the effect of wind farms on air surveillance systems. The wind farms obstruct the line-of-sight (LOS) of air surveillance sensors to targets causing illumination of the wind turbine instead of the target. This prevents air surveillance systems from observing targets behind the wind farms. Additionally, the spinning blades of the turbines may cause emergence of false targets which are complicated to distinguish from adversary targets (see, e.g., de la Vega et al., 2013). The adverse effects of wind farms are a vast issue for the air surveillance authorities. Therefore, these effects establish a conflict between different sectors of administration. On one hand, the environmental and energy-related objectives require installing new wind farms. On the other hand, the air surveillance authority must oppose wind farms deteriorating the air surveillance capability. This constitutes a coexistence issue between the air surveillance system and the wind farms.

In Finland, to obtain permission for building a new wind farm, a contractor must apply for acceptance from local air surveillance authorities. They evaluate the adverse effects of a proposed wind farm and assess on their severity. If the wind farms deteriorate the air surveillance capability significantly, the permission is declined without further reasoning (Joensuu et al., 2021). This unilateral evaluation has been found problematic by contractors (Joensuu et al., 2021). Despite the willingness to increase the number of accepting statements, maintaining the air surveillance capability requires declining applications with unacceptable adverse effects. From the perspective of wind farm contractors, there is a limited number of feasible production sites. Therefore, relocating wind farms may be financially infeasible. However, for the air surveillance authorities, there are even fewer feasible sites for air surveillance sensors. Due to limited resources, the mitigation of adverse effects is not possible. Hence, the obstructive projects must be declined.

A prominent solution to the problem discussed is to modify an existing air surveillance system to mitigate the adverse effects of certain wind farms. However, this requires both ability to find feasible alternative sites for sensors and funding for implementing the modifications. Even if possible alternatives would exist, the mitigation has a cost. As the air surveillance authorities do not have resources for modifying the air surveillance systems, external funding is required. It can be obtained, e.g., by setting a fee for wind power contractors who wish to install wind farms at specific regions. Such a region has been implemented in Finland at the Bay of Bothnia. This type of compensation of adverse effects on a specific region is regulated by the Act on compensation areas for wind energy (Act on compensation areas for wind energy 28.6.2013/490). According to Joensuu et al. (2021), this act could also be extended to cover other regions as well. Therefore, employing a similar idea, if an alternative air surveillance system preserving the air surveillance capability exists, then it would be a viable solution to the mitigation of the adverse effects. If the wind power contractor is willing to cover the costs of modifying the existing system, the wind farm could be permitted.

Implementing the compensation idea requires a method for evaluating the air surveillance capability, the adverse effects of wind farms on air surveillance systems and the effect of different mitigation measures. To solve the coexistence issue of air surveillance systems and wind farms, this thesis develops a spatial multi-criteria decision analysis (SMCDA) (see, e.g., Harju et al., 2019; Simon et al., 2014) model for assessing the air surveillance capability of alternative air surveillance systems. Furthermore, a comparison procedure for evaluation and comparison of alternative systems is introduced. The SMCDA model utilizes an existing computational tool that determines metrics describing the performance of the air surveillance system. Using the metrics, the air surveillance capability of an air surveillance system is quantified. Additionally, by evaluating alternative air surveillance systems constructed by applying different mitigation measures, the SMCDA model allows quantifying their ability to compensate adverse effects.

The comparison procedure employing the SMCDA model is utilized to compare and rank alternative air surveillance systems based on air surveillance capability. The procedure establishes a systematic framework for identifying the adverse effects of wind farms and comparing alternative systems for their ability to mitigate them. It enables distinguishing the air surveillance system with the best possible air surveillance capability, which that also is guaranteed to mitigate the adverse effects.

With the comparison procedure and the SMCDA model, the conflict between air surveillance needs and wind farm projects can be resolved. By comparing the alternative means for mitigating adverse effects, a solution satisfying both parties can be sought. Furthermore, the SCMDA model and the procedure aid in analyzing adverse effects of the wind farms and the efficiency of possible mitigation measures in a well-justified and transparent manner.

In the existing literature, multiple alternative optimization, simulation and decision analysis models for wind farm siting and layout optimization have been presented (see, e.g., Cranmer et al., 2018; Fetanat and Khorasaninejad, 2015; Marmidis et al., 2008). However, these approaches do not consider the wind farm siting from the viewpoint of air surveillance authorities. Additionally, the literature does not contain solutions for assessing the efficiency of alternative mitigation measures in the compensation of adverse effects. Hence, this thesis supplements the existing literature by introducing a novel approach to siting of wind farms and the compensation of their adverse effects.

The structure of this thesis is the following. In Chapter 2, relevant background information related to the coexistence of air surveillance systems and wind farms is discussed. Chapter 3 formulates the compensation problem which defines the requirements for a preferred air surveillance system compensating adverse effects. Chapter 4 describes how an existing computational tool can be utilized to determine the air surveillance capability. Furthermore, it presents how adverse effects can be taken into account with the existing tool. In Chapter 5, the SMCDA model is presented. In Chapter 6, the comparison procedure for structuring and solving the compensation problem is introduced. The comparison procedure is then demonstrated in Chapter 7 through solving an example compensation problem. Finally, the thesis is concluded in Chapters 8 and 9 with discussion on results and possible future work.

Chapter 2

Coexistence of air surveillance systems and wind farms

In this chapter, the coexistence of air surveillance systems and wind farms is covered. The chapter presents necessary prerequisites for understanding the conflict between them. Furthermore, basics on air surveillance systems, their modeling and adverse effects of wind farms on air surveillance are provided.

2.1 Air surveillance capability

Air surveillance refers to the systematic observation of airspace with electronic, visual or other means. Its purpose is to identify and determine the movements of both friendly and adversary aircraft and missiles (NATO, 2021). A modern air surveillance system consists mainly of varying types of radars and other electronic sensors. In addition to the sensors, there is a tracker combining and processing the observations of the sensors. Based on the combined observations, the air surveillance system produces situational awareness, e.g., in a form of air picture. Situational awareness is a necessity in monitoring and securing territorial integrity and operational planning.

The air surveillance capability is established by the air surveillance system. It describes the overall performance of an air surveillance system in detecting and tracking airborne targets in the 3D airspace. Therefore, the air surveillance capability affects, e.g., the ability to produce the air picture and situational awareness.

The air surveillance sensors measure targets by transmitting and receiving radio-frequency electromagnetic radiation (RF signal). When a transmitted signal contacts a target, it is reflected and scattered. Based on the reflected and then received signals, the air surveillance system determines the range, direction and velocity of the target. Moreover, the air surveillance system produces a track of each target. The track describes the location and velocity of the target in the airspace. For further details on radar imaging, see, e.g., Skolnik (1980).

An air surveillance system is determined by a collection of sensors and corresponding sites. Each sensor is associated with a single site representing its geographical location. The site is described by a 3D coordinate point. Moreover, each site is associated with information about sensor types that can be placed at the site. The sensors are described by a sensor type defining their technical properties. The technical properties, e.g., the range, affect the sensors' ability to detect targets.

The air surveillance system is utilized to respond to air surveillance goals. These goals aim in maintaining the air picture, which establishes the basis for air operations (see, e.g., Finnish Air Force, 2022). The changing air surveillance goals can be responded to by modifying the air surveillance system. In this thesis, the air surveillance system planning with respect to the surveillance goals is not considered in detail. However, it is assumed that given air surveillance systems fulfill the underlying air surveillance goals.

2.2 Adverse effects of wind farms

Wind farms consist of separate wind turbines. Installing wind farms may cause some of the wind turbines to interrupt the line-of-sight (LOS) between a sensor and a target. In this case, the sensor illuminates, i.e., attempts to measure, a wind turbine instead of the target. Similarly to the target, the illumination of the wind turbine causes reflection and dispersion of the RF signal.

When a wind turbine disrupts the LOS to the target, a shadowing effect is observed. The shadowing effect significantly diminishes the ability to observe targets behind the turbine (Angulo et al., 2014; de la Vega et al., 2013). In addition to reflecting, the RF signal also disperses when it contacts the turbine. This causes Doppler effects and clutter in the sensor image, which increase the detection threshold and decrease the ability to detect targets (Angulo et al., 2014; Theil et al., 2010). The contact of the RF signal with the wind turbines may also cause false targets and false tracks (de la Vega et al., 2013), which reduce the quality of the air picture. Additionally, the false targets are difficult to distinguish from real ones. This may lead to unnecessary interception and identification missions to identify targets (see, e.g., Finnish Air Force, 2022). The existing literature highlights shadowing and clutter as primary adverse effects. In addition to the false targets, other adverse effects include, e.g., multipath propagation, range sidelobe effects, receiver saturation and processor overload (de la Vega et al., 2013; Theil et al., 2010).

The adverse effects of wind farms on air surveillance systems are a well-known issue in the existing literature. For example, Lindgren et al. (2013) address the problem related to the coexistence of wind farms and military aviation. They reflect the topic from the point of view of the Nordic countries, especially from the Swedish perspective. Similarly, Auld et al. (2013) examine the coexistence issue specifically in the United States. In addition to the military context, adverse effects of wind farms on radar systems are recognized, e.g., in weather forecasting and aviation security. For example, Vogt et al. (2009) describe adverse effects of wind farms on weather radar systems in the United States. On the other hand, de la Vega et al. (2013) consider adverse effects on civilian air surveillance radars and systems. Furthermore, Joensuu et al. (2021) examine streamlining the wind farm installations in Finland. The report also points out the conflict between air surveillance and wind power production as a major issue due to the legislative role of air surveillance and reconnaissance. Overall, according to the existing literature, the coexistence of wind farms and air surveillance systems is unsolved and, therefore, a topical global challenge.

To maintain the air surveillance capability, the interests of the air surveillance authorities need to be promoted while installing new wind power capacity to support the green transition. However, the air surveillance authorities cannot allow decreasing air surveillance capability. Therefore, the conflict between energy production and air surveillance needs to be resolved. A potential solution for enabling the siting of new wind farm projects is to mitigate the adverse effects by modifying either wind farms or the air surveillance system.

2.3 Mitigation of adverse effects

In addition to the adverse effects, their mitigation is a widely studied topic in the existing literature (see, e.g., Cranmer et al., 2018; de la Vega et al., 2013; Karlson et al., 2014; Uysal et al., 2016). The mitigation of adverse effects can address either the wind farms or the air surveillance system. Furthermore, Borely (2014) suggests operational mitigation. Borely (2014) defines operational mitigation as the modification of procedures to accommodate the expected reduction in surveillance quality. For air surveillance systems, this corresponds to, e.g., adapting the utilization of the sensors or lowering the expected air surveillance capability and quality of the air picture. The operational mitigation deteriorates the air surveillance capability already in normal conditions and could compromise it in a state of emergency or under military conflict. Therefore, the operational mitigation is not taken into account as a mitigation measure as the permanent decrease in the air surveillance capability could endanger the fulfillment of the legislative role in territorial surveillance. Next, the mitigation of adverse effects is considered separately for wind farms and air surveillance systems.

2.3.1 Modification of wind farms

The modification of wind farms can be classified into two separate categories. They can be either technical, i.e., affecting the severity of adverse effects, or related to the layout, i.e., shape and size of the wind farms or location of the wind farm site.

First, the technical modification to wind farms can be conducted either by modifying the physical dimensions of the wind turbines or by applying coating or paint to the wind turbines to decrease the severity of adverse effects. For example, Karlson et al. (2014) suggest reduction of the radar cross section (RCS) of the turbines through modifying their shape, size and materials. On the other hand, Lim (2018) proposes reduction of interference through radar absorbing materials. Furthermore, to reduce the Doppler effects, Lim (2018) presents addition of a shroud and wire grid screen.

Second, adverse effects can be mitigated by modifying the siting of wind farms. The siting or layout of a wind farm should be designed such that the sensors of the air surveillance system do not illuminate the wind turbines. For example, Vogt et al. (2009) suggest creation of LOS maps with respect to each sensor to find suitable sites for wind farms. Similarly, Jackson and Butler (2007) and Lim (2018) propose terrain screening, i.e., finding geographical locations, where the sensors cannot illuminate the wind turbines. Based on the same idea, Sharma et al. (2021) present a siting strategy for the coexistence of wind farms and radars. In addition to siting the sensors outside the LOS of the air surveillance system, Karlson et al. (2014) recommend modification of the layout of the wind farm. In accordance with this idea, Brigada and Ryvkina (2021) introduce a wind turbine siting model minimizing the radar impact of wind turbines.

The existing operations research literature suggests several alternative approaches to site selection and layout optimization. The problem formulations vary widely, and the scope of methods is broad. The presented decision analysis approaches include, e.g., geographical information system (GIS) based solutions, (Castro-Santos et al., 2016; Mahdy and Bahaj, 2018; Van Haaren and Fthenakis, 2011), multi-criteria decision analysis based methods, such as

VIKOR (San Cristóbal, 2011; Xu et al., 2020), ELECTRE (Fetanat and Khorasaninejad, 2015) and analytic hierarchy process (AHP) (Díaz and Soares, 2020). Additionally, optimization approaches for site selection are common. For example, Cranmer et al. (2018) formulates a layout optimization problem to maximize wind power production while taking into account environmental objectives. The optimization approaches also include multi-objective optimization approaches (see, e.g., Hou et al., 2016; Mytilinou and Kolios, 2019), goal programming (Jones and Wall, 2016) and heuristic methods (Pérez et al., 2013). Simulation-based approaches are less common. Yet, e.g., Marmidis et al. (2008) present solution to a layout optimization problem utilizing Monte Carlo simulation. In general, the operations research literature does not consider mitigation of adverse effect but focuses on finding suitable sites for wind farms and maximizing production.

The mitigation of adverse effects can also be carried out by utilizing legislation and regulations. For example, Borely (2014) describes alternative design principles to constitute safeguard zones, i.e., zones where no obstacles to air surveillance systems are allowed. Another example of the possible legislative mitigation measures is a wind power compensation area, at the Bay of Bothnia, in Finland, which is secured by legislation. The compensation area is based on Act on compensation areas for wind energy (see, Act on compensation areas for wind energy 28.6.2013/490), which determines a geographical region, where wind farms can be erected without any further permits. However, the contractors must pay a fee of 50 000€ per wind turbine to compensate the measures enabling the compensation area (Joensuu et al., 2021).

The wind farm contractors are free to select the turbines and their layout. In this thesis, the wind farms are assumed given. Thus, in general, these cannot be altered. Therefore, the mitigation of adverse effects through modifying either the wind turbines or their layout is not considered.

2.3.2 Modification of air surveillance system

Similarly to the modification of wind farms, the mitigation through altering the air surveillance systems can be classified into technical and physical modification. First, the air surveillance system can be improved by utilizing new sensors and technologies. This can either be implemented by upgrading sensors, i.e., replacing the sensors with more advanced or efficient ones, as Karlson et al. (2014) suggest, or via developing the information processing of the air surveillance system. The ability to upgrade sensors is dependent on possibility to acquire or develop the more advanced sensors. In general, this is a long and expensive process. The existing literature provides a variety of alternative methods for mitigation of adverse effects through signal processing (see, e.g., de la Vega et al., 2013; Dutta et al., 2021; Uysal et al., 2016). Other proposed methods contain, e.g., matrix completion theory (Shen et al., 2020), dynamic clutter maps (Jia et al., 2013) and waveform diversity approaches (Krich et al., 2017). Additionally, Sharma and Chintala (2022) suggest an approach based on Kalman filter.

Second, the air surveillance system can be physically modified by altering the siting of sensors. The existing literature suggests gap filler sensors to cover for the adverse effects (see, e.g., Aarholt and Jackson, 2010; de la Vega et al., 2013). The gap filler sensors are utilized to supplement the air surveillance systems by patching the air surveillance capability in regions where adverse effects are observed. In addition to gap fillers, the air surveillance system can be expanded by adding a new sensor or relocating the existing sensors. However, this requires availability of sensors. Furthermore, the relocation is dependent on the owner of the sensors, i.e., the air surveillance authorities. Thus, it cannot be enforced by wind farm contractors. Additionally, available sites for relocated or added sensors are required. Moreover, there must be adequate resources for transporting the sensors. Having the resources and funding, the relocation and expanding the sensor system can be considered as mitigation measures.

In this thesis, the mitigation of adverse effects is conducted by modifying the air surveillance system. Especially, the modification of the siting of the sensors and expanding the air surveillance system are studied. However, the technical modification via information processing is not taken into account, as its effect on the air surveillance capability is difficult to quantify. This thesis aims to develop an approach for planning and assessing the alternative mitigation measures. It could be adopted by the air surveillance authorities to aid in planning of wind farm siting.

Chapter 3

The compensation problem

In this chapter, the compensation of adverse effects is examined by formulating a compensation problem. The compensation problem constructs a structured form for the premises and restrictions regarding the compensation of adverse effects. Furthermore, the formulation of the problem allows considering analytical methods for solving the problem.

In the compensation problem, adverse effects of wind farms decrease the air surveillance capability of an air surveillance system. To enable the installation of a new wind farm project, its adverse effects need to be compensated. A solution would be that the wind farm contractors fund the necessary modifications to the air surveillance system that would mitigate the adverse effects. However, establishing such a mechanism requires ability to evaluate and reason the significance of the adverse effects. Without the ability to demonstrate the presence of adverse effects, there is no ground for demanding their compensation. Being able to evaluate the adverse effects of a wind farm allows determining whether the effects are severe enough that they need to be mitigated. Furthermore, while considering the severity, it can be examined whether the adverse effects could be avoided using mitigation measures.

To avoid or mitigate the adverse effects an alternative air surveillance system can be constructed. The modified air surveillance system should be capable of restoring the initial level of the air surveillance capability. Finding such an air surveillance system requires ability to evaluate the air surveillance capability of alternative modified systems. The idea that wind farm contractors compensating the costs of mitigating the adverse effects of wind farms motivates the compensation problem.

3.1 Objective

The compensation problem refers to a decision making problem, where the decision maker (DM) considers how adverse effects of a wind farm project should be compensated. The compensation can be conducted utilizing different mitigation measures to compensate adverse effects. Examples of mitigation measures are addition or relocation of sensors. Furthermore, the compensation can be implemented through by mitigation measures to wind farms. The solution of the compensation problem is a modified air surveillance system, which restores the air surveillance capability.

The objective of the compensation problem is to find the best possible air surveillance system that compensates the adverse effects. The compensation of the adverse effects means that the alternative air surveillance system at least restores the air surveillance capability of the initial system. Therefore, the air surveillance capability of the modified system must exceed the capability of the initial system. The adverse effects are typically directed to certain subregions of the geographical region considered. Assuming that these adverse effect regions can be separated from other subregions, then all feasible alternatives should fulfill the following conditions.

Condition 1: On the adverse effect regions the adverse effects on the air surveillance capability are compensated .

Condition 2: The air surveillance capability in other subregions is not deteriorated significantly.

Conditions 1 and 2 (**C1** and **C2**) are the feasibility conditions for compensation alternatives. A compensation alternative is feasible if it fulfills the two conditions.

In addition to being feasible, the mitigation should be efficient. Assuming that the resources for mitigation are limited, their cost-efficient utilization is favored. Therefore, the solution of the compensation problem must be both feasible and efficient. The efficiency is analyzed through cost-efficiency analysis in which the alternatives are compared based on the air surveillance capability and the prevailing cost.

In the compensation problem, there is an initial air surveillance system, which is assumed to be optimal with respect to some underlying air surveillance goals. Then, a proposed wind farm project is considered with respect to the initial air surveillance system. To accept the proposed project, its adverse effects are quantified and analyzed. If the adverse effects are found significant, they must be compensated. In this thesis, the wind farm project is assumed given, i.e., the layout, siting or turbines cannot be modified. Therefore, the mitigation by modifying the wind farms is not taken into account. Furthermore, the technical improvements to the tracker processing the information are omitted, as their impact on the air surveillance capability is difficult to quantify. Hence, the compensation is directed to the sensors of the air surveillance system.

