Evaluation of quality of air surveillance using spatial multi-criteria decision analysis

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Abstract

Air surveillance systems are designed to monitor airspace. The systems must be capable of fulfilling multiple objectives of surveillance established by a decision maker who oversees air surveillance. These objectives concern different targets and areas of the airspace, and their importance may differ. Hence, the evaluation of the quality of air surveillance is a challenging task. This thesis introduces a novel approach for assessing the quality of air surveillance through a spatial multi-criteria decision analysis framework. The framework takes into account the preferences of the decision maker on the objectives of surveillance and allows the assessment of the performance of air surveillance systems. Additionally, a new way to depict these objectives with air surveillance requirements is presented. The requirements describe the objectives with performance metrics of surveillance systems calculated with an existing computational tool. These metrics enable the framework to measure the fulfillment of the requirements. Moreover, the framework contains several other measures that allow for a more in-depth analysis of the requirements' fulfillment. The use of the framework is demonstrated with an example air surveillance planning problem. Based on the results of the example, the framework is a viable tool for comparing and ranking air surveillance systems. It provides an approach for the evaluation of air surveillance which is missing in the existing literature. Altogether, the framework offers a transparent and well-justified way to evaluate the quality of air surveillance which can be understood with limited knowledge of technical details of surveillance systems.

Keywords air surveillance, air surveillance requirement, multi-criteria decision analysis, spatial decision analysis

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Ilmavalvontajärjestelmillä tarkkaillaan ilmatilaa ilmavalvonnasta vastaavan päätöksentekijän asettamien tavoitteiden ohjaamina. Ilmavalvonnan tavoitteet koskevat tiettyjä ilmatilan osa-alueita, ja niiden tärkeys voi vaihdella. Näin ilmavalvonnan laadun kokonaisvaltainen arviointi on haasteellinen tehtävä. Tässä työssä kehitetään uusi spatiaaliseen monikriteeriseen päätösanalyysiin perustuva lähestymistapa ilmavalvonnan laadun arviointiin. Se mahdollistaa ilmavalvonnan tavoitteisiin liittyvien päätöksentekijän preferenssien huomioon ottamisen. Lisäksi työssä esitellään uusi tapa kuvata ilmavalvonnan tavoitteita ilmavalvontavaatimuksilla. Valvontavaatimukset perustuvat ilmavalvontajärjestelmän valvontakykyä mittaaviin suorituskykymittareihin, joiden arvot lasketaan olemassa olevalla laskentatyökalulla. Uusi päätösanalyyttinen lähestymistapa tarjoaa useita tunnuslukuja, joilla mitataan valvontavaatimusten täyttymistä eri näkökulmista. Sen hyödyntäminen ilmavalvonnan suunnittelun tuessa demonstroidaan ratkaisemalla esimerkkiongelma. Esimerkki osoittaa, että lähestymistapa on toimiva työkalu ilmavalvontajärjestelmien suorituskyvyn analysointiin ja vertailuun. Tämän tyyppistä spatiaaliseen päätösanalyysiin perustuvaa valvonnan suunnittelun tukikäytännettä ei ole aiemmin esitetty olemassa olevassa kirjallisuudessa. Kaiken kaikkiaan lähestymistapa mahdollistaa ilmavalvonnan laadunarvioinnin läpinäkyvällä ja perustellulla tavalla, joka on ymmärrettävissä ilman valvontajärjestelmien tekniikan tuntemista.

Avainsanat ilmavalvonta, ilmavalvontavaatimus, monikriteerinen päätösanalyysi, spatiaalinen päätösanalyysi

Preface

I would like to express my gratitude to my instructor and supervisor, Professor Kai Virtanen, for giving me the opportunity to undertake this thesis and for the chance to work in his team. I also want to thank Professor Virtanen for his invaluable mentorship throughout my thesis journey. His extensive guidance, dedication, and patience have been essential to the success of this project. Furthermore, I would like to thank my colleagues and friends at Aalto University for their support through all the good and challenging experiences over the years. And finally, I would like to thank my family for their unwavering support throughout my years at Aalto.

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Markus P. Virtanen

Contents

Abbreviations and Acronyms

AOI	Area of interest
ASR	Air surveillance requirement
SMCDA	Spatial multi-criteria decision analysis
MCDA	Multi-criteria decision analysis
CVF	Consequence value function
AVF	Additive value function
DM	Decision maker
ASP	Air surveillance picture
RCS	Radar cross section
NATO	North Atlantic Treaty Organization
EM	Electromagnetism
ARM	Anti-radiation missile

1 Introduction

Aerial surveillance is a critical component of national sovereignty. The capability of monitoring and controlling national airspace is crucial for nation's security and economic well-being as well as the enforcement of its laws and regulations. As the global security landscape continues to shift, marked by the rapidly changing geopolitical dynamics, the capability to secure national sovereignty, of which air surveillance is a core part, is ever more important. The changing geopolitical situation and thus increased importance of air surveillance have also been expressed by both the NATO's Secretary General Jens Stoltenberg (NATO, 2022) and the EU Institute for Security Studies (EUISS, 2022).