The compensation must be conducted with the available material resources. The resources and related restrictions are described in Section 3.3. Based on the resources, compensation alternatives representing the potential solutions to the compensation problems are constructed. The determination of the alternatives is presented in more detail in Section 3.2.

As the implementation of the alternatives inflicts costs, and there is no budget reserved for modifying the air surveillance system, the funding for compensation should be provided by the wind farm contractors. The required monetary compensation corresponding to each alternative is determined by its cost. Therefore, finding the solution of the compensation problem also yields an estimate for the cost of funding the implementation of the selected alternative. The costs can then be provided for the wind farm contractor as a condition for implementing the project.

The active parties involved in the compensation problem are the DM, i.e., the person or a group of people responsible for the performance of the air surveillance system. Other stakeholders in the compensation problem are the wind farm contractors proposing alternative wind farm projects. The DM, who is responsible for the performance of the air surveillance system, should balance between accepting new wind farm projects to support the governmental energy production goals and maintaining the air surveillance capability. This requires critical assessment of the projects and possibly rejecting unsuitable ones to preserve the performance of the air surveillance system. However, all projects cannot be rejected. In this thesis, the air surveillance capability is assumed to be strictly enforced. That is, the capability should always be restored at least to the initial level, and alternatives that do not restore the capability are rejected. If no alternative fulfilling this requirement is found, the requirement must be relaxed or the resources must be increased. Especially, in a real-life scenario, there might be a need to relax this requirement to find any feasible compensation alternatives.

To solve the compensation problem, the air surveillance capability of alternative air surveillance systems must be evaluated. Therefore, a measure for determining the performance of the alternative with respect to the air surveillance capability is required. This allows considering the severity of adverse effects. Furthermore, by determining the air surveillance capability of all compensation alternatives, the best alternative can be sought. The compensation alternatives must be implemented by modifying the initial air surveillance system with available resources and mitigation measures. Comparison of all possible alternatives yields the alternative with the best air surveillance capability. This alternative is the solution of the compensation problem. The solution yields the mitigation measures and resources required to compensate the adverse effect. Additionally, the solution provides the costs related to the alternative. Then, assuming that the wind farm contractor accepts the cost and funds the compensation, the wind farm project can be accepted. This also ensures the preservation of the air surveillance capability.

3.2 Compensation alternatives

Compensation alternatives describe alternative air surveillance systems, which are constructed in an attempt to compensate the adverse effects. All the compensation alternatives must be obtained from the initial air surveillance system with the available mitigation measures and resources. The mitigation measures determine actions that can be taken to modify the air surveillance system to compensate the adverse effects. Further limitations regarding compensation alternatives are discussed in Section 3.3.

Each compensation alternative consists of two parts: an air surveillance system and a wind farm system. The air surveillance system consists of the sensor system, which forms the air surveillance capability. The wind farm system determines the wind turbines of the new wind farm project, which possibly interfere with the air surveillance system. It can also consist of multiple separate wind farms. However, the wind farm system does not have to contain any wind turbines. This supports constructing alternatives acting as a baseline for the comparison. For example, if the effects of alternative wind farm systems are compared, then the effects can be considered with respect to a system with no wind farms.

Furthermore, each compensation alternative is associated with a cost. The cost of an alternative is the sum of all costs related to the implementation of the compensation alternative. Determination of costs is discussed in more detail in Section 3.4.

3.3 Resource restrictions

Compensation alternatives are restricted by the DM's resources. The resources consist of factors enabling the utilization of mitigation measures. Examples of the resources are sensors, sensor sites and available workforce. The resources can also include ability to acquire materials or workforce. Therefore, e.g., ability to acquire new sensors is considered as a resource.

The air surveillance systems are restricted by the availability of material resources such as sensors and corresponding sites. The sensor sites determine the maximum number of sensors that can be sited. However, the number of sites is restricted due to limited availability of geographically feasible locations. On the other hand, the utilization of the sites is also limited due to sensor-related restrictions. For example, part of the sites are only suitable for certain types of sensors, e.g., due to the physical size, required infrastructure or mobility of the sensor. Additionally, the number of sensors that can be located at each site restricts the alternatives. In this thesis, it is assumed that each site can only contain one sensor. If a site can fit multiple sensors, the corresponding site can be duplicated. In addition to sites, the air surveillance system is restricted by the availability of sensors. The availability of the sensors of each type limits the possible sensor combinations. Additionally, the total number of sited sensors or sensors of certain types may be limited due to the availability of competent sensor operators.

The restrictions related to each mitigation measure depend on the measure itself. For example, addition of a new sensor requires considering the availability of sensors of the corresponding type. On the other hand, the relocation of a sensor may be restricted by the available time or maximum range of relocation. Moreover, relocation might be dependent on the sites of other sensors, as the distance between two sensors may, e.g., have a lower bound making some sites infeasible. The restrictions may also depend on the sensors which the corresponding alternative concerns. For example, in the case of relocation, the distances to new prospective sites depend on the relocated sensor.

In general, the air surveillance authority is funded by the government. As the budget passes through the government, the maximum budget, i.e., the monetary resource may be restricted, e.g., due to political pressure. The budget is expended to cover the costs of utilizing the mitigation measures. In this thesis, the budget is considered flexible. That is, the DM does not take the costs into account while defining the alternatives. Omitting the budget in comparison of the alternatives aids in enforcing the selection of an alternative with the best air surveillance capability. If the budget is restricted, the constraint is imposed while selecting the best alternative after the comparison.

3.4 Costs

The costs of a compensation alternative depict the inflicted cost of utilization of the resources for mitigation. For example, addition of a new sensor inflicts a cost corresponding to the price of the sensor, and, hence, the sensor resource can be described with its cost. Mapping the utilization of resources to corresponding costs allows considering the efficiency of alternatives in relation to the obtained air surveillance capability. The cost of an alternative determines the monetary investment required to implement the modifications of the alternative to the prevailing air surveillance system.

Each mitigation measure has a unique cost which is based on the DM's estimate on the corresponding costs in real-life. The costs related to a certain measure may depend on the alternative. For example, the cost of addition of a new sensor may depend only on the sensor type added. On the other hand, the cost of relocation may also depend on the relocated sensor, as the distance between sites varies, and the longer relocation distance inflicts a larger cost. Furthermore, in the case of relocation, the new site may require modification to infrastructure, which, in general, poses additional site-dependent costs.

The implementation of certain alternatives may require sequential utilization of multiple mitigation measures, e.g., both addition and relocation of a sensor. If multiple measures are required to implement an alternative, the corresponding cost is the sum of costs from all mitigation measures. The costs may also depend on how the modifications are conducted. That is, certain compensation alternatives can have several possible implementations. In this thesis, it is assumed that if the compensation alternative has multiple implementation options, the option with the minimum cost is selected.

Chapter 4

Determination of the air surveillance capability with a computational tool

This chapter presents how the air surveillance capability of an air surveillance system is determined using an existing computational tool. The computational tool is employed to evaluate performance metrics describing the air surveillance capability, i.e., the performance of the air surveillance system. The tool contains sensor models and a tracker model. The sensor models represent and quantify the performance of the sensors of each type, and the tracker model combines the separate sensors to estimate a track of the target. The estimated track describes the position and velocity of the target in the airspace based on the simulated detections provided by the sensor models.

The air surveillance capability of the air surveillance system is considered in the 3D airspace with respect to multiple targets. The computational tool calculates the performance metrics on a 2D plane at a fixed altitude and against a single target type at once. To examine the air surveillance capability in the 3D airspace, the performance metrics are determined on multiple 2D planes corresponding to several altitudes. Furthermore, to consider the air surveillance capability with respect to multiple targets, the metrics must be calculated for each target separately.

4.1 Inputs

The computational tool calculates the performance metrics based on a specific air surveillance system, an area-of-interest (AOI) and a target. Additionally, in the computation, the tool takes into account the effect of terrain profile and other geographical information, such as the curvature of the Earth affecting the range of the sensors.

The air surveillance system is defined into the computational tool via a user interface. Each sensor is placed at the coordinates where the sensor is located. Furthermore, the sensor type and other possible parametrization is set accordingly.

The computational tool determines the metrics on a specified AOI. The AOI is a restricted geographical region on a 2D plane. The AOI consists of discrete points which denote the coordinate points in the 3D airspace. The points form a square lattice that corresponds to the 2D plane within the AOI. The tool calculates the performance metrics at each point of the AOI against a selected target. The AOI is described as the outline of the region via the user interface. Additionally, in the user interface, a lattice resolution determining the sparsity of the points on the 2D plane is set.

A target is defined with a type, velocity and flight direction. The type specifies the shape and size of the target which is characterized by a RCS model. The RCS model describes the effective size of the target for the observing sensor from the direction of observation (see, e.g., Knott et al., 2004). The velocity and direction of the target represent its anticipated motion. Together with the target type, they affect the detectability of the target. Similarly to sensors, the target, with its altitude, velocity and flight direction, is specified via the user interface.

4.2 Metrics of the air surveillance capability

The computational tool calculates various performance metrics representing the air surveillance capability. The metrics describe the performance of the air surveillance system through different quantities, which can be employed to depict the fulfillment of the underlying air surveillance goals. Examples of the possible performance metrics have been described by Karlson et al. (2014). In this thesis, three metrics are used to model the air surveillance capability. These metrics are probability of detection, time between observations and track accuracy, which are presented in Table 4.1.

Table 4.1: Metrics of the computation tool describing the air surveillance capability.

Metric	Abbreviation	Unit	Definition
Probability of detection	p_d	-	The probability of at least one sensor of the air surveillance system detecting the target while all sensors conduct one scan or have one opportunity to detect the target (see, e.g., Karlson et al., 2014).
Time between observations	t_{ob}	s	The average time between two observations of the target.
Track accuracy	Δ	m	Distance between the location estimate provided by the air surveillance system and the true location of the target.

In addition to the numerical values of the metrics, the tool yields visualizations of the metrics on a map. The visualizations are color-coded such that the colors correspond to the desirability of the values. Red refers to an unsatisfactory value and green to a preferred value of a metric, respectively. Example visualizations of the metrics are presented in Figure 4.1.

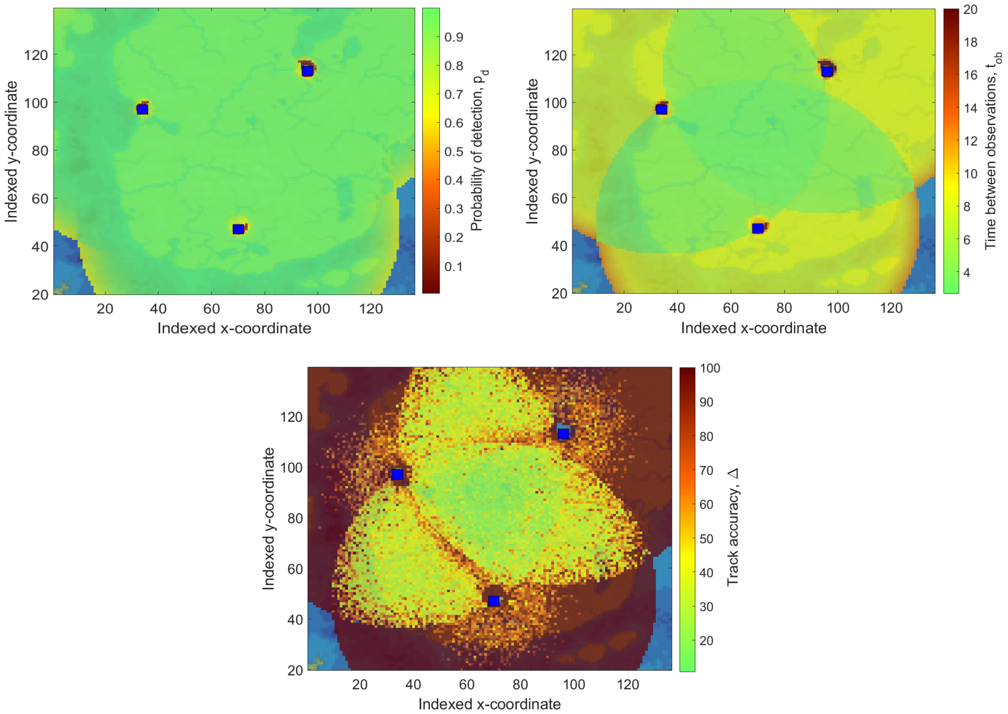

Figure 4.1: Example visualization of the performance metrics for an air surveillance system provided by the computational tool. The altitude is 5 000 m and the target is a ball with RCS of 1 m^2. The sensors, which are denoted with blue rectangles, correspond to middle-range surveillance radars.

Figure 4.1 presents the probability of detection p_d, time between observations t_{ob} and track accuracy Δ for an imaginary air surveillance system. The system consists of three sensors which are denoted with blue rectangles. Each of the sensors corresponds to a middle-range surveillance radar. The background map is generated with Mapgen4 (Red Blob Games, 2018). The visualizations describe the air surveillance capability within the AOI. In the middle of the three sensors, the air surveillance capability is better with respect to all three metrics. Outside the range of all three sensors, the air surveillance capability decreases notably. This is well illustrated by the visualization of Δ.

Similar visualization and the values of the metrics can be calculated for any air surveillance system that can be modeled into the computational tool. Based on the metrics, the alternatives can be compared and ranked with respect to their air surveillance capability. In this thesis, the computational tool is utilized to calculate the performance metrics describing the air surveillance capability for each compensation alternative.

4.3 Representing adverse effects of wind farms

In the existing literature (see Section 2.2), the shadowing effect and clutter effects of wind farms are recognized as the most significant adverse effects. To estimate severity of the adverse effects on the air surveillance capability, they should be quantified. The computational tool contains an adverse effect model that is utilized to take into account the adverse effect of the wind farms on the metrics. The adverse effect model determines the shadowing effect of the wind farms. However, the adverse effect model does not describe the clutter effect.

The adverse effect model assumes that individual wind turbines of wind farms correspond to obstacles, which limit the LOS of the sensors. If the obstacle is on the LOS from the sensor to the target, the target cannot be detected. The size of the obstacles corresponds to the physical size of the wind turbines. Its height equates to that of the turbine, and the width is a constant. The obstacles are located to a 3D coordinate point describing the location of the turbine.

Wind turbines are specified into the computational tool via a user interface. The computational tool yields performance metrics at each point of the AOI and visualizations, similarly as without any wind farms. In Figure 4.2, the adverse effect model is utilized to consider the adverse effects of a wind farm on the air surveillance system presented in Figure 4.1.

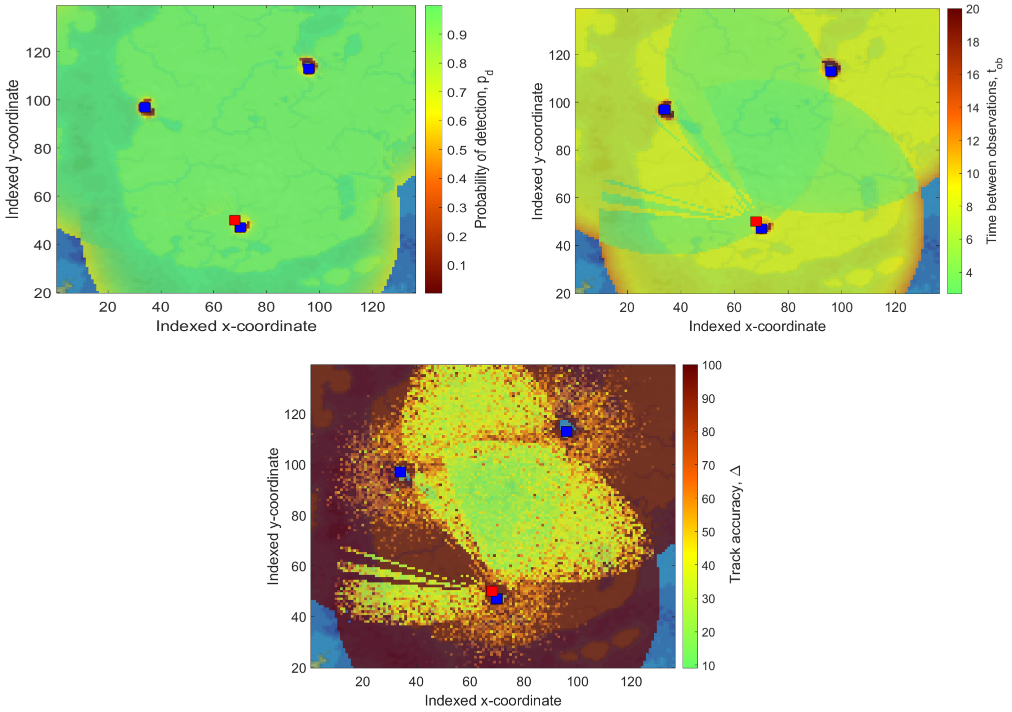

Figure 4.2: Example of the performance metrics taking into account the adverse effects of a wind farm. The sensors are represented with blue and the wind farm with red rectangles, respectively.

Figure 4.2 presents performance metrics of the same air surveillance system as in Figure 4.1. However, now adverse effects of an imaginary wind farm, which is denoted with a red rectangle, are taken into account. Comparing the metrics with and without the wind farm, a decrease in the capability is observed. The adverse effect is the most clear in the time between observations t_{ob}. In the region which is shadowed by the wind farm t_{ob} doubles from 4 s to 8 s. Similar observation is also done from the visualization of the track accuracy Δ. However, in probability of detection p_d, such clear decline is not observed. This is due to that the scales of the metrics are different and the absolute change in p_d is smaller.

By utilizing the adverse effect model of the computational tool, the adverse effects of the wind farms can be determined and visualized. Yet, as seen in the case of p_d, the visualizations of the computational tool do not always illustrate the adverse effects such that its visual identification is easy.

Chapter 5

The spatial multi-criteria decision analysis model for assessing the air surveillance capability of compensation alternatives

In this chapter, a new spatial multi-criteria decision analysis (SMCDA) model for assessing the air surveillance capability is presented. The SMCDA model allows quantification of the performance of compensation alternatives with respect to the air surveillance capability. By assessing the alternatives with the SMCDA model, potential air surveillance systems compensating the adverse effects of wind farms are identified and ranked.

In the SMCDA model, the overall performance of the alternatives is evaluated with a spatial value function. It yields a total value for each alternative based on fulfillment of air surveillance goals from the perspective of the compensation problem. Furthermore, the SMCDA model contains spatial measures supporting the assessment of the air surveillance capability of the compensation alternatives. The spatial measures are also employed to identify the adverse effects of the wind farms and assess the capability spatially. However, the spatial value function and the spatial measures do not take into account the costs of the alternatives. To ensure cost-efficient utilization of resources, the SMCDA model is associated with the cost-efficiency analysis of the alternatives. With this analysis, the efficiency of the alternatives is considered while compensating the adverse effects.

5.1 Spatial value function

The spatial value function of the SMCDA model is based on utilizing a spatial additive multi-criteria value function (see, e.g., Harju et al., 2019; Simon et al., 2014). The performance of a compensation alternative describes the air surveillance capability of the corresponding air surveillance and wind farm system. It is quantified by employing the metrics of the computational tool as criteria of a spatial value function.

The air surveillance capability is considered in the 3D airspace as a whole. Therefore, in order to utilize the computational tool, the airspace is discretized to consist of multiple separate altitudes on which the capability is determined with respect to several targets. However, the air surveillance capability also is a spatial quantity. That is, it depends on the location in the 3D airspace. Thus, an explicit spatial dependency on the 3D location is included in the value function.

The air surveillance capability is determined separately for each compensation alternative. The alternatives are denoted with z^k, which stands for kth alternative, and they are enumerated with $k = 1, ..., K$ where K is the number of compensation alternatives. The spatial value function measures the performance of an alternative with respect to fulfillment of the air surveillance goals in the 3D airspace as a whole. Hence, in the spatial value function, the effect of alternative targets and altitudes are taken into account. The altitudes are denoted with $h = 1, ..., H$, where H corresponds to the number of altitudes, and the targets with $t = 1, ..., T$, where T is the number of target types. The spatial value function $V(z^k)$ yields the total value of compensation alternative z^k, and it is of the form

$$V(z^k) = \sum_{h=1}^{H} a_h \sum_{s=1}^{S(h)} \alpha_s^h \sum_{\substack{x_i \in R_s^h \\ y_i \in R_s^h}} \left(\sum_{t=1}^{T} w_t^h \sum_{j=1}^{C} b_{t,j}^h f_{t,j}^h (c_{t,j}^h (z^k; (x_i, y_i, h))) \right), \tag{5.1}$$

where

- $c_{t,j}^h(z^k; (x_i, y_i, h))$ are the consequences of each alternative z^k at each point (x_i, y_i, h) of the AOI,
- $f_{t,j}^h$ are the consequence value functions (CVF),
- $b_{t,j}^h$ are the criterion weights for each criterion $j = 1, ..., C$, where C is the number of criteria,

- w_t^h are the target type weights at altitude h for each target type $t = 1, ..., T$, where T is the number of target types,
- R_s^h are the subregions $s = 1, ...S(h)$ corresponding division of the AOI at altitude h, where $S(h)$ is the number of subregions at altitude h,
- α_s^h are the spatial weights for each subregion $s = 1, ...S(h)$ at altitude h,
- a_h are the altitude weights for each $h = 1, ..., H$, where H is the number of altitudes.

The consequences $c_{t,j}^h(z^k; (x_i, y_i, h))$ determine the performance of alternative z^k with respect to each criterion j and against target type t at each point (x_i, y_i, h) of the AOI at altitude h. The criteria correspond to the three performance metrics of the computational tool presented in Section 4.2. Therefore, the consequences are the values of the performance metrics.

The consequences are of different units and magnitudes. To combine the consequences, they are normalized into values on interval [0, 1]. The normalized consequences $v_{t,j}^h$ are

$$v_{t,j}^h(z^k; (x, y, z)) = f_{t,j}^h(c_{t,j}^h(z^k; x, y, h)), \tag{5.2}$$

where $f_{t,j}^h$ are the CVFs.

A CVF describes the DM's judgment on worth of each consequence (Malczewski and Rinner, 2015). The CVFs normalize consequences to a unit scale. That is, each consequence is mapped to the interval of [0, 1], where 0 corresponds to the worst possible consequence and 1 to the best, respectively. The CVFs do not need to be linear, but they should be monotonous. Hence, depending on the criterion, the CVF is either increasing or decreasing function.

The CVF is determined separately for each criterion as well as for each target and altitude. Specifying separate CVFs for different altitudes and targets allows, e.g., taking into account specific properties of the targets. The elicitation of the CVFs are considered in more detail in Section 6.4.1.

The normalized consequences $v_{t,j}^h$ are called the consequence values. The consequence values depict the subjective value of achieving each level of the consequence. The normalized consequences are weighted with criterion weights $b_{t,j}^h$, which represent the relative importance of each criterion against target t at altitude h. The criterion weights are non-negative and sum up to one. The criterion weights can be set separately for each target at all altitudes. This allows examining the air surveillance capability on different altitudes with respect to criteria relevant at that specific altitude. The elicitation of criterion weights are discussed in more detail in Section 6.4.3.

The criterion-weighted consequence values are summed over all the C criteria. The sum describes the performance of the alternative with respect to all criteria against a certain target at an altitude. This sum is then calculated for each target, and the resulting sums are weighted with target type weights w_t^h. These weights illustrate the relative importance of each target type in expressing the air surveillance capability at the altitude h. The target weights are set separately for each altitude which allows to focusing on observing targets that most probably appear at the altitude. Similarly to the criterion weights, the target type weights are non-negative and sum up to one. The elicitation of the target type weights is also examined in Section 6.4.3.

To consider the varying spatial importance of the air surveillance capability in different locations, the AOI is partitioned into subregions R_s^h. The subregions consist of coordinate points such that the importance of each point within a subregion is equal. The division is arbitrary, but it should take into account the geographically important subregions of the AOI. Furthermore, in addition to the equal importance of points within a subregion, the division has two additional formal requirements. First, the subregions should be non-overlapping, i.e., the intersection of any two subregions is empty. Second, the subregions should cover the whole AOI at the corresponding altitude. That is, the AOI is the union of the subregions. The fulfillment of the two requirements guarantees that each point belongs to exactly one subregion. The construction of the division of the AOI is discussed in more detail in Section 6.4.2.

The criterion and target type weighted consequence values are then averaged over all points of each subregion R_s^h separately. These averages yield the overall capability at each subregion. The spatial importance is taken into account by multiplying the subregion-specific capabilities with the spatial weights α_s^h of each subregion. These weights describe the relative importance of the air surveillance capability at the subregions. That is, how much more important having a certain level of air surveillance capability at some subregion is compared with another. The spatial weights are determined separately for each subregion R_s^h. They are non-negative and sum up to one. The elicitation of spatial weights is studied in more detail in Section 6.4.3.

Summation of the spatial-weighted subregion-specific air surveillance capabilities over all subregions provides the capability of the alternative at a specific altitude. The output of the spatial value function (5.1) is obtained as the weighted sum of the altitude-specific capabilities and altitude weights a_h. The altitude weights represent the relative importance of each altitude in expressing the air surveillance capability in the 3D airspace. They are non-negative and sum up to one. Furthermore, the altitude weights also illustrate the importance of observing targets at certain altitudes. For example, if observing targets in high altitudes would be considered important, this would increase the weight related to the higher altitudes. In Section 6.4.3, the elicitation of the altitude weights is described more precisely.

The output of the spatial value function (5.1) $V(z^k)$ is called the total value of the compensation alternative z^k. It is a scalar on interval [0, 1] that depicts the performance of the compensation alternative. Based on the total value of compensation alternatives, they are ranked and compared based on the air surveillance capability. Furthermore, the alternatives can be compared with the total value of the initial air surveillance system to evaluate whether the alternative restores the air surveillance capability to the initial level.

5.2 Spatial measures

The spatial value function (5.1) outputs a scalar total value, which describes the performance of the alternative. However, the air surveillance capability is a spatial quantity. Despite the total value being an aggregated overall measure, it is inadequate for identifying adverse effects. That is, it does not directly signify if there are any adverse effects. To identify the existence of adverse effects, the total value of an alternative must be compared with another alternative that does not contain wind farms. Furthermore, if there are adverse effects, the total value does not aid in locating them more accurately. Similarly, the total value does not enable examining the spatial distribution of the air surveillance capability. Therefore, the spatial measures, which describe the air surveillance capability in the airspace as a function of the 2D or 3D location, should be utilized to support the identification of the possible adverse effects and assess the air surveillance capability spatially.

The spatial measures are derived as special cases from the spatial value function. With them, the DM can examine the distribution of the air surveillance capability visually and draw conclusions on the performance of the alternatives. The spatial measures are visualized like the performance metrics. However, the spatial measures aggregate the performance metrics while maintaining interpretability of the aggregates. This simplifies analyzing the performance of the alternatives, as the aggregates encapsulate more information compared to the separate metrics.

The simplest spatial measure is a single performance metric. The output visualizations of the computational tool allow examining the air surveillance capability with respect to individual criteria for a single altitude and target. However, determining the metrics separately at each altitude and against all targets increases the amount of separate visualization. Yet, with the metrics, the analysis of more complex aggregates can be supported. The metrics can be utilized, e.g., to understand and interpret the values of the other spatial measures. This might be necessary if, e.g., the values of an aggregated spatial measure seem counter-intuitive.

Consequence values

The consequence values $v_{t,h}^{h}$ illustrate the DM's subjective judgment on achievement of each value of the metrics. Therefore, they can be utilized to consider the performance of the alternative with respect to a single criterion. Comparing with the plain performance metrics, the consequence values signify the quality of air surveillance capability more pragmatically as they include the subjective judgment of the DM via CVFs. Furthermore, the consequence values commensurate the metrics to the unit interval and allow their mutual comparison.

Total criterion values

The consequence values can be aggregated over alternative targets to obtain the total criterion value (TCV). The TCV combines the criteria by taking into account their relative importance. It is defined as the weighted sum of the consequence values over all C criteria

$$\hat{V}_t(z^k;(x,y,h)) = \sum_{j=1}^{C} b_{t,j}^{h} v_{t,j}^{h}(z^k;(x,y,h)). \tag{5.3}$$

The TCV represents the performance of an alternative against a target at an altitude. It points out regions where the air surveillance capability stands out. If the capability is either poor or excellent, this is generally reflected in all targets at the same location. Therefore, the TCVs are especially useful in identification of possible blind spots, i.e., locations where the air surveillance system cannot observe targets due to obstacles such as terrain.

The TCVs can also be averaged over the multiple altitudes to take into account the airspace as a whole. The resulting measure is called the 3D total criterion value (3D-TCV). It is obtained by weighting the TCVs with altitude weights a_h, i.e.,

$$\hat{V}_{t,3D}(z^k;(x,y,h)) = \sum_{h=1}^{H} a_h \hat{V}_t(z^k;(x,y,h)). \tag{5.4}$$

The 3D-TCV presents the pointwise performance of the alternative in the airspace for a single target type. In the 3D-TCV, the overall picture is blurred as the TCVs on the separate altitudes may differ notably. Therefore, the resolution of details is hindered.

Pointwise total values

The TCVs can be aggregated over multiple targets to determine the performance of the alternative at each point of the AOI at a specific altitude. This is called the pointwise total value (PTV). The PTV is obtained as a weighted linear combination of the TCVs and target type weights. With $t = 1, ..., T$ alternative target types, the PTV is

$$\hat{V}(z^k;(x,y,h)) = \sum_{t=1}^{T} w_t \hat{V}_t(z^k;(x,y,h)). \tag{5.5}$$

Through aggregation over the alternative targets, the PTV reduces the amount of detail even further compared to the TCVs. However, simultaneously the PTV increases the amount of information in the measure.

Similarly to the TCVs, the PTVs can be aggregated over multiple altitudes to consider the performance in the airspace as a whole. The resulting measure is called the 3D-PTV, and it is obtained by weighting the PTVs with altitude weights, i.e.,

$$\hat{V}_{3D}(z^k;(x,y,h)) = \sum_{h=1}^{H} a_h \hat{V}(z^k;(x,y,h)). \tag{5.6}$$

Similarly to the 3D-TCV, the identification of details from the metrics is challenging. However, the values of the 3D-PTV describe the air surveillance capability more accurately according to the DM's preferences in comparison to the simpler spatial measures, as the target type weights are taken into account.

Areawise total value

In addition to observing the spatial measures at each point of the AOI, the performance of the alternative can be aggregated for each subregion R_s^h. The measure describing the performance at the subregions is called the areawise total value (ATV). It is defined as the average of the PTVs within subregion R_s^h at altitude h

$$A(z^k; R_s^h) = \frac{1}{n(R_s^h)} \sum_{x_i \in R_s^h} \sum_{y_i \in R_s^h} \hat{V}(z^k; (x_i, y_i, h)), \tag{5.7}$$

where $n(R_s^h)$ is the number of points within subregion R_s^h and $\hat{V}(z^k; (x_i, y_i, h))$ represents the PTVs. Furthermore, the ATVs describe how much each subregion contributes to the spatial value function (5.1) and how the air surveillance capability is distributed between the subregions.

Summary of the spatial measures

The spatial measures are utilized selectively to support the assessment of the air surveillance capability. They are employed especially when the spatial distribution of the capability must be considered. To summarize, the spatial measures are presented in Table 5.1.

Table 5.1: Spatial measures for assessing the air surveillance capability.

Spatial measure	Shorthand	Definition
Performance metrics	-	Output of the computational tool
Consequence values	$v_{t,j}^h$	Eq. (5.2)
Total criterion value	TVC	Eq. (5.3)
3D total criterion value	3D-TVC	Eq. (5.4)
Pointwise total value	PTV	Eq. (5.5)
3D pointwise total value	3D-PTV	Eq. (5.6)
Areawise total value	ATV	Eq. (5.7)

5.3 Identification of adverse effects utilizing spatial measures

Identification of adverse effects of wind farms refers to locating geographical 2D or 3D regions where the effects occur and quantifying their magnitudes. Adverse effects can be identified by comparing the spatial measures with and without the wind farms. However, if a measure is aggregated over multiple altitudes or targets, distinguishing the adverse effects from other blind spots may be challenging. Similarly, if the difference in measures with and without wind farms is either small in magnitude or the adverse effect regions are small or scattered, the identification through visual comparison of the spatial measures may be infeasible. Therefore, to aid the identification of the adverse effects, the differences in the spatial measures should be highlighted.

To support the identification of adverse effects pointwise differences of the spatial measures with and without the effect of wind farms are utilized. Moreover, in the visualization of these differences, adverse effects are highlighted. By considering the spatial measures only inside the range of the air surveillance system, the natural blind spots, which are caused by, e.g., terrain, are filtered. This filtering prevents confusion between natural blind spots and ones caused by the adverse effects. A visualization of a pointwise difference, where the natural blind spots are removed, is called an adverse effect metric (AEM).

Figure 5.1 introduces an example AEM where the air surveillance and wind farm system corresponds to one presented in Figures 4.1 and 4.2.

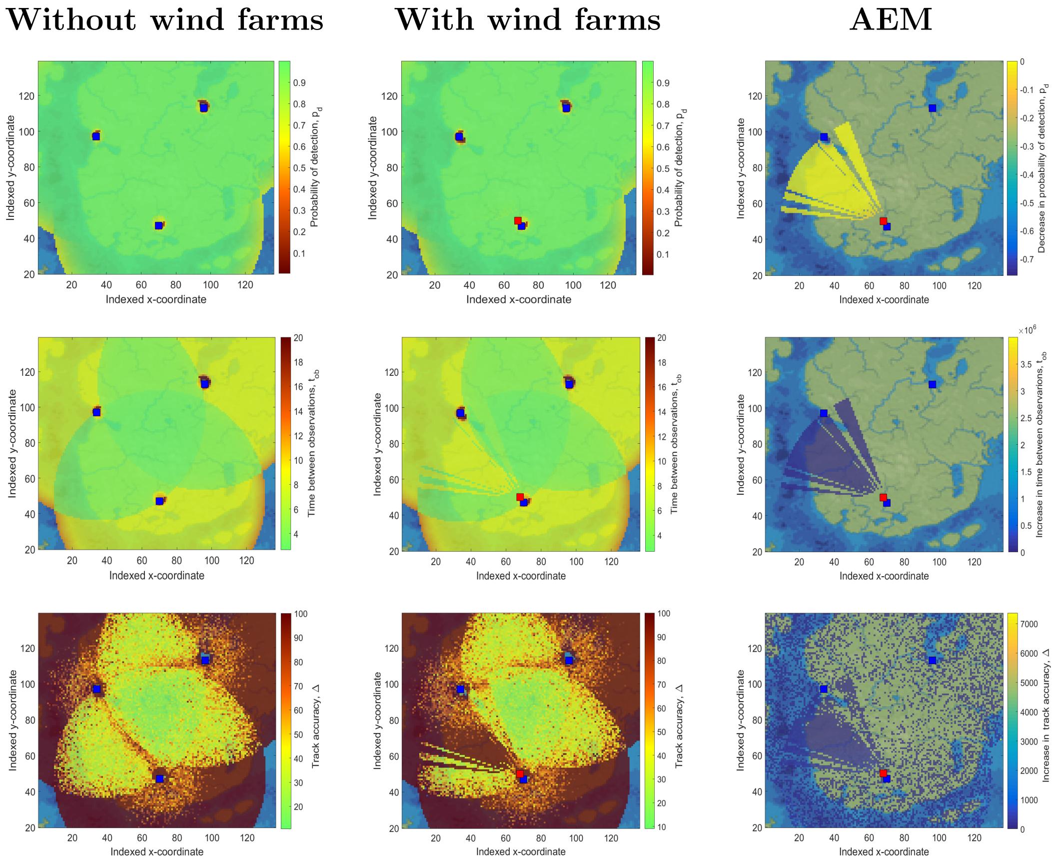
Without wind farms **With wind farms** **AEM**

Figure 5.1: Example AEM (right) illustrating the difference between the performance metrics presented in Figures 4.2 (left) and 4.1 (middle).

In Figure 5.1, the AEMs corresponding to the performance metrics are presented. Furthermore, to highlight the benefit of the AEMs, the metrics are shown also with wind farms in the middle and without them on the left.

By comparing the performance metrics with and without the adverse effects of wind farms, Figure 5.1 points out the AEM is particularly useful in supporting the comparison of p_d. As the magnitude of the difference in p_d is small, the visual identification of the adverse effect is almost impossible. For t_{ob}, the AEM presents the same information, which is clearly seen from the visualization of the adverse effects. Yet, by filtering out unnecessary information, the AEM aids the DM to focus on relevant aspects. Hence, the AEM is also useful in situations where the adverse effects are clear, as it allows identifying the effects without comparing the visualizations with and without the wind farms. In the AEM of the track accuracy Δ, there are also points outside the region where adverse effects have been located in the other metrics. These are due to the randomness in the calculation of Δ. As the error is estimated by the computational tool, the estimates may sometimes deviate such that the difference indicates a local increase in the error that the track accuracy estimates.

5.4 Determination of the cost-efficiency of the compensation alternatives

As resources for compensating adverse effects are assumed to be limited, their efficient utilization is important. A rational DM selects the solution of the compensation problem from the set of alternatives utilizing the resources efficiently. Therefore, it is necessary to assess the efficiency of the compensation alternatives while solving the compensation problem. As the costs of an alternative depict the utilization of the resources as a whole, the efficiency can be considered between the costs and air surveillance capability.

In the cost-efficiency analysis, the performance of an alternative is evaluated regarding its cost. The performance of an alternative is measured with respect to the air surveillance capability using the spatial value function (5.1). An alternative is efficient if no alternative with a lower cost and better air surveillance capability exists. The efficient alternatives are said to dominate the non-efficient alternatives, which are called dominated alternatives.

Formally, the cost-efficiency analysis corresponds to evaluating the following equations for all alternatives

$$g_i(z') \geq g_i(z), \text{for all } i = 1, ..., I, \tag{5.8}$$

$$g_i(z') > g_i(z), \text{for some } i = 1, ..., I, \tag{5.9}$$

where g_is are the value functions utilized to evaluate the alternatives z and z' and I is the total number of these functions. In this thesis, these correspond to the spatial value function (5.1) and the negative costs of the alternative, as the air surveillance capability should be maximized and the costs minimized. The cost-efficiency analysis classifies the feasible alternatives into efficient and dominated alternatives. If alternative z' fulfills Equations (5.8)-(5.9), it dominates z, and, therefore, is efficient. The evaluation of these equations is conducted for all pairs of the alternatives to determine whether the alternative is efficient or dominated.

Chapter 6

The Comparison Procedure of Compensation Alternatives

In this chapter, a procedure for comparing compensation alternatives of compensation problem is introduced. The procedure consists of seven phases, which incorporate the DM's preferences and selections into a structured decision making process.

To find the best solution to the compensation problem, the alternatives need to be compared and ranked. Furthermore, to ensure that the air surveillance capability is restored, the alternatives must be compared to the initial air surveillance system. The total value of the spatial value function (5.1) allows ranking the alternatives based on the air surveillance capability. However, not even a high total value guarantees that adverse effects are compensated at all subregions. In the compensation problem, only alternatives that compensate the adverse effects adequately are feasible. The feasibility conditions presented in Section 3.1 ensure that an alternative fulfilling them is feasible. Yet, feasibility of an alternative does not guarantee that the alternative is preferred. In addition to feasibility, a compensation alternative should utilize resources efficiently. Therefore, the solution of the compensation problem must also be efficient. In the compensation procedure, the DM's preferences are taken into account, and the solution, i.e., the compensation recommendation, is guaranteed to be feasible and efficient.