Surveillance of airspace is conducted with air surveillance systems which typically comprise electronic sensors, primarily radars. The sensors can be ground-based or airborne. Furthermore, air surveillance can also be conducted visually from an airplane. However, this thesis focuses solely on air surveillance systems that consist of ground-based, stationary sensors. For instance, a ground-based air surveillance system can consist of long-, medium- and short-range radars, along with passive sensors and visual air surveillance networks (Lehto and Lamberg, 2010). Such systems aim to detect, track, and identify a range of different objects, such as distinct aircraft and missiles (Melvin and Scheer, 2012; Öström et al., 2024). The observations and tracks of individual sensor systems are aggregated to create an air surveillance picture (ASP) (Shynar and Degen, 2000; Jylhä et al., 2017). This picture is used to aid decision making related to tasks such as locating and identifying targets, area defense, early warning, battlefield surveillance, and air policing (Pearson and Rocca, 2001; NATO, 2015; Finnish Air Force, 2024). Air surveillance tasks can focus on a specified area or the entire airspace under observation. Further, multiple tasks may be required to be conducted simultaneously in the same area or the tasks' areas may overlap. Hence, the air surveillance system must be capable of fulfilling potentially conflicting objectives of multiple tasks simultaneously.

A way to effectively evaluate the quality of surveillance produced by air surveillance systems as well as to compare and rank them is vital. Therefore, in this thesis, the planning problem of an air surveillance system is considered. The problem is formulated as follows. Firstly, there is a fixed number of ground-based radars, and feasible alternative locations exist for these radars. Additionally, there is a 3D area of interest (AOI) where the quality of air surveillance is evaluated. The goal of the problem is to find the air surveillance system that best fulfills the objectives of multiple air surveillance tasks while complying with constraints of the problem. To be more specific, the goal is to find the best placement option for the radars out of all the viable locations.

Solving the air surveillance planning problem requires a way of evaluating the quality of air surveillance accomplished with the ground-based radars within the AOI. The evaluation must account for multiple factors such as air surveillance objectives, as well as targets' characteristics and location. On the other hand, both the shape of flight vehicles and materials used in their construction affect the radars' capability to detect them. Furthermore, the radars have also a limited range, and they cannot detect targets if obstructed. Consequently, an increase in the number of radars capable of surveilling a location increases the quality of air surveillance in this location.

In this thesis, the performance of an air surveillance system consisting of several radars is evaluated using an existing computational tool (Lahti, 2022, Chapter 4). The tool takes an AOI, terrain, the type of a target, locations of radars, and their technical characteristics as inputs. It provides performance metrics that describe the system's performance in a 3D airspace. The metrics used in this thesis are the probability of detection, the time between observations, and the accuracy of track.

The thesis introduces a novel spatial multi-criteria decision analysis (SMCDA) (see, e.g., Harju et al., 2019; Simon et al., 2014; Malczewski and Rinner, 2015; Malczewski and Jankowski, 2020) framework for supporting the solution of the planning problem of an air surveillance system. Objectives of several air surveillance tasks are formally taken into account with air surveillance requirements (ASRs) dictated by the commander of the tasks. An ASR consists of a designated surveillance zone, a target type, quality statements regarding performance metrics, and priorities of ASRs under consideration. The surveillance zone describes the area concerning the task. The shape, direction and velocity of the target air vehicle are described by the target type. The quality statements determine how good values are demanded for the performance metrics to fulfill the task. Priorities represent the relative importance of ASRs. The SMCDA framework facilitates the evaluation of the capability of an air surveillance system to fulfill ASRs. The quality of air surveillance is then derived by aggregating the fulfillment of several ASRs. To evaluate the fulfillment of the ASRs, a spatial value function is developed. The fulfillment of an ASR measures how well the system can fulfill the required values for each performance metric defined by the ASR. Additionally, to visually represent the fulfillment of an ASR, a 2D value function is derived which describes the fulfillment of an ASR in 2D.

In the evaluation of an ASR's fulfillment, there might exist significant variation in how well the individual performance metrics meet the required values of the ASR. This is not accounted for in the assessment of the fulfillment of the ASR. Thus, the fulfillment of an ASR may look sufficient for the decision maker (DM), such as the commander of air surveillance, despite some of the values of performance metrics being low. This kind of shortcoming in the performance of the system is not desired. To measure this variation, a realization level function is introduced. The realization level function provides the realization level value which describes the percentage of the ASR's surveillance zone where each performance metric exceeds a certain threshold level. Furthermore, to visually represent the realization level value in 2D, a 2D realization level function is developed.