6.1 Phases of the comparison procedure

The phases of the comparison procedure are the following.

Phase 1: Definition of a compensation scenario

Phase 2: Identification of adverse effects

Phase 3: Elicitation of preference information

Phase 4: Identification of feasible compensation alternatives

Phase 5: Identification of efficient compensation alternatives

Phase 6: Sensitivity analysis

Phase 7: Generation of compensation recommendation

In Phase 1 of the procedure, the DM constructs a compensation scenario that yields the scope of the compensation problem. The scenario contains the geographical region, air surveillance and wind farm systems and available mitigation measures and resources. In Phase 2, the DM analyzes the effect of wind farms on the initial air surveillance system and identifies the adverse effects on its air surveillance capability. Phase 3 of the procedure consists of eliciting preference information, e.g., weights of the spatial value function (5.1). In Phase 4, the feasibility conditions **C1-C2** are evaluated for each alternative. The alternatives which do not compensate the adverse effects identified in Phase 2 are omitted. Next, in Phase 5, the cost-efficiency of the feasible alternatives identified in the previous phase is analyzed to ensure the efficient utilization of the resources. The cost-efficiency analysis of Phase 5 results in a set of feasible and efficient alternatives from which the compensation recommendation is selected. In Phase 6, a sensitivity analysis is conducted to examine whether the feasible and efficient alternatives are robust to changes in, e.g., the costs of the alternatives. Its aim is to ensure that the efficient alternatives are robust also under uncertainty in, e.g., preference information. In the final phase, the feasible and efficient alternatives are ranked to provide a compensation recommendation. This recommendation corresponds to the best solution to the compensation problem.

The phases of the comparison procedure are illustrated in Figure 6.1. However, in practice, the comparison procedure is iterative. That is, if observations at any phase do not coincide with the DM's understanding, the preceding phases are reconsidered, and the calculations are repeated.

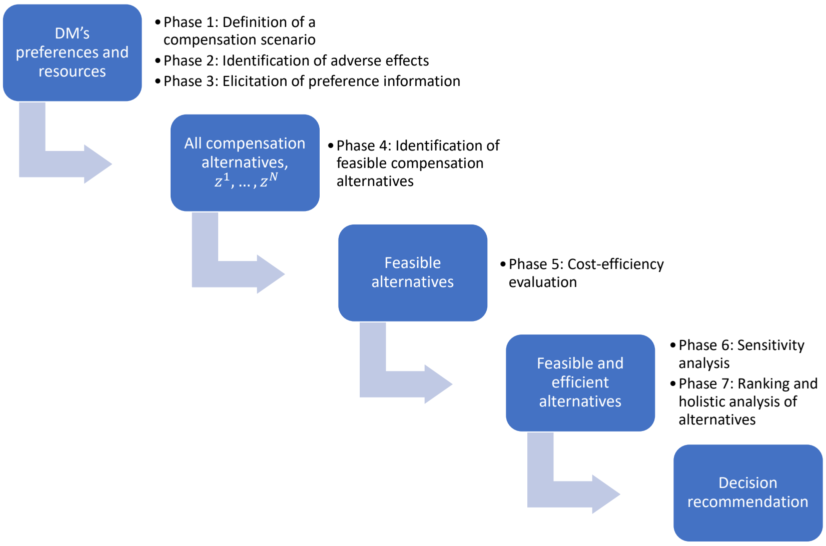

Figure 6.1: Phases of the comparison procedure.

6.2 Definition of a compensation scenario

The compensation problem is related to a certain scenario. In the first phase of the comparison procedure, the compensation scenario is defined. This scenario consists of one or more compensation alternatives, a reference alternative, targets and airspace discretization. The compensation alternatives describe the alternative air surveillance and wind farm systems that are being compared with respect to the reference alternative.

The reference alternative depicts the initial air surveillance and wind farm system, which is being modified to install new wind farms. It is denoted with z^0. The reference alternative establishes a baseline for the evaluation of the alternatives to ensure that the compensation alternative to be selected restores the air surveillance capability.

The targets are selected based on the DM's risk and threat assessment or other possible surveillance goals. The DM should select targets that are important or probable.

The discretization of the 3D airspace is established by altitudes, AOIs and lattice resolutions. The altitudes determine the 2D planes on which the air surveillance capability is calculated. The altitudes are selected to match the expected flight altitudes of the selected targets. Each AOI describes the geographical region on which the air surveillance capability is considered at the altitude. They are formed by the borderlines of the region restricting the

2D plane. Finally, the lattice resolution fixes the distance between the points of the rectangular lattice and, thus, affects the sparsity of points within the AOIs. The resolutions may vary depending on altitudes and AOIs.

The performance of the alternatives is dependent on the scenario. Hence, the measures of the air surveillance capability are only comparable within one scenario. If the scenario is modified, the calculated metrics and measures change. For example, changing the altitudes requires re-evaluating the total values as the altitudes and possibly the corresponding altitude weights change.

6.3 Identification of adverse effects

In Phase 2, adverse effects of wind farms are analyzed. The adverse effects are identified by examining the spatial measures with and without wind farms. Furthermore, the AEMs are utilized to support the identification. The AEMs are especially useful in the identification of adverse effect regions, i.e., the subregions of the AOI where adverse effects are focused. They can also be employed in determining the significance of the decrease in the air surveillance capability due to the wind farms.

Based on the assessment of the spatial measures and AEMs, the identified adverse effect regions form the basis of the division of the AOI constructed in Phase 3. This division is required to take into account the varying spatial importance of the air surveillance capability in different subregions. Furthermore, the adverse effect regions affect the evaluation of feasibility of the compensation alternatives conducted in Phase 4.

6.4 Elicitation of preference information

In the third phase of the comparison procedure, preference information required to evaluate the spatial value function (5.1) is elicited from the DM. Preference information captures the DM's preferences of value and importance of different aspects in the SMCDA model. The spatial value function (5.1) captures preference information through consequence value functions, divisions of AOIs and different weights. Next, principles regarding elicitation of this information are discussed.

6.4.1 Consequence value function

The existing literature provides alternative methods for eliciting CVFs from the DM. The methods rely on posing elicitation questions to elicit the CVF. The answers to the questions are called preference statements. Von Winterfeldt and Edwards (1986) classifies the elicitation methods into two categories: indifference and direct methods. In the indifference methods, the value function is elicited by considering a sequence of equally preferred differences. An example indifference method is the bisection method (Keeney and Raiffa, 1976). The direct methods aim in obtaining the values of consequences or consequence intervals directly. Example direct methods are, e.g., direct rating and ratio estimation (Von Winterfeldt and Edwards, 1986).

In practice, the CVF is not explicitly determined for all possible consequences, but interpolation is utilized between selected consequences to reduce the number of required preference statements. Additionally, the elicitation of the CVF can also be based on expert judgment so that a subject matter expert assesses the values of the CVF for each consequence.

6.4.2 Division of the area-of-interest

The division of the AOI should be chosen such that the DM can compare and state the importance of the subregions. Furthermore, the division should reflect the DM's understanding about important regions with respect to the air surveillance capability. For example, in the air surveillance planning application by Harju et al. (2019), the division takes into account geographical regions but also major cities and nuclear power plant areas. Hence, the division should complement the underlying air surveillance goals and geographically important locations.

The division of the AOI includes the adverse effect regions such that they are isolated as separate subregions. The isolation of these regions allows analyzing the adverse effects in different alternatives later in the procedure. As each adverse effect region is selected as a separate subregion, the division consists of adverse effect regions and other subregions, which are called undistorted regions from now on. Subregions are indexed such that the adverse effect regions are assigned to indices $s = 1, ..., p$, where p is the number of adverse effect regions. Similarly, undistorted regions are assigned with indices $s = p + 1, ..., S(h)$, where $S(h)$ is the total number of subregions at altitude h. This classification allows evaluating the feasibility conditions, which are separate for these two groups of subregions.

6.4.3 Weights

Weights represent the relative importance of corresponding aspects in describing the performance of an alternative with respect to the air surveillance capability. In the spatial value function (5.1), there are four types of weights: criterion, target type, altitude and spatial weights. Next, techniques for eliciting the weights are discussed.

The existing literature describes a variety of methods for eliciting weights. For example, in trade-off weighting (Keeney and Raiffa, 1976), the DM states consequences for $C-1$ equally preferred alternatives, where C is the number of criteria. Each statement sets a constraint for the weights. Furthermore, as the weights sum up to one, an additional normalizing constraint is obtained. The DM's preference statements and the normalizing constraint form a system of equations that can be solved to obtain unique weights. However, yielding the preference statements required in the trade-off weighting may cause difficulties for the DM. Therefore, the tradeoff-weighting is seldom utilized in practice. More common elicitation methods suggested in the literature are, e.g., SWING (Von Winterfeldt and Edwards, 1986), SMART and SMARTS (Edwards, 1977; Edwards and Hutton, 1994) and analytic hierarchy process, AHP (Saaty, 1980). Guitouni and Martel (1998) present a review on the alternative weighting methods, and the convergence behavior of alternative weighting methods is compared by, e.g., Pöyhönen and Hämäläinen (2001) and Virtanen et al. (2021).

6.5 Feasible compensation alternatives

In Phase 4, the feasibility conditions **C1-C2** presented in Section 3.1 are evaluated for each compensation alternative. The ability to restore the air surveillance capability is examined by comparing the areawise total values (5.7) (ATVs) at each subregion to ATVs of the reference alternative. The feasibility conditions are separate for adverse effect regions and undistorted regions. The evaluation of the conditions of both groups results in a set of feasible compensation alternatives.

The feasibility conditions **C1-C2** state that at each adverse effect region, the effects must be compensated completely. At the undistorted regions, the air surveillance capability is not allowed to deteriorate significantly. If a compensation alternative does not fulfill both of the feasibility conditions, the alternative is not feasible. Furthermore, for an alternative to be feasible, the feasibility conditions must hold for all subregions and altitudes. Thus, the evaluation of feasibility must be carried out separately for each subregion at all altitudes.

Next, the feasibility conditions are presented formally for both adverse effect regions and undistorted regions. Finally, visual analysis of the feasibility is considered.

6.5.1 Evaluation of feasibility for adverse effect regions

At the adverse effect regions, it is required that the effect of wind farms is compensated completely. However, in practice, this may not be possible, and, therefore, the requirement must be alleviated. Hence, by including a significance threshold, the DM can determine how strictly the complete compensation is enforced. The level of significance depends on the DM's preferences. The threshold corresponding adverse effect region R_s^h is denoted with δ_s^h. It describes how much below the ATV of the reference alternative the ATVs of compensation alternatives are allowed to decline.

A compensation alternative z^k is feasible with respect to an adverse effect region R_s^h if the ATV of the subregion is greater than that of the reference alternative z^0. The ATV must be exceeded at least by a margin of δ_s^h, which is defined separately for each subregion at all altitudes. Assuming that the decline is in relation to the value of ATV, then δ_s^h can be selected to represent a percentage of the ATV of the reference alternative. Therefore, the feasibility condition for subregion R_s^h at altitude h is

$$A(z^k; R_s^h) \geq \delta_s^h A(z^0; R_s^h), \forall s = 1, ..., p, \tag{6.1}$$

where $A(z^k; R_s^h)$ is the ATV of subregion R_s^h. Hence, to be feasible, the ATV of alternative z^k must be above the ATV of the reference alternative by a factor of δ_s^h. Setting $\delta_s^h = 1.0$ corresponds to the initial requirement of the ATV being higher than that of the reference alternative z^0. By decreasing the value of δ_s^h, the requirement concerning the compensation is alleviated, and vice versa.

6.5.2 Evaluation of feasibility for undistorted regions

In the undistorted regions, the air surveillance capability is not allowed to decrease substantially. Therefore, a compensation alternative is feasible with respect to an undistorted region if the ATV is not significantly less than that of the reference alternative. The feasibility condition is formulated similarly to adverse effect regions. By including a separate significance threshold ϵ_s^h for all subregions $s = p + 1, ..., S(h)$, the feasibility condition for an undistorted region at altitude h is

$$A(z^k; R_s) \geq \epsilon_s^h A(z^0; R_s), \forall s = p+1, ..., S(h). \tag{6.2}$$

Now, as the feasibility condition states the the decrease cannot be significant, ϵ_s^h can be assumed to be $0 \leq \epsilon_s^h \leq 1.0$. That is, a certain fraction of the ATV of the reference alternative suffices to fulfill the feasibility condition. Otherwise, the condition would require the air surveillance capability of compensation alternatives to be worse than initially. For instance, let us assume that the significance threshold for the undistorted regions is $\epsilon_s^h = 0.95$. This corresponds to a maximum of 5% decline in the values of ATVs.

6.5.3 Visual evaluation of feasibility of compensation alternatives

To support the comparison of the compensation alternatives visual evaluation of feasibility can be utilized. A visual feasibility figure (VFF) presents the ATVs (5.7) of each compensation alternative with respect to each subregion. A strength of the VFF is that the significance thresholds δ_s^h and ϵ_s^h do not need to be defined precisely, but they can be assessed visually. Furthermore, instead of providing only binary feasibilities of the alternatives, the VFF also allows their comparison based on the ATVs.

An illustrative example of the VFF is presented in Figure 6.2. Each alternative is represented with a polyline depicting the ATVs, which describe the air surveillance capability within the corresponding subregion. Additionally, the visualization includes the ATVs of the reference alternative with and without the wind farms.

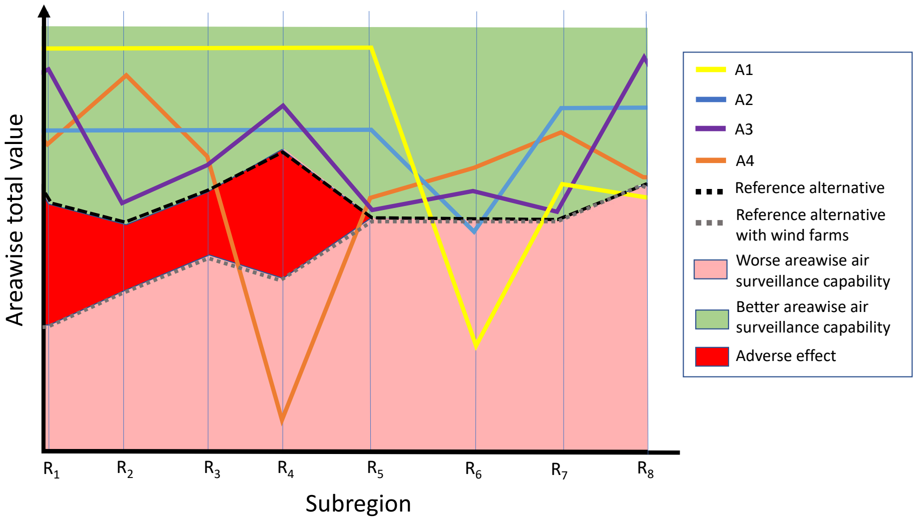

Figure 6.2: Example visual feasibility figure (VFF) for alternatives A1-A4 with respect to subregions $R_1 - R_8$. The background color describes the ATV with respect to the reference alternative. Green background corresponds to better and red worse ATV, respectively. Adverse effect is highlighted with dark red area.

The example presents evaluation of four compensation alternatives with a VFF. The ATVs of each alternative A1-A4 are depicted with a polyline. The dashed polylines correspond to the reference alternative on black without and on gray with wind farms, respectively. In the example, the subregions $R_1 - R_4$ are adverse effect regions, which is implied by the dark red adverse effect area. Alternative A1 (yellow) yields higher ATV than the reference alternative on all the adverse effect regions $R_1 - R_4$. Yet, the ATV falls below that of the reference alternative at subregion R_6. Hence, A1 is not feasible. The ATVs of A2 (blue) are better than the reference alternative at all subregions except R_6. However, subregion R_6 is not an adverse effect region. Moreover, the decrease in the ATV is smaller than for A1. As the alternative A2 exceeds the ATVs of the reference alternative at all other undistorted regions, it is feasible. A3 (purple) does not achieve the ATV of the reference alternative in any of the subregions. Thus, it fulfills the feasibility conditions. Lastly, A4 (orange) exceeds the reference alternative at all subregions except at R_4. The decline is significant, and subregion R_4 is an adverse effect region, where no decline is allowed. Therefore, A4 is not feasible.

To summarize, based on the evaluation of feasibility, alternatives A2 and A3 are feasible. In Phase 5, the efficiency of these two alternatives would be analyzed further, whereas alternatives A1 and A4 would be omitted.

6.6 Cost-efficiency analysis

In Phase 5 of the comparison procedure, the efficiency of compensation alternatives is analyzed. The cost-efficiency analysis is conducted for the feasible compensation alternatives. The efficient alternatives are obtained by finding the alternatives fulfilling Equations (5.8)-(5.9). Therefore, in the following phases, the solution to the compensation problem is sought from the set of feasible and efficient alternatives.

Similarly to the visual evaluation of feasibility, the cost-efficiency analysis can also be conducted visually. The efficient alternatives can be identified using a figure representing the total value of the spatial value function (5.1) as a function of costs. The efficient alternatives are such that neither spatial value function nor the costs can be improved without relaxing the other. Figures illustrating the efficiency of alternatives are called cost-efficiency figures (CEF). An example CEF is presented in Figure 6.3.

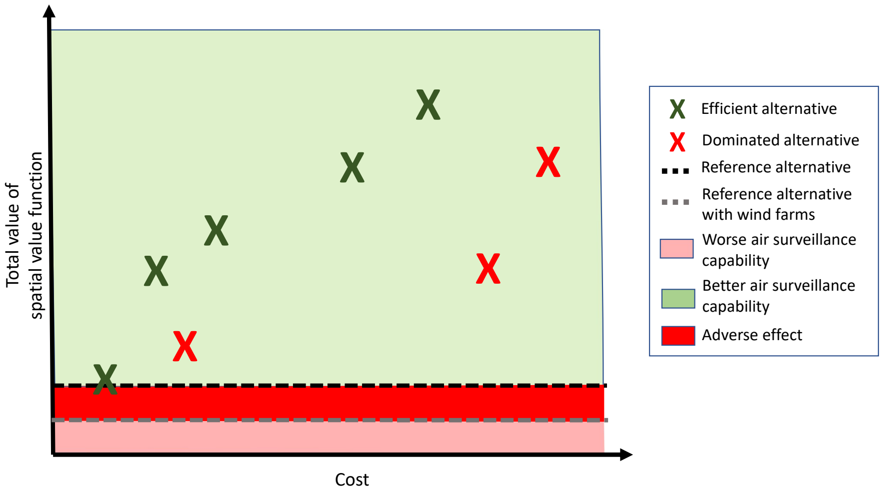

Figure 6.3: Example CEF. The background color presents the air surveillance capability of the alternatives with respect to the reference alternative. Green corresponds to better and red worse capability, respectively. The dark red area highlights the adverse effect.

The example consists of eight feasible compensation alternatives. The efficient alternatives are marked on green and the dominated alternatives on red, respectively. A CEF also visualizes the air surveillance capability in comparison to the reference alternative with the background color. The alternatives on green background have better air surveillance capability with respect to the spatial value function (5.1) than the reference alternative. Conversely, the alternatives on red background have worse capability. An alternative with worse capability compared with the reference does not compensate the air surveillance capability adequately in the whole airspace. Therefore, if a feasible alternative is worse than the reference, it is omitted while selecting the best compensation alternative.

CEFs can also be utilized to analyze the alternatives with respect to the costs. By setting an upper limit to the costs, the CEF allows identifying all alternatives fulfilling a possible budget constraint. However, in Phase 5, the possible budget constraints are not yet taken into account. The relaxation of this constraint allows considering high-cost alternatives with higher total values.

6.7 Sensitivity analysis

In Phase 6 of the comparison procedure, sensitivity analysis is conducted for compensation alternatives before generation of a compensation recommendation. The sensitivity analysis aims to analyze and identify how uncertainty in parameters of the SMCDA model or compensation scenario affects the feasibility, efficiency and ranking of the alternatives. The sensitivity analysis supports the comparison and identification of preferred compensation alternatives by studying the robustness of the alternatives to changes in the parameters of the SMCDA model.

In Phase 1, uncertainty is related to the discretization of the airspace, i.e., the selected altitudes, AOIs and lattice resolutions. Even though the DM selects the airspace discretization for the scenario, it affects the performance of the alternatives through the spatial value function (5.1). For example, the selected AOIs affect the geographical region where the air surveillance capability is observed. Outside the AOIs, e.g., the adverse effects are not taken into account. Therefore, in the sensitivity analysis, the effect of the selected altitudes and AOIs on feasibility, efficiency and ranking of the alternatives should be considered. Furthermore, the effect of lattice resolution on feasibility of the alternatives should be examined as it affects the resolution of the performance metrics. The increasing precision may cause emergence of new adverse effect regions or affect the shape and size of the existing ones.

In the second phase, the effect of identification of the adverse effect regions is studied. How the DM selects adverse effect regions affects the feasibility of alternatives. Therefore, the sensitivity analysis can be utilized to investigate the effect of small changes in identified adverse effect regions on feasibility of the alternatives. Furthermore, it can be observed whether combining separate adverse effect regions into larger regions affects the feasibility of the alternatives. In practice, the sensitivity analysis regarding Phase 2 can be conducted in Phase 3 while examining the effect of division of the AOI.

In the third phase, the uncertainty is related to the DM's preferences and their translation to preference information. It is either caused by difficulties of expressing the true preferences or inability to properly translate the preferences to weights and value functions. In the sensitivity analysis concerning Phase 3, the weights are varied one-by-one while keeping the others constant, and effect on the total value is observed. Similarly, the CVFs can be altered while keeping the weights constant.

In addition to the weights and CVFs, the division of the AOI has an effect on the total value through the subregions and spatial weighting. Therefore, the effect of the division of the AOI on the total value can be examined. In the sensitivity analysis regarding the division, the DM can select differently shaped and sized divisions and vary the number of subregions. Furthermore, the effect of omitting geographically important locations in the division can be considered.

In Phase 4, the effect of significance thresholds on feasibility of alternatives is studied. Examining the significance thresholds corresponds to reviewing the DM's attitude towards how strictly the air surveillance capability is protected. That is, how much the ATVs are allowed to decrease or if they are required to increase. Assessing appropriate values of the significance thresholds may be difficult, as the total values are relative to the scenario, and the total values do not have any general interpretations. The effect of thresholds δ_s^h and ϵ_s^h is observed through determining the feasible alternatives with different pairs $(\delta_s^h, \epsilon_s^h)$. If the changes in feasibility are notable, the analysis can be extended to the changes in efficiency.

In Phase 5, the efficiency is dependent on the air surveillance capability, i.e., the total value of the spatial value function (5.1) and the costs of the alternative. As the sensitivity of the spatial value function is observed in the sensitivity analysis regarding Phase 3, in this phase, it suffices to examine the sensitivity of the efficient alternatives on changes in costs. This can be conducted utilizing a CEF. It allows observing how changing the budget affects the feasible and efficient alternatives which fulfill the budget constraint. By fixing a compensation alternative, the CEF points out how much additional budget is required to implement an alternative with better air surveillance capability. Considering increasing the budget is important as small increases to the budget may, in some cases, result in a vast increase in the total value.

6.8 Compensation recommendation

In Phase 7, the identified feasible and efficient compensation alternatives are compared and ranked to generate a compensation recommendation. It is formed by analyzing the alternatives in the light of all available information. Hence, the recommendation is based on a holistic assessment of the air surveillance capability.

First, the possible budget must be taken into account as in the compensation problem it cannot be exceeded. Therefore, all alternatives exceeding the budget are rejected. Next, the DM also takes into account the results of the sensitivity analysis. If certain alternatives are found too sensitive for changes in certain parameters, these alternatives can be rejected. However, if all alternatives share the uncertainty, the value of the parameter can be checked. After evaluating the required quantities again, the recommendation can be re-considered. If the uncertainty cannot be decreased, the DM takes it into account while selecting the best alternative.

The compensation recommendation is selected as the result of a holistic assessment of alternatives. First, the alternatives are ranked utilizing the spatial value function (5.1). Second, the spatial measures, AEMs, VFFs and CEFs are analyzed to evaluate the air surveillance capability as a whole. Through examining the spatial measures holistically, the DM ranks the alternatives to decide which alternative is the most preferred.

The compensation recommendation is the alternative with the best overall air surveillance capability. This solution of the compensation problem allows the DM to determine the mitigation measures that must be taken to compensate the adverse effects. Furthermore, the solution yields the costs of the alternative, which can be given to the wind farm contractor as a condition for the wind farm project. If the contractor accepts the cost, the wind farm can be installed. Hence, a viable solution to the coexistence issue of the air surveillance systems and wind farms is obtained.

Chapter 7

Solution of an example compensation problem using the comparison procedure

This chapter presents the analysis of an example compensation problem. The example is simplified and illustrative. The goal is to demonstrate the utilization of the comparison procedure in a compensation problem phase-by-phase. Furthermore, the practical relevance of the procedure in a real-life decision making problem is pointed out.

In the example, the air surveillance capability of an imaginary country is assessed in a situation where a wind farm contractor wishes to install a wind farm project on the territory of the country. To allow siting of the new wind farm, its adverse effects on the air surveillance capability must be assessed. The example compensation problem is solved by first identifying the adverse effects of the wind farms on the existing air surveillance system. Then, the best compensation alternative, i.e., air surveillance system which compensates the adverse effects and restores the air surveillance capability on at least initial level, is sought.

7.1 Phase 1: Definition of the compensation scenario

The example concerns the air surveillance system of an imaginary country. It consists of a single sensor surveying the southern vicinity of the country. A wind farm contractor pursuits installation of a wind farm system that contains three separate wind farms. To allow the wind farm project, the initial air surveillance capability cannot be deteriorated by the adverse effects of the wind farms. Therefore, the effect of wind farms on the air surveillance capability must be analyzed. If the adverse effects are severe enough, they must be compensated by modifying the existing air surveillance system. To compensate the adverse effects, an air surveillance system constituting at least the initial air surveillance capability must be sought. If such an alternative is found, its cost can be set as a condition for the wind farm project. If the contractor accepts the costs, the wind farms are allowed. Next, the construction of the compensation scenario is presented by considering the prevailing air surveillance capability and the DM's resources for mitigating the adverse effects.

7.1.1 Air surveillance system

A map illustrating the proximity of the country considered in the example is presented in Figure 7.1. The map is generated with Mapgen4 generator (Red Blob Games, 2018), and it is utilized as a topographic base of visualizations later on in this example. On the map, green areas correspond to terrain and blue ones to the bodies of water, respectively. The territory of the country is located in the northeastern part of the map. It is restricted by the borderlines depicted by the red line.

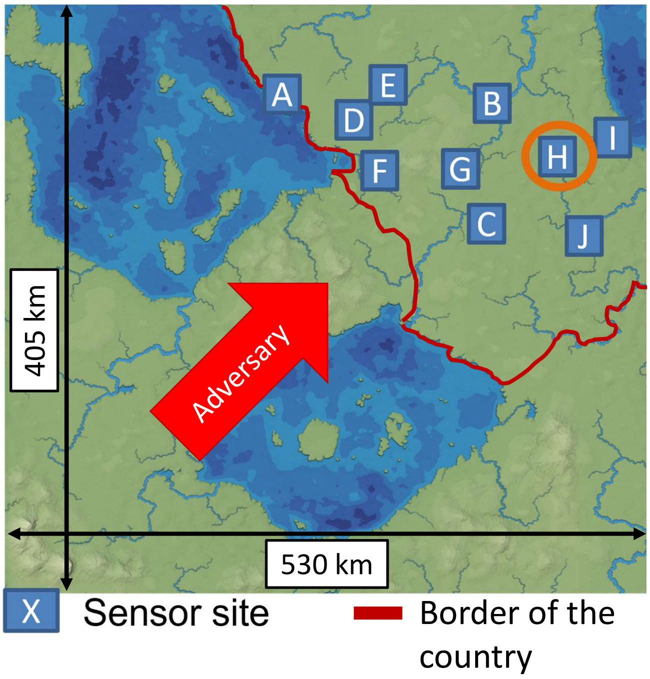

Figure 7.1: Geography of the example scenario. Sensor sites are denoted with blue boxes and the border of the country with red lines. The only sensor of the air surveillance system is denoted with an orange ellipse. The red arrow highlights the assumed direction of an adversary.

Figure 7.1 also presents the available sensor sites of the air surveillance system. There are ten sensor sites available in total. They are marked with blue boxes and denoted by capital letters $A - J$. The initial air surveillance system consists of a single middle-range surveillance radar. The radar is located at site H, which is highlighted with an orange ellipse.

The most probable direction for a potential adversary to conduct air operations or other violations of sovereignty is southwest. This is illustrated in Figure 7.1 with a red arrow. Therefore, the emphasis of surveillance is in that direction. Furthermore, the initial air surveillance system is assumed to fulfill underlying air surveillance goals. The air surveillance capability of the initial system is assumed to reflect these goals.

7.1.2 Wind farms

The wind farm system of the example problem contains three separate wind farms which the contractor wishes to install. The approximate locations of the wind farms are presented in Figure 7.2 with red boxes. Their layout is assumed to form a rectangular lattice such that turbines are facing towards the initial air surveillance sensor. The number of wind turbines of each wind farm and their heights are summarized in Table 7.1. The heights are measured as height above average ground level (AAGL).

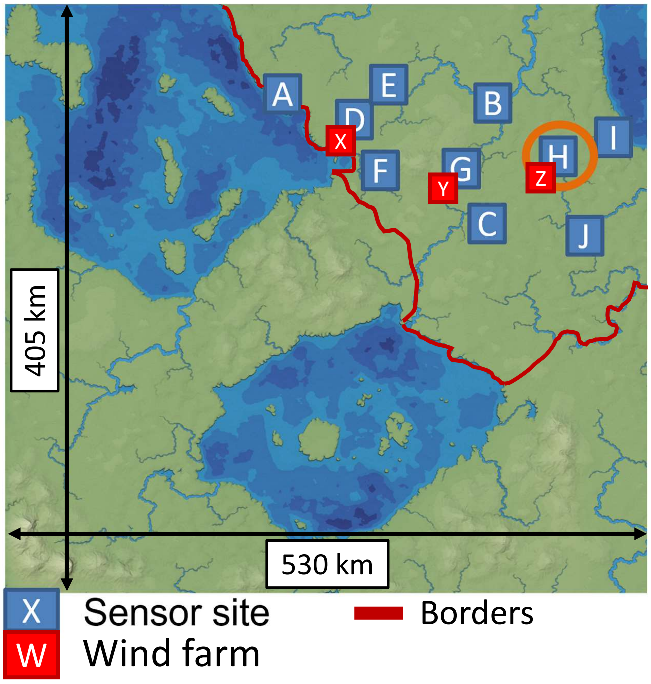

Figure 7.2: Geography of the scenario. Sensor sites are illustrated with blue and the locations of wind farms with red boxes, respectively. The borders of the country are depicted by the red line.

Table 7.1: Parameters of the wind farms.

Location	Number of wind turbines	Height (AAGL)
X	10	300
Y	32	300
Z	24	300

7.1.3 Targets

The air surveillance capability is assessed with respect to two target types: a passenger airplane and a fighter jet. The types depict a big and slow and a small and fast target. Their velocities are 50 m/s and 300 m/s, respectively. Both targets have the same expected flight direction of 45 degrees with respect to grid north. This is represented by the red arrow in Figure 7.1.

7.1.4 Airspace discretization

The airspace discretization consists of altitudes, corresponding AOIs and their lattice resolutions. In the example, the airspace is divided into three altitudes: low, medium and high, which are 500 m, 3000 m and 10 000 m, respectively. At all altitudes, the AOI is selected to be similar. The AOI corresponds to the area presented in Figures 7.1 and 7.2. It is a rectangle with a width and height of 530 km and 405 km. The lattice resolution is 5 km at all altitudes. The parameters of the airspace discretization are summarized in Table 7.2.

Table 7.2: Parameters of the airspace discretization.

Parameter	Value
Discretization altitudes	500 m 3 000 m 10 000 m
AOI	405 km x 530 km rectangle (region presented in Figures 7.1 and 7.2)
Lattice resolution	5 km

7.1.5 Compensation alternatives

Compensation alternatives are determined by available resources and mitigation measures. The air surveillance system can be modified by utilizing all ten alternative sites denoted with $A - J$. To mitigate the adverse effects, the DM can acquire one additional middle-range surveillance radar. Additionally, the existing sensor at site H can be relocated. Therefore, the possible mitigation measures are

I Relocation of the existing sensor from initial site H,

II Addition of a second sensor to a free site $A - J$,

III Relocation of the existing sensor from site H and addition of a new sensor to a free site $A - J$.

The compensation alternatives are denoted with symbols consisting of letters corresponding to the sites of the sensors. For example, if the existing sensor is relocated to site F, this compensation alternative is referred as alternative F. Similarly, if a new sensor is added to site A and the initial sensor remains at site H, the alternative is denoted with AH. Furthermore, an alternative where the existing sensor is relocated to site F and a new sensor is added to site J is indicated with FJ. The three measures I-III allow constructing all combinations of the sites with one or two sensors. This yields total of 54 compensation alternatives.

The alternatives have an additional restriction related to the relocation of the initial sensor. The relocation must be conducted within the maximum allowed downtime. This is because the air surveillance system cannot be offline for excessively long periods of time. In the example, this downtime is 8 hours. Yet, extraction and installation of a sensor take 3 hours each. Therefore, the maximal time left for relocating the sensor is 2 hours. The relocation can be carried out with an average velocity of 45 km/h. The two-hour relocation time is equivalent to a range of 90 km. Hence, the relocation of the existing sensor from H to sites A, D and E is not possible. Taking into account the relocation constraint, there are 51 alternatives left as alternatives AD, AE and DE cannot be implemented due to the restriction.

The compensation alternatives are compared to a reference alternative. It depicts the initial air surveillance and wind farm system constituting the prevailing air surveillance capability. The reference alternative corresponds to the existing middle-range surveillance radar at site H. Therefore, analogously to the compensation alternatives, the reference alternative is referred as alternative H.

Costs

The costs of the compensation alternatives are determined separately for each alternative, and in this example, they are purely illustrative. The costs depend on the utilized mitigation measures. The cost of addition of a new sensor is determined by the price of the new sensor and a cost related to acquisition and modification of the site for the new sensor.

The cost of a medium-range surveillance radar is assumed to be approximately 18 M€. The evaluation is based on the information presented in the government bill for the Act on compensation areas for wind energy (HE 55/2013 vp, 2013).

In addition to the sensor cost, mid-life upgrade, labor, maintenance, infrastructure, information and communications technology (ICT) costs should be accounted. In this example, the mid-life upgrade cost is assumed to be included in the acquisition cost. Furthermore, the labor and maintenance costs can be omitted, as they are assumed to be equal for all middle-range surveillance radars independent of the location. The infrastructure and ICT costs are accounted via a site-specific cost. It consists of acquiring the corresponding site and implementing necessary modifications to the site. The site-specific costs are presented in Table 7.3.

Table 7.3: The site-specific costs.

Site	A	B	C	D	E	F	G	H	I	J
Cost (M€)	10	8	8	7	5	15	10	0	6	9

In the relocation of the existing sensor, the costs are determined only by of the site-specific costs, which are given in Table 7.3. For example, the cost of relocating the initial sensor from H to F is 15 M€. Considering alternative FJ, where both relocation and addition of a sensor are conducted, the acquisition and modification of sites F and J inflicts a cost of 15 M€ and 9 M€, respectively. As the new sensor costs 18 M€ the total cost of alternative FJ is 42 M€.

7.2 Phase 2: Identification of the adverse effects

The adverse effects are identified by comparing the air surveillance capability of the initial air surveillance system with and without wind farms. Therefore, to assess the adverse effects, the prevailing air surveillance capability must be determined. Figure 7.3 presents the capability of the reference alternative, i.e., the initial air surveillance system, employing the performance metrics at the altitude of 10 000 m. The metrics at the altitudes of 500 m and 3 000 m are presented in Appendix A.

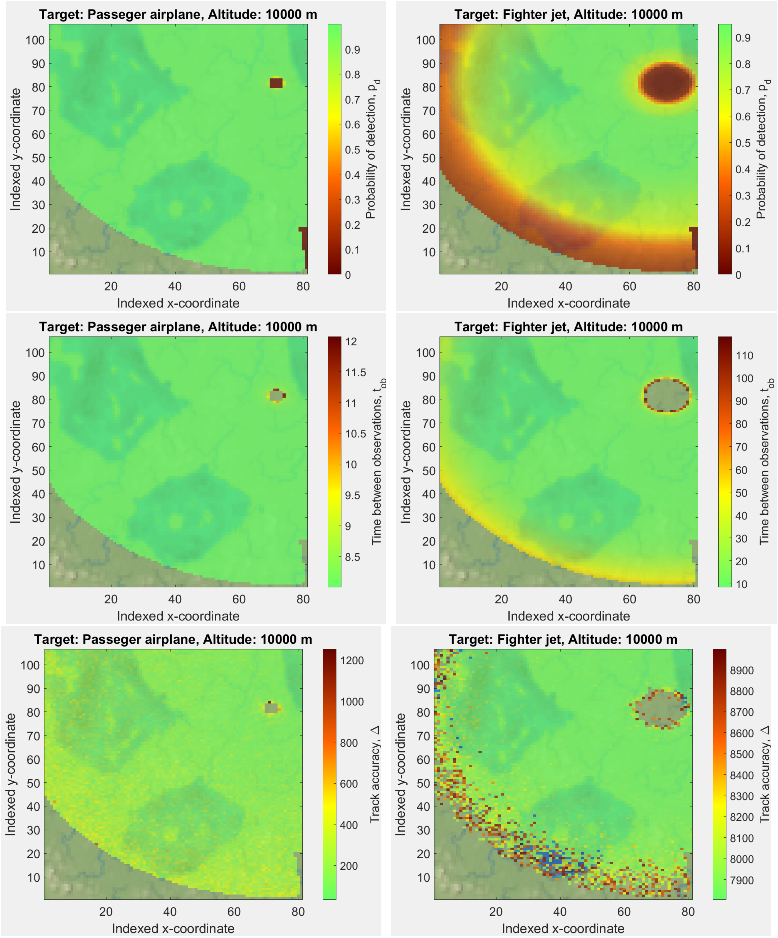

Figure 7.3: Performance metrics describing the air surveillance capability of the reference alternative at 10 000 m. Each visualization presents a single metric with respect to either passenger airplane (left) or fighter jet (right).

Figure 7.3 points out that the initial air surveillance system covers almost the entire AOI at 10 000 m. The probability of detection p_d is close to its maximum value of 1.0 almost everywhere. Similarly, the time between observation t_{ob} is approximately 10 seconds at the same regions. The values of p_d and t_{ob} do not have significant dependence on the target type close to the sensor. Far away and extremely close to the sensor, the values of the metrics decline as the target is closer to the maximum range. In the track accuracy Δ, there is a clear dependence on the target. For the passenger airplane, Δ is approximately 200-300 m almost everywhere. For the fighter jet, Δ is notably larger with an approximate value of 8000 m which indicates an error of 8 km. The poor track accuracy for the fighter jet is due to its high velocity and relatively small RCS. Therefore, maintaining the track is challenging. As the initial air surveillance capability is assumed to fulfill the underlying surveillance goals, the low track accuracy is not an issue. However, it emphasizes the need for maintaining the air surveillance capability, as the capability cannot be further compromised.