In order to take into account simultaneously several ASRs originating from the objectives of multiple air surveillance tasks, the fulfillment of individual ASRs are aggregated. The ASRs may have differing importances, and they are often contradictory in the sense that modifying the air surveillance system to fulfill one ASR better might result in lower fulfillment for another ASR. The evaluation problem resembles a multi-criteria decision making problem, where ASRs correspond to decision criteria. Thus, weights representing the importances of criteria, i.e., ASRs, are utilized. The criterion weights can be elicited from the DM using various techniques, such as Swing, tradeoffs, or pairwise comparisons (see, e.g., Pöyhönen and Hämäläinen, 2001). However, when defining ASR, only priorities that describe their ordinal importance are given. Hence, an ordinal weighting method should be used. In this thesis, weights for ASRs are derived with the centroid weights method (see, e.g., Ahn, 2011). To evaluate the quality of air surveillance, an additive value function (AVF) (see, e.g., Keeney and Raiffa, 1993) is used. In the AVF, ASRs correspond to attributes used in decision analysis models. The spatial value function, that measures the fulfillment of a single ASR, is the attribute-specific value function of the AVF. The ASRs' weights are utilized as the attribute weights. This AVF is referred to as the air surveillance quality function. Additionally, the realization level can be evaluated for each of the ASRs. A weighted sum can be calculated over the individual realization level values, which describes the average of the realization level values of ASRs. This average is referred to as the total realization level.

In the existing literature, spatial multi-criteria evaluation methods have been applied to numerous spatial problems, such as site search and selection problems, location-allocation problems, and suitability assessment of land (Jelokhani-Niaraki, 2021). However, there is a lack of literature related to the application of SMCDA methods in air surveillance. Currently, there exist only studies where multi-criteria decision analysis (MCDA) has been applied to radar technology and the use of radars. For example, MCDA has been applied to the performance optimization of phase array radars (Hull et al., 2018), and in the site selection of weather radars (Boudjemaa et al., 2019). Hence, this thesis supplements the existing literature by introducing a new framework for the evaluation, comparison and ranking of air surveillance systems.

Spatial problems can be classified as implicit or explicit (Malczewski and Jankowski, 2020). In spatially implicit problems, evaluation criteria involve spatial variability only in an indirect manner. Such criteria involve spatial relationships like proximity, adjacency, or contiguity. Conversely, in spatially explicit problems, evaluation criteria depend on the location and sometimes even time. SMCDA methods are capable of analyzing and modeling both spatially explicit and implicit problems (Malczewski and Jankowski, 2020). The performance metrics of the computational tool correspond to such spatially explicit criteria. Thus, SMCDA methods appear to be well-suited for addressing the planning problem considered in this thesis. A study by Harju et al. (2019) provides an example of a spatially explicit problem where SMCDA methods have been utilized. Here, an air defense planning problem with incomplete preference information is considered. The problem relates to finding optimal positions for air bases such that the air defense capability is maximized. The importance of various criteria is expressed through preference statements, which do not specify the exact weights of criteria but rather indicate the DM's ordinal preferences between the criteria leading to interval weights.

The application of the SMCDA framework is illustrated by solving an example air surveillance planning problem. The example demonstrates how the quality of air surveillance can be evaluated based on the system's ability to fulfill multiple ASRs. The framework provides a systematic, transparent, and well-justified way to evaluate the performance of air surveillance systems. It helps to identify potential shortcomings in system performance and allows the comparison of alternative systems whilst taking into account the preferences of the DM who is in charge of air surveillance.

This thesis is structured as follows. Chapter 2 discusses the basics of air surveillance and air surveillance systems. In Chapter 3, a computational tool for determining values of performance metrics is presented. Chapter 4 considers ASRs for measuring the fulfillment of air surveillance tasks. SMCDA means to assess the fulfillment of a single air surveillance requirement and to assess the fulfillment of multiple air surveillance requirements are introduced in Chapter 5 and Chapter 6, respectively. In Chapter 7, the use of the SMCDA framework is demonstrated by solving an example air surveillance problem. Finally, Chapter 8 concludes the thesis.

2 On the basics of air surveillance

Air surveillance is defined as the systematic observation of airspace by electronic, visual, or other means, with the primary purpose of identifying and determining the movement of aircraft and missiles in the airspace under observation (NATO, 2015). The monitoring of airspace is conducted using air surveillance systems, which primarily consist of radars. Modern radars are used to detect and track multiple different aerial vehicles simultaneously. To achieve this, radar systems utilize advanced electronics, compact antennas, phased arrays, and efficient signal processing. This allows them to achieve reduced response times, high accuracy, and low probability of false alarm. It also enables detection of unambiguous aerial vehicles, tracking at extended