Next, the severity of adverse effects is determined. The adverse effects of the wind farms are identified by taking into account the wind farm system presented in Figure 7.2 and Table 7.1. They are pointed out utilizing adverse effects metrics (AEMs). Figure 7.4 presents the AEMs of p_d against fighter jet at all altitudes. The AEMs for t_{ob} and Δ are presented in Appendix B.

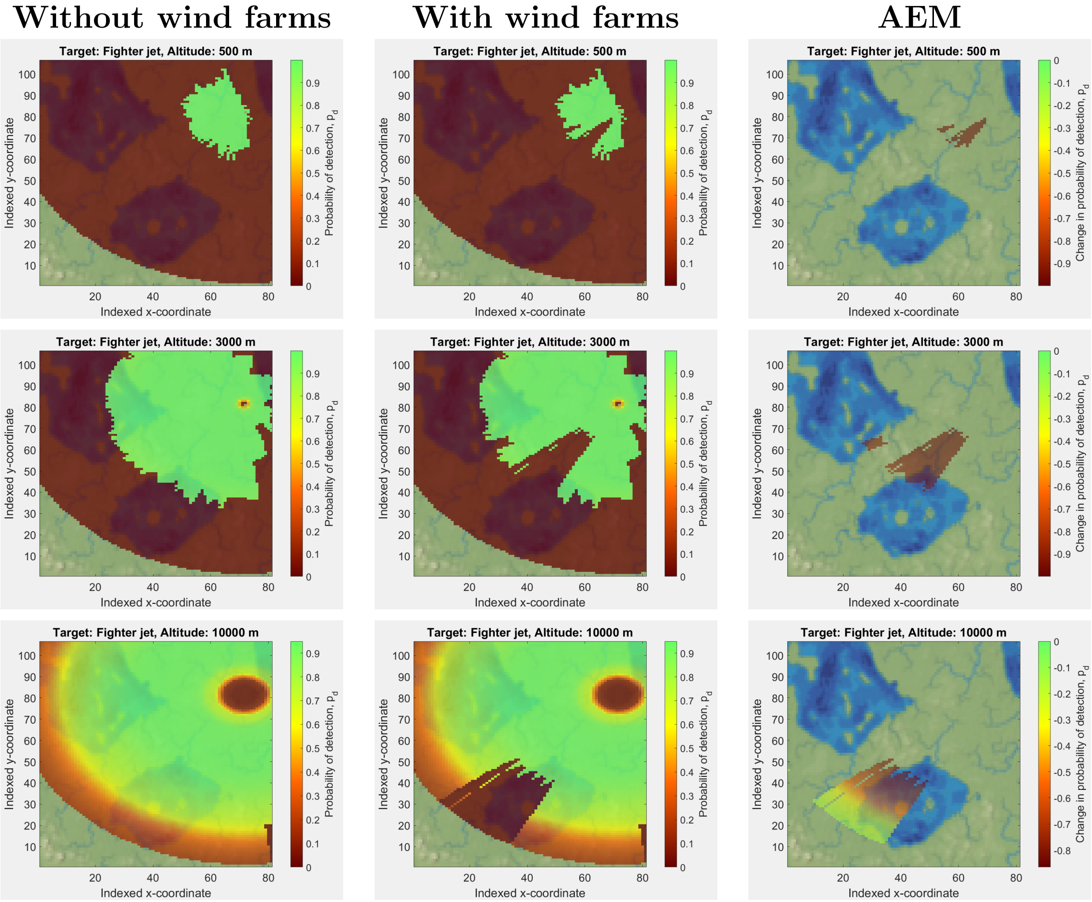

Figure 7.4: AEMs of the probability of detection p_d against fighter jet at altitudes 500 m, 3000 m and 10 000 m (right), and p_d of the initial air surveillance system without wind farms (left) and with the wind farms (middle).

The AEMs, on the right in Figure 7.4, point out the emergence of adverse effects and adverse effect regions. The wind farms cause significant decreases to air surveillance capability at all altitudes. At the 10 000 m, the adverse effects are directed to the southwestern part of the AOI. Decreasing the altitude, they shift towards the sensor in the northeast. The decreases in the performance metrics indicate that the adverse effects are severe, and they must be compensated. In this example, the adverse effect regions are specified while constructing the division of the AOI in the following phase.

7.3 Phase 3: Elicitation of preference information

To evaluate and assess the compensation alternatives with the spatial value function (5.1), preference information must be elicited. Next, the elicitation of the DM's preferences to quantify the air surveillance capability is presented. It consists of CVFs of metrics, the division of the AOI and weights.

7.3.1 Consequence value functions

The CVFs are selected for each performance metric that is included into the spatial value function (5.1) as criterion. In this example, the criteria are probability of detection, p_d time between observations t_{ob}, and track accuracy Δ.

Probability of detection

The CVF for the probability of detection p_d is a piecewise linear function, see Figure 7.5. The higher p_d, the better the air surveillance capability. If p_d is low, then combined with high values of time between observations does not enable maintaining the track. Therefore, the slopes of the linear pieces of the CVF increase with the increasing value of p_d, which highlights the importance of its high levels.

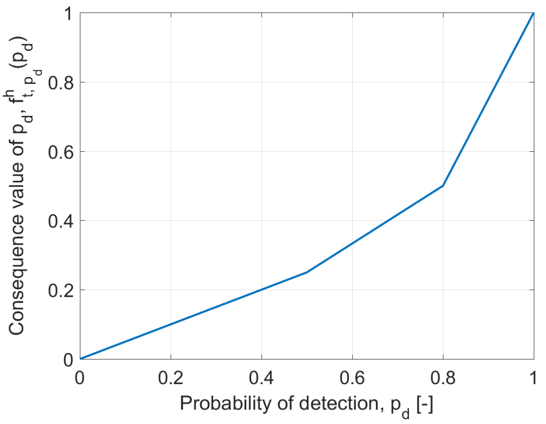

Figure 7.5: CVF f^h_{t,p_d} for probability of detection p_d.

Time between observations

The shorter the time between observations t_{ob}, the better the ability to observe and track the target. Therefore, short t_{ob} allows maintaining the tracks of targets with higher precision. With the increasing t_{ob}, the ability to track targets diminishes fast. Theoretically, the preferred t_{ob} would be 0 seconds. On the other hand, in the worst case, the t_{ob} would be infinitely long. To capture this behavior of t_{ob}, the CVF is an exponential function with the functional form of

$$f^h_{t,t_{ob}}(z^k;(x,y,h)) = 1 - e^{-10/t_{ob}},$$

that is presented in Figure 7.6.

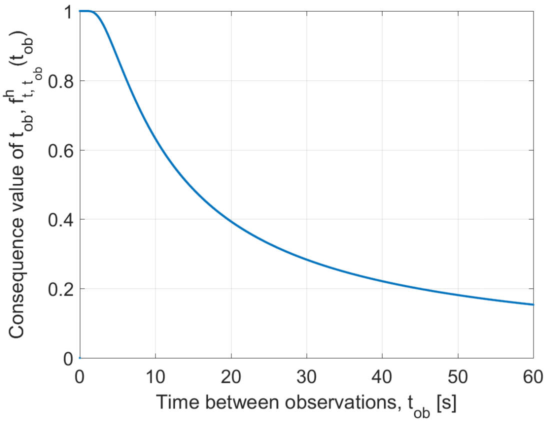

Figure 7.6: CVF $f^h_{t,t_{ob}}$ for time between observations t_{ob}.

Track accuracy

Track accuracy Δ measures the error in the estimated track of a target. The smaller the error, the more accurate the track is. Theoretically, the error is between 0 and infinite meters. However, errors greater than 3 km are too large for maintaining meaningful track. Therefore, the value of Δ larger than that is 0.

The CVF for Δ is a piecewise linear function, see Figure 7.7. The absolute values of slopes of the pieces decrease with the increasing value of Δ. The piecewise linear function obtains value of one at 0 m and value zero at 3 km or more, respectively.

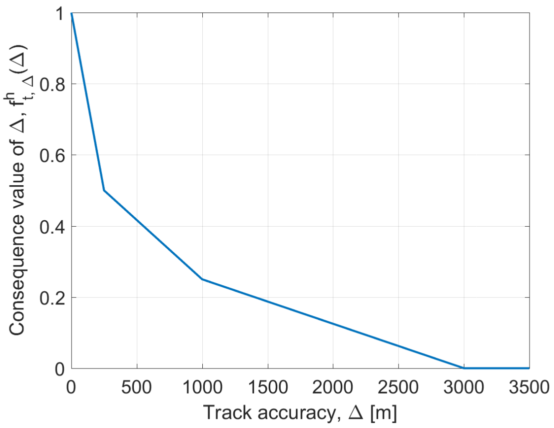

Figure 7.7: CVF $f^h_{t,\Delta}$ for the track accuracy Δ.

7.3.2 Division of the area-of-interest

The division of the AOI is based on identification of adverse effect regions from AEMs presented in Figure 7.4 and Appendix B. The adverse effect regions at different altitudes are in the southwest of the territory of the country. The higher altitude, the further away from the sensor the adverse effects are observed. Now, all the adverse effects at the three altitudes can be captured within a single adverse effect region. This allows utilization of the same division of the AOI at all altitudes. Therefore, in this example, only a single adverse effect region (Subregion 1) is selected, see Figure 7.8.

In addition to the identified adverse effect region, geographically important regions are considered as the basis for the selection of the undistorted regions. The body of water in the northwest and the territory of the country in the northeast are selected as undistorted regions (Subregions 2 and 3) as the DM considers both geographically important. To cover the whole

AOI, the reminder of the AOI is selected as Subregion 4. The division of the AOI, which is determined by the selected adverse effect region and three undistorted regions, is presented in Figure 7.8.

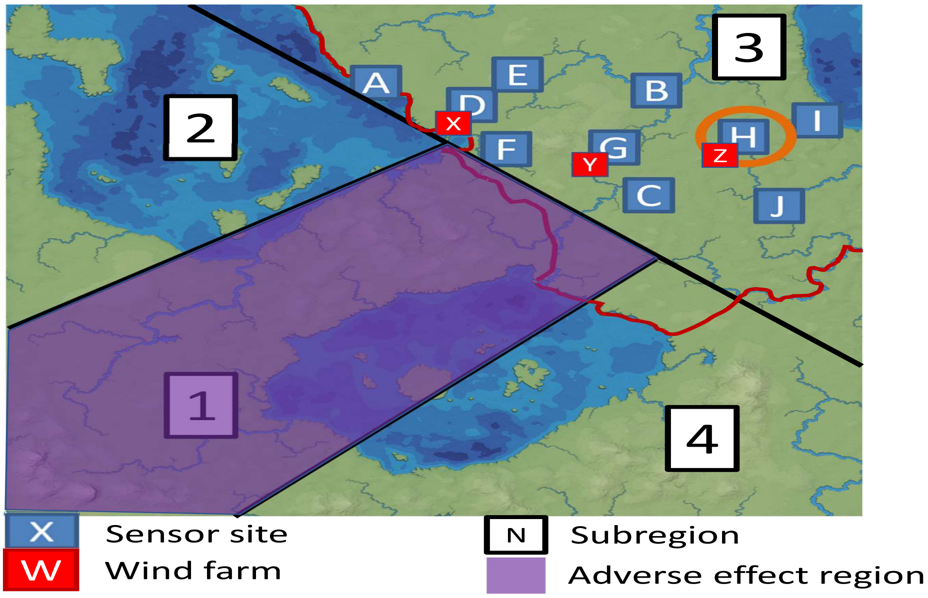

Figure 7.8: Division of the AOI. The adverse effect region is highlighted with purple and denoted with number 1. The undistorted regions are marked with numbers 2-4.

7.3.3 Weights

The weights of the spatial value function (5.1) are criterion, target type, altitude and spatial weights, and they are selected as follows. First, the criterion weights can be specified separately for each target at each altitude. However, according to the DM, there is no difference in the importance of the criteria either between different altitudes or targets. Therefore, the criterion weights are criterion-specific. Furthermore, according to the DM's judgment, there is no difference in the importance of the three criteria, and the criterion weights are equal. As the weights are required to sum up to one, the resulting criterion weights are $b^h_{t,j} = 1/3$.

Second, the target type weights correspond to the DM's judgment on the relative importance of passenger airplanes and fighter jets. The DM wishes to enforce the ability to observe the fighter jets to enhance the early-warning ability. Therefore, according to DM's preferences, the observation of the fighter jets should be two times as important as the identification of the passenger airplanes. Assuming that w_1^h corresponds to the weight of the passenger airplane and w_2^h the fighter jet, respectively, it holds that $w_2^h = 2w_1^h$. As the target type weights must sum up to one, the weights are $w_1^h = 1/3$ and $w_2^h = 2/3$.

The third type of weights is the altitude weights. The DM emphasizes higher altitudes, as the probability of adversary aircraft penetrating the airspace with low altitudes is assumed unlikely. Therefore, the DM selects the altitude weights as follows: low (500 m) $a_1 = 0.2$, middle (3000 m) $a_2 = 0.4$, high (10 000 m) $a_3 = 0.4$.

Finally, the spatial weights regarding the importance of the subregions of the AOI are elicited. The DM considers that the importance of altitudes between the subregions at different altitudes is equal. Hence, the spatial weights at all altitudes are equal too. Furthermore, as there is no clear difference in the importance of air surveillance between the subregions, the DM selects the weights to be equal at each subregion. Therefore, each subregions gets weight $\alpha_s^h = 1/4$.

7.4 Phase 4: Identification of feasible compensation alternatives

The feasibility of compensation alternatives is determined by finding all alternatives fulfilling the feasibility conditions **C1** and **C2**, which are formalized in Equations (6.1) and (6.2). To evaluate them, the significance thresholds δ_s^h and ϵ_s^h should be set for each altitude and subregion. However, now the feasibility is evaluated with a visual feasibility figure (VFF), see Figure 7.9. Therefore, the significance thresholds do not need to be explicitly defined.

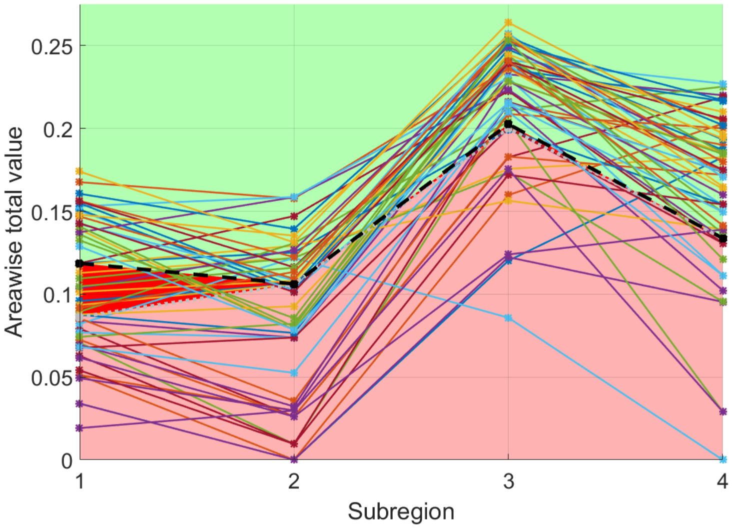

Figure 7.9: VFF of all compensation alternatives. Each polyline represents a single alternative. The adverse effect region is Subregion 1, whereas Subregions 2-4 are undistorted regions. The background color illustrates the air surveillance capability of each subregion compared to the reference alternative. Green corresponds to better and red to worse capability. Dark red area highlights the adverse effect.

Figure 7.9 presents the areawise total value (ATV) (5.7) of each subregion. Furthermore, the ATVs of the reference alternative, with and without the wind farms, are illustrated with dashed polylines on gray and black, respectively.

To assess the feasibility, the adverse effect region, i.e., Subregion 1, is first considered. If any of the alternatives undercuts the black dashed polyline, which visualizes the ATVs of the reference alternative, the alternative is infeasible. In total, there are 29 such alternatives. Therefore, 22 alternatives fulfill the feasibility condition **C1** of Equation (6.1). These alternatives are illustrated in Figure 7.10.

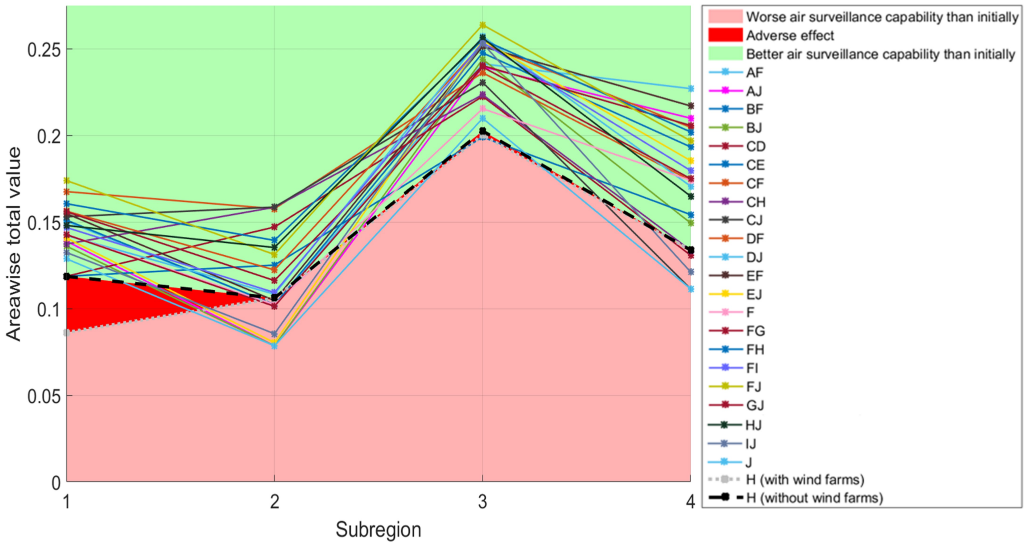

Figure 7.10: VFF of the compensation alternatives fulfilling condition **C1**. Each polyline presents an alternative which is feasible with respect to the feasibility condition for the adverse effect regions.

Next, the undistorted regions are considered in numerical order. First, in Subregion 2, alternatives J, AJ, BJ, EJ and IJ undercut the ATV of the reference alternative significantly. Therefore, these alternatives are infeasible and are omitted. Subregion 3 does not have any alternatives which have not yet been eliminated. Lastly, in Subregion 4, alternative CJ declines the ATV of the reference alternative significantly. Hence, after the evaluation of feasibility conditions, there are 16 feasible compensation alternatives which are further analyzed in the next phase. All these alternatives fulfill the feasibility conditions, i.e., compensate the adverse effects adequately.

7.5 Phase 5: Cost-efficiency analysis

The cost-efficiency analysis is conducted for 16 feasible compensation alternatives. It is carried out utilizing a cost-efficiency figure (CEF), see Figure 7.11.

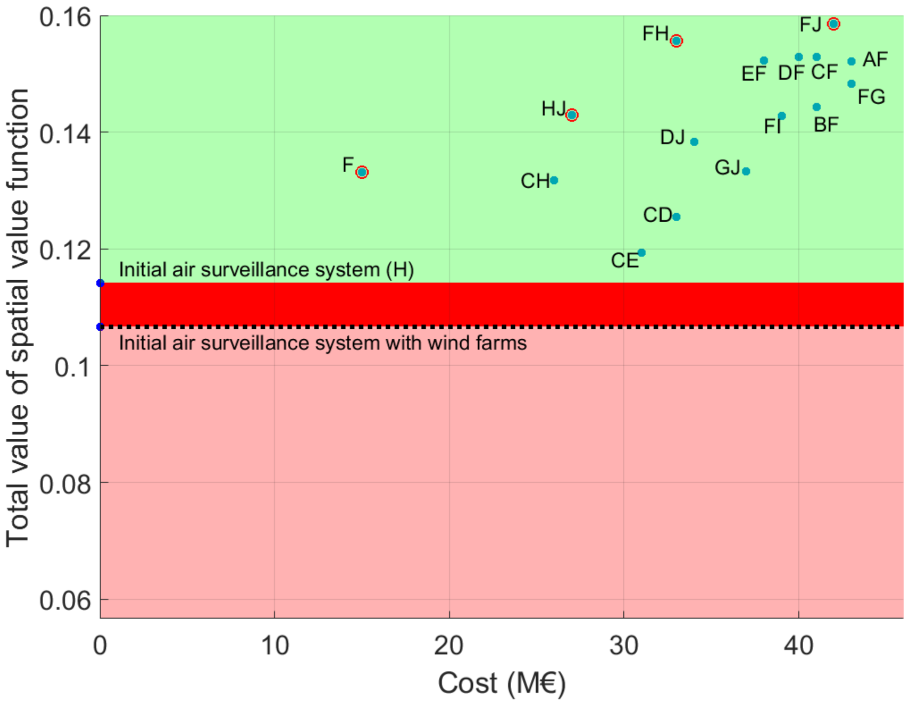

Figure 7.11: Cost-efficiency figure (CEF) illustrating the efficiency of the feasible alternatives. Each point denoted one alternative, and the efficient ones are highlighted with a red outline. The background color indicates the performance of the alternatives with respect to the reference alternative. A green background corresponds to better and red worse air surveillance capability. Adverse effect is emphasized with the dark red area.

Figure 7.11 represents the total values of the spatial value function (5.1) for all feasible alternatives with respect to their costs. The efficient alternatives can be either determined by evaluating Equations (5.8)-(5.9) or by identifying them from the CEF in Figure 7.11. In this example, four feasible and efficient alternatives are identified. These alternatives, i.e., F, HJ, FH and FJ, are denoted with a red ring in Figure 7.11. From these alternatives, FJ has the highest total value. The next best alternative FH has only slightly smaller total value but notably lower cost. However, between the second and third-best alternatives, HJ and FH, the difference in the total value is already notable.

7.6 Phase 6: Sensitivity analysis

As discussed in Section 6.7, sensitivity analysis aims at ensuring that uncertainty in the parameters of the SMCDA model does not have significant effect on the feasibility, efficiency or ranking of compensation alternatives. By conducting sensitivity analysis, the DM ensures that feasible and efficient alternatives remain preferred even though small changes in the parametrization would occur. On the other hand, it aims to verify that no other alternatives should be taken into consideration if the parameters change. Therefore, sensitivity analysis supports the generation of a compensation recommendation.

Elicitation processes concerning preference information are not in the scope of this example. This prevents proper justification of preferences and their re-evaluation. Therefore, sensitivity analysis regarding Phases 1-3 is not meaningful, and sensitivity analysis is only presented regarding Phases 4 and 5.

Feasibility of alternatives with respect to the significance threshold

Considering the formal feasibility conditions (6.1)-(6.2), the feasibility of compensation alternatives depends on the selected significance thresholds δ_s^h and ϵ_s^h. The significance threshold δ_s^h describes the DM's preference on how much below the ATVs of adverse effect regions are allowed decline so that the alternative remains feasible. Similarly, ϵ_s^h yields the same for the undistorted regions. In the example, the sensitivity of feasibility to the selection of the significance thresholds is important, as it justifies the utilized visual evaluation of feasibility. If the feasible alternatives are not sensitive to small changes in the selected significance thresholds, then the visual evaluation is sufficient.

The effect of the significance thresholds on feasibility is considered by calculating the number of feasible alternatives with varying the values of δ_s^h and ϵ_s^h. The value of δ_s^h is assumed to be 1.0, which corresponds to the complete compensation of the air surveillance capability at adverse effect regions. Similarly for ϵ_s^h, the value is $\epsilon_s^h = 0.95$, which corresponds to a 5% decline in the values of ATVs. To assess the proximity of these values, the sensitivity analysis is conducted by determining the number of feasible alternatives with the significance threshold values δ_s^h, $\epsilon_s^h \in [0.8, 1.2]$. This interval is divided linearly with a step of 0.01. Figure 7.12 presents the number of feasible alternatives for each pair $(\epsilon_s^h, \delta_s^h)$.

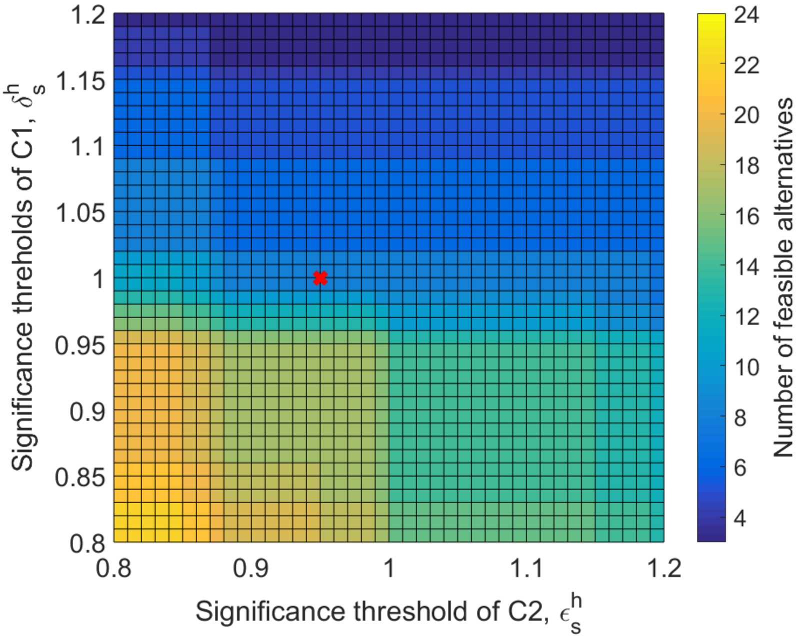

Figure 7.12: Sensitivity analysis of the number of feasible compensation alternatives with respect to changing significance thresholds δ_s^h and ϵ_s^h. Initial parameters are denoted with a red cross.

Based on Figure 7.12, when both ϵ_s^h and δ_s^h are in the vicinity of their initial values, the number of feasible alternatives is fairly robust. Changes in the value of ϵ_s^h have almost no effect on the number of feasible alternatives. As ϵ_s^h concerns the undistorted regions, this is expected, as most infeasible alternatives are infeasible by a great margin. However, increasing δ_s^h while keeping ϵ_s^h constant has a greater effect on the number of feasible alternatives. That is, increasing δ_s^h above 1.0 decreases the feasible alternatives quickly. The effect of δ_s^h is greater than that of ϵ_s^h as there is only a limited number of extremely high-performing alternatives at the adverse effect region. Only these alternatives can achieve the required ATVs when significance threshold values are above 1.0. Therefore, increasing the required ATVs on the adverse effect region decreases the number of feasible alternatives more heavily as the number of excellent alternatives is low.

As a whole, the selection of the significance thresholds does not have a notable effect on the feasibility of the alternatives. Hence, the visual evaluation of feasibility suffices, and the explicit determination of the thresholds are not assumed to affect the feasible alternatives. Thus, based on the sensitivity analysis regarding Phase 4, the uncertainty in the significance thresholds does not require attention while making the compensation recommendation.

Effect of changes in costs and budget on efficient alternatives

The sensitivity of the efficient alternatives on costs is next examined. The compensation recommendation should be such that despite a small increase in the costs, the selected alternative would remain efficient. On the other hand, the change in costs should not cause surfacing of new efficient alternatives either. Additionally, this sensitivity analysis allows considering if small changes in budget varies the set of efficient alternatives vastly.

First, the effect of the available budget on efficient alternatives that can be implemented within it is analyzed by considering the CEF presented in Figure 7.11. The CEF points out that the alternatives are classified into three groups with respect to the cost. Both alternatives F and FJ are separated into their own groups, whereas HJ and FH belong to the same group. As the differences in the costs between the alternatives are relatively large, the selection of the best alternative is not likely to be highly sensitive to the changes in the budget. If the budget is between two of the three groups, significant increases in the budget are required to obtain a new efficient alternative. However, if it is in between alternatives HJ and FH, then the DM should consider if the increase would be worth obtaining better air surveillance capability.

Considering the sensitivity of the efficiency of alternatives with respect to changes in costs, the set of efficient alternatives is fairly robust. The smallest difference between the costs is between HJ and FH, and the difference is 5 M€. If the costs change less than that, the efficient alternatives remain the same. The smallest change in the costs of a single alternative that would cause emergence of a new efficient alternative is a decrease of 4 M€ in the cost of alternative EF. Therefore, the set of efficient alternatives is robust, as the required changes in the costs of the efficient alternatives are relatively large in comparison with the site-specific costs. If the ordinal ordering of the costs of the sites would change, this could affect the efficiency of some alternatives. Now, it is assumed that the ordinal order of the costs is correct. Thus, the efficient alternatives are not expected to change even if small changes in the costs would occur.

7.7 Phase 7: Compensation recommendation

In the last phase of the comparison procedure, the feasible and efficient alternatives are compared to generate a compensation recommendation. While generating the recommendation, possible constraints related to the budget and the results of the sensitivity analyses are taken into account. The compensation recommendation is generated by conducting a holistic evaluation of the feasible and efficient alternatives to find the best overall air surveillance capability. It is carried out by considering the air surveillance capability with respect to all available measures, i.e., total values, spatial measures, AEMs, VFFs and CEFs.

In this example, the set of feasible and efficient alternatives consists of four alternatives: F, HJ, FH and FJ. Furthermore, to demonstrate the budget constraint, let us assume that the budget is limited to 30 M€, which restricts alternatives FH and FJ out of consideration. Therefore, the DM should decide between alternatives F and HJ. The DM should also consider whether the increase in the air surveillance capability is worth the increasing cost. It is now assumed that the DM can utilize the whole 30 M€ without pressure to save in costs.

Based on the sensitivity analyses, the alternatives are not especially sensitive to changes in the parameters analyzed. However, the budget is between alternatives HJ and FJ. Therefore, the DM must consider whether the increase of 6 M€ would be worth having possibility to implement alternative FJ. Based on comparison with the reference alternative, the DM find the improvement in the air surveillance capability provided by the less expensive alternatives adequate. Thus, the DM will not pursue extending the budget.

Having taken into account the budget and the sensitivity analyses, the compensation recommendation is based on evaluation which alternative has better overall air surveillance capability. The holistic evaluation is conducted by examining the ATVs and the pointwise total values (PTV). The ATVs are presented in Figure 7.10. The ATVs of HJ exceed those of F at all subregions. Furthermore, they are also clearly above those of the reference alternative. However, alternative F undercuts the reference alternative at Subregion 2 slightly. This decline encourages for favoring alternative HJ.

The PTVs of alternatives F and HJ are presented in Figure 7.13. The DM finds that the air surveillance capability of HJ is better than that of alternative F. At the lowest altitude of 500 m, the PTVs of F are better, as the air surveillance capability of alternative HJ is partially directed outside the AOI from the east. At high and medium altitudes, HJ outperforms F clearly. Overall, comparing the two alternatives, alternative HJ constitutes better air surveillance capability at all altitudes and against both targets. Therefore, its air surveillance capability is not only better with respect to the total value of the spatial value function (5.1), but it is better according to the assessment of the spatial measures, i.e., ATVs and PTVs.

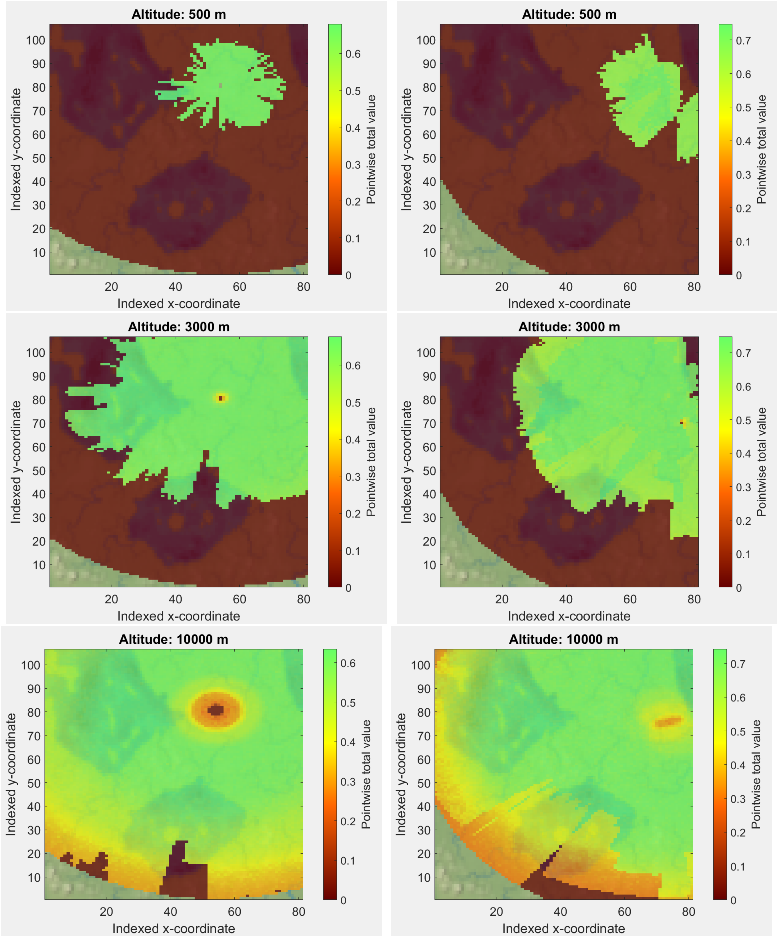

Figure 7.13: Pointwise total values (PTV) of alternatives F (left) and HJ (right) for altitudes 500 m, 3000 m and 10000 m.

The holistic evaluation of the air surveillance capability points out that compensation alternative HJ outperforms alternative F. Therefore, the compensation recommendation, i.e., the solution of the compensation problem, is alternative HJ, which corresponds to adding a new sensor to site J while the existing sensor remains in its initial location, i.e., at site H. Hence, if the wind farm contractor accepts the cost of alternative HJ, which is 27 M€, the wind farm can be accepted.

Chapter 8

Discussion

This thesis studies the coexistence of air surveillance systems and wind farms, and especially compensation of adverse effects of wind farms on the air surveillance systems. The coexistence is enabled by introducing the SMCDA model that allows determining the air surveillance capability of alternative air surveillance systems and examining the adverse effects of wind farms. Furthermore, a comparison procedure based on this model is presented. The procedure is demonstrated by solving an illustrative example problem.

Solving the example problem points out that the comparison procedure allows finding a viable solution to the coexistence of the air surveillance systems and wind farms. Furthermore, it is demonstrated that the adverse effects and the air surveillance capability can be quantified with the SMCDA model. The procedure can be employed for supporting the planning of wind farm siting. Furthermore, its visualizations can be used to argue decisions to wind farm contractors. Moreover, the comparison procedure can be utilized to evaluate whether the prevailing air surveillance system can be improved and at what cost. Overall, the use of the procedure and the SMCDA model increases transparency and trust in the compensation recommendation given as a solution for the compensation problem.

Even though viable solutions to the compensation problem are obtained, there are limitations related to both the comparison procedure and the SMCDA model. Next, these limitations and themes for future work are discussed.

8.1 Limitations

The comparison procedure and the SMCDA model contain some limitations which restrict their use and generality of results. Partly, the limitations are related to the example of this thesis, and they do not restrict the application of the procedure and the SMCDA model in general.

8.1.1 Example problem

Regarding the limitations of the example problem, it is both imaginary and rough. The geography of the scenario is not realistic, which prevents sophisticated interpretations related to, e.g., the built environment. Furthermore, the adversary is only speculative. Similarly, the discretization of the airspace is only illustrative. Hence, e.g., altitudes may not represent realistic flight altitudes for the selected targets. The number of altitudes is low, and they are relatively far from each other. Moreover, the imaginary geography also obstructs precise identification of adverse effects and adverse effect regions. As the geography does not include, e.g., major cities, they cannot be appropriately taken into account. The imaginary geography also leads to the selection of similar AOIs at each altitude.

In the example, the initial air surveillance system is simple since it consists only of one sensor. Furthermore, the available resources are limited. Thus, the utilization of only one additional sensor is possible. Moreover, all the sensors are medium-range surveillance radars. In real-life, air surveillance systems may contain multiple sensors of varying types. Despite the simplicity of the example, more complex air surveillance systems with several types of sensors can be examined with the comparison procedure.

The mitigation measures and resources, which constitute the compensation alternatives, are also limited to simplify the example. However, with more resources, the number of compensation alternatives increases, but the use of the comparison procedure and the evaluation of the air surveillance capability do not change. Additionally, now only two mitigation measures are considered. However, together with the resources, the mitigation measures only affect the compensation alternatives. Hence, should the DM have the possibility to utilize more diverse mitigation measures they can be taken into account. Similarly, all costs and cost structures are imaginary. Finally, as the elicitation of preference information is not in the scope of this thesis, it is only illustrative in the example.

8.1.2 The comparison procedure and the spatial multi-criteria decision analysis model

Regarding the comparison procedure, limitations are mostly related to a compensation scenario. In addition to the scenario fulfilling the requirements of the compensation problem, compensation alternatives must be obtained by modifying an initial air surveillance system, i.e., the reference alternative. Hence, the reference alternative must be common for all the compensation alternatives.

The SMCDA model is restricted by the functional form of spatial additive multi-criteria value function. The theoretical assumptions related to the construction of such value function must hold in order to the SMCDA model to be valid. A value function describing the DM's preferences only exists if the DM accepts certain underlying assumptions. These assumptions are further discussed by Harju et al. (2019) and Simon et al. (2014). In addition to the theoretical assumptions, the SMCDA model captures preference information of the DM. Thus, the DM's ability to elicit it is essential to guarantee that the SMCDA model describes the air surveillance capability properly.

The utilization of the SMCDA model in comparison of air surveillance capabilities between different scenarios is not possible. As the metrics depend on the scenario, e.g., altitudes and AOIs, they can be compared only within a single scenario. Hence, the total values of the spatial value function (5.1) does not represent the absolute worth of the alternatives.

The adverse effect model of the computational tool is fairly rough, as it only takes into account the shadowing effect of wind farms. Hence, it is likely to overestimate adverse effects of wind farms. On the other hand, the tool does not take into account other adverse effects, e.g., Doppler effects or clutter. Thus, it should be further developed to enhance the reliability of the SMCDA model and the comparison procedure.

8.2 Future work

The comparison procedure and the SMCDA model can be developed in several ways. First, underlying air surveillance goals, which provide the basis of modeling air surveillance capability should be considered explicitly. The goals are in this thesis assumed implicitly. Thus, they are not taken into account while the criteria of the air surveillance capability were selected. The explicit determination of the goals and justified selection of the criteria allow representing the capability more accurately according to the DM's judgment.

The computational tool can output several other metrics in addition to the three presented in Section 4.2. An example of such a metric is minimum observable RCS which determines the size of a target that can be observed with a probability of 80% on average. By selecting the criteria more carefully, the representation of the air surveillance capability is enhanced. On the other hand, the criteria do not need to be determined with the computational tool.

They can be provided by other models, real-life data or expert judgment. The utilization of such criteria should be considered. An example criterion that could be added to the SMCDA model is the costs of alternatives. Currently, the costs of compensation alternatives are not taken into account explicitly but only through the efficiency evaluation.

The comparison procedure does not consider contractors' ability to fulfill the cost, which is set as a condition for a project. That is, the cost of compensating adverse effects may be too high for the contractors. This issue is pointed out, e.g., by the study about wind farm production in Finland (Joensuu et al., 2021). Therefore, if it is known that the contractors' ability to pay does not exceed a certain limit, this should be considered while determining the budget of the compensation problem.

In this thesis, the comparison procedure and the SMCDA model are only demonstrated in an artificial scenario. In future work, more realistic scenarios should be considered. In these scenarios, alternative target types and altitudes should be addressed. Altitudes should be selected more carefully so that they represent the movement of the target types in the 3D airspace realistically. Additionally, utilizing varying AOIs at different altitudes should be examined. Moreover, the effect of lattice resolution should be considered. In addition to the aforementioned, solving the compensation problem with realistic the cost and cost structures could be studied.

Spatial preference information, i.e., the division of AOIs and spatial weights, is essential in presenting the air surveillance capability as a spatial quantity. To ensure that the spatial preference information can be elicited appropriately, real-life scenarios where, e.g., geographically important regions are explicit, should be analyzed. For example, the compensation task could be considered in a similar scenario presented by Harju et al. (2019), where clear differences in the importance of subregions arise.

The effect of identified adverse effect regions should be considered. That is, what kind of effect do small changes in the subregions have on, e.g., feasibility of alternatives. Furthermore, as spatial weights represent the relative importance of the subregions, their effect on the efficiency of alternatives should be assessed.

In addition to spatial preference information, the effect of altitude, target type and criterion weights, as well as the effect of CVFs, should also be examined. Furthermore, alternative elicitation methods and their effect on compensation recommendations could be considered. A similar study has been conducted by Virtanen et al. (2021) in the context of mental workload assessment in air combat. The use of incomplete preference information (see, e.g., Harju et al., 2019; Weber, 1987) in the SMCDA model should also be studied.

In this thesis, the air surveillance capability and adverse effects are determined utilizing the computational tool. To improve the credibility of results, the tool could be further developed. By taking into account that wind farms are not completely impenetrable and including Doppler effects, the reliability of metrics and, hence, the SMCDA model could be increased. Additionally, even though the wind farms are assumed fixed in this thesis, their modification tool should be enabled in the computational. For example, as discussed in Section 2.3, the coating of wind turbines and their blades with special materials has been suggested in multiple studies. Therefore, models for taking into account the alleviating effect of coating should be examined.

Alternative solution methods for the compensation problem could also be considered. The problem can be formulated as a portfolio optimization problem (see, e.g., Cranmer et al., 2018), where sensors are represented with binary decision variables determining the location of each sensor. The objective function could be the spatial value function (5.1) describing the air surveillance capability. The constraints could then be defined by available resources. Solving this problem would yield an optimal air surveillance system, i.e., collection of sensors and corresponding sites, that would maximize the air surveillance capability.

In addition to the determination of the best compensation alternative with respect to given wind farms, alternative ways to use the SMCDA model could be considered. For example, the SMCDA model and Phases 4 and 5 of the comparison procedure could be utilized for finding optimal wind farm layouts leading to the best possible power production or monetary profit. Additionally, a model where the goals of air surveillance authorities and wind farm contractors would be taken into account to find the mutually best solution. In this case, alternatives to be compared would consist of both alternative air surveillance systems and alternative wind farm layouts.

Chapter 9

Conclusions

This thesis studied the coexistence of air surveillance systems and wind farms. Wind farms cause emergence of adverse effects on air surveillance systems. To enable siting new wind farms, the air surveillance capability of a prevailing air surveillance system must be maintained. Therefore, if adverse effects are significant, they must be mitigated by modifying the air surveillance system. However, the mitigation causes costs for the air surveillance authority and there is no budget reserved to cover them. Yet, the modification costs can be designated for the contractors as a condition for the wind farm project. The goal of this thesis was to develop an approach to identify and assess adverse effects of wind farms on air surveillance systems and enable finding a compensation alternative with the best overall air surveillance capability.

To enable the coexistence of air surveillance systems and wind farms by mitigating adverse effects, this thesis formulated a spatial decision analysis problem. Solving this problem requires the evaluation of alternative air surveillance systems, i.e., compensation alternatives, based on their air surveillance capability. For this evaluation, a SMCDA model employing a spatial additive value function (see, e.g., Harju et al., 2019; Simon et al., 2014) and an existing computational tool was developed. With this model, the air surveillance capability of compensation alternatives can be quantified, and the adverse effects of wind farms can be identified and analyzed. Additionally, the thesis introduced a comparison procedure that enables the holistic comparison of the alternatives. It allows identifying an alternative that compensates adverse effects of wind farms and leads to the best overall air surveillance capability. The applicability of the procedure utilizing the SMCDA model was demonstrated with an illustrative example problem. Based on the example, the comparison procedure can be used to provide viable alternatives for compensating the adverse effects.

The existing literature presents several optimization, simulation and decision analysis models for wind farm siting and planning. These models aim at maximizing the benefit of wind farm contractors by optimizing production or profit. However, in this thesis, the wind farm siting is considered from the viewpoint of an air surveillance authority which is a novel approach. There are currently no approaches addressing the wind farm siting task which would consider possible modifications of existing infrastructure such as air surveillance systems. Planning the compensation of adverse effects of wind farms and comparison of compensation alternatives are not addressed in the existing literature. With the comparison procedure and the SMCDA model introduced in this thesis, alternative mitigation measures for adverse effects can be assessed and compared. This allows finding compensation alternatives that are viable from the viewpoints of both air surveillance authorities and wind farm contractors. Overall, the comparison procedure can be utilized to promote wind farm siting and to support the green transition mitigating the climate change such that the required air surveillance capability is preserved.

The comparison procedure does not only act as a tool for supporting the solution of the compensation problem. It can also be employed to expand knowledge on the adverse effects of wind farms and the efficiency of mitigation measures. The visualizations of the procedure can be utilized to communicate decisions transparently for wind farm contractors. Proper argumentation for the contractors increases trust in the judgment of an air surveillance authority and aids the planning of acceptable wind farm projects. The SMCDA model and the comparison procedure offer also versatile possibilities for future work regarding elicitation practices of preference information, description of compensation alternatives' cost structures and development of air surveillance models included in the computational tool.

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Appendix A

Initial air surveillance capability in the example problem

A.1 Performance metrics describing the air surveillance capability at 500 m

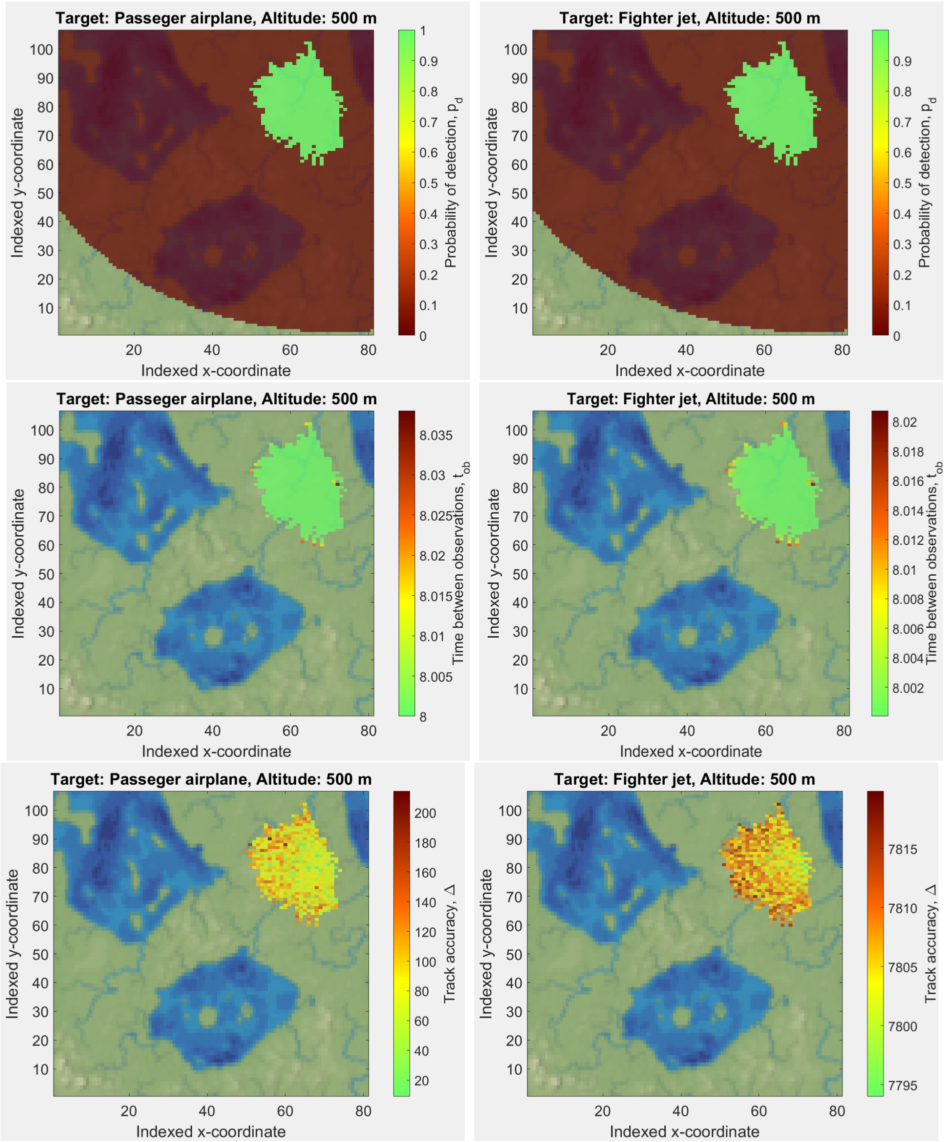

Figure A.1: Performance metrics describing the air surveillance capability of the reference alternative at 500 m. Each visualization presents a single metric with respect to either passenger airplane (left) or fighter jet (right).

A.2 Performance metrics describing the air surveillance capability at 3 000 m

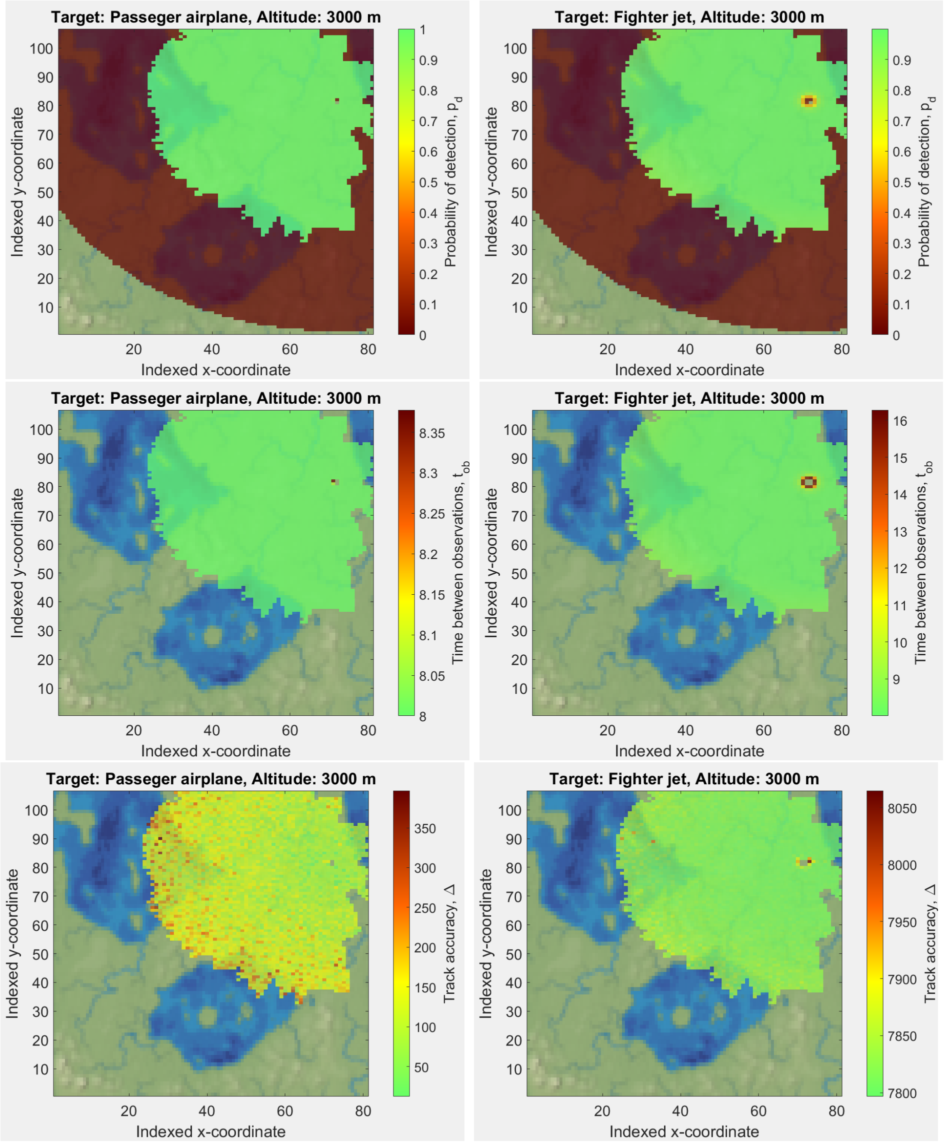

Figure A.2: Performance metrics describing the air surveillance capability of the reference alternative at 3000 m. Each visualization presents a single metric with respect to either passenger airplane (left) or fighter jet (right).

Appendix B

Adverse effect metrics of the example problem

B.1 Time between observations

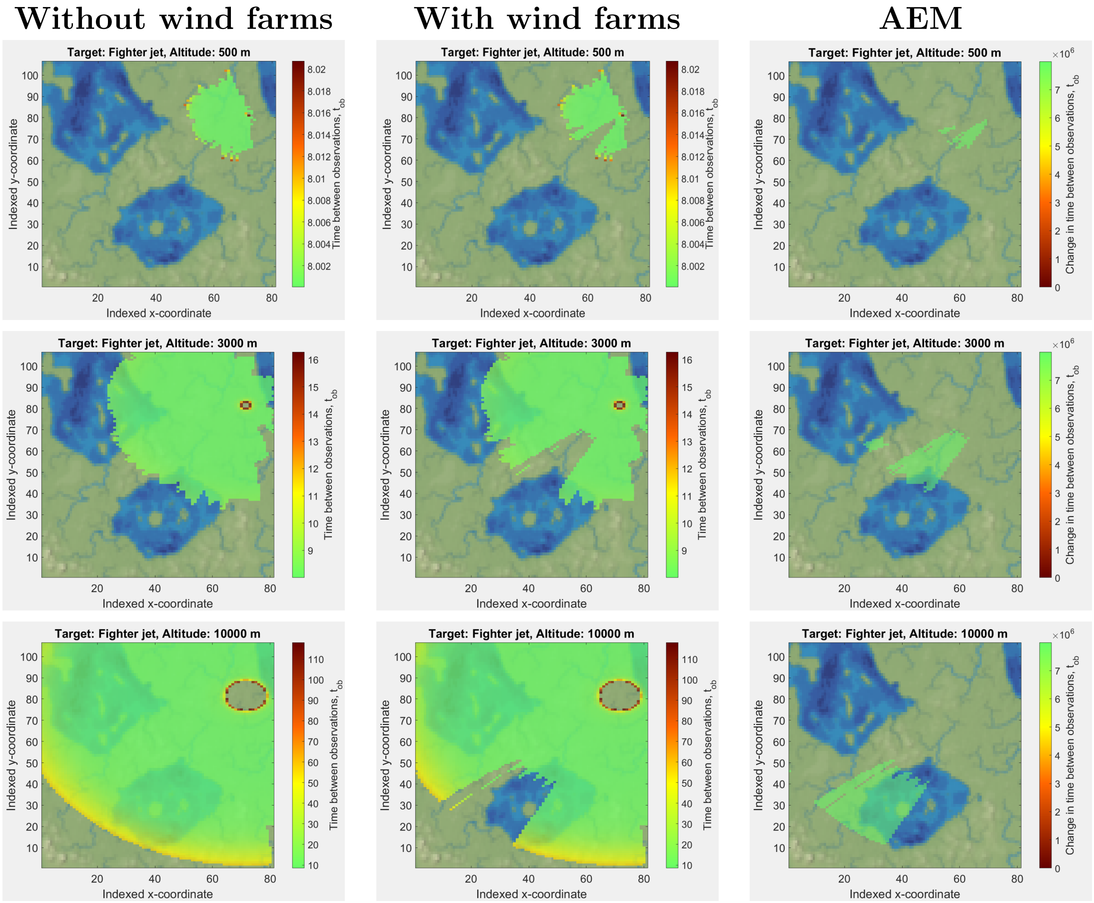

Figure B.1: AEMs of the time between observations t_{ob} against fighter jet at altitudes 500 m, 3000 m and 10 000 m (right), and t_{ob} of the initial air surveillance system without wind farms (left) and with the wind farms (middle).

B.2 Track accuracy

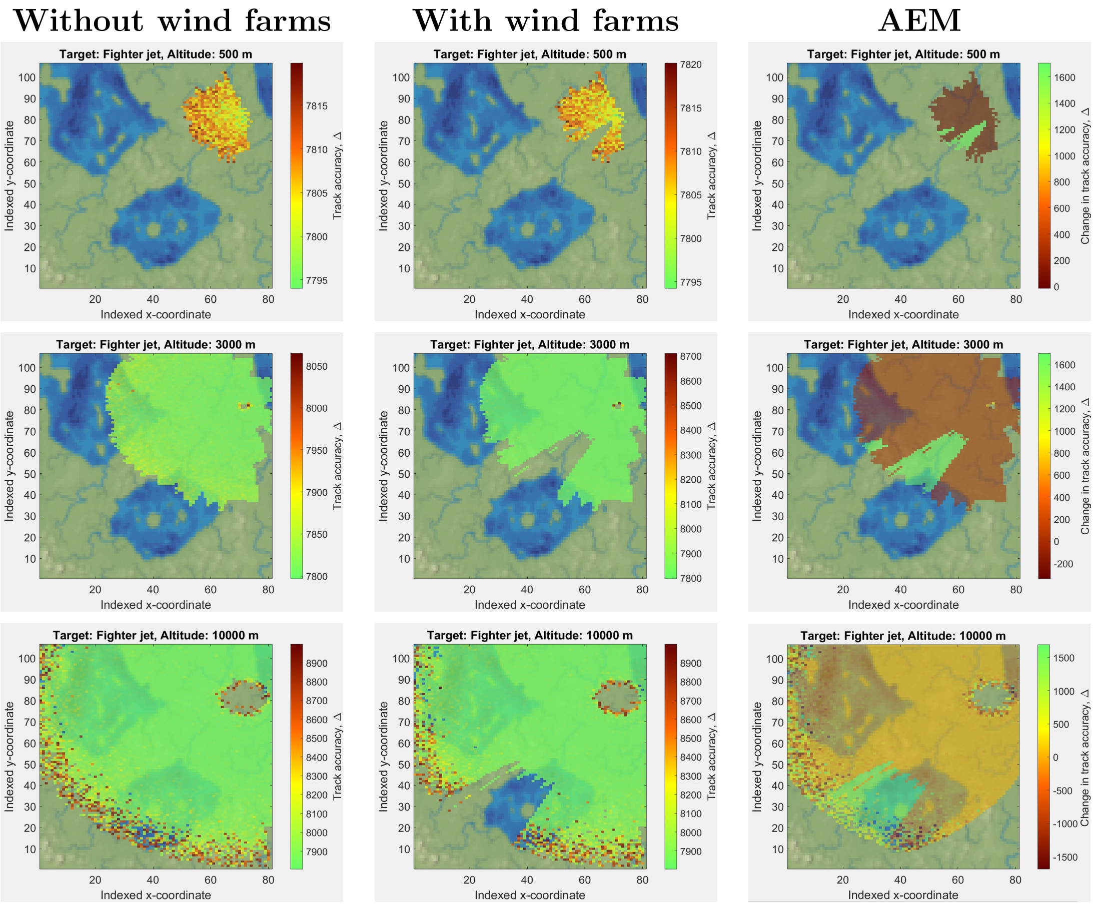

Figure B.2: AEMs of the track accuracy Δ against fighter jet at altitudes 500 m, 3000 m and 10 000 m (right), and Δ of the initial air surveillance system without wind farms (left) and with the wind farms (middle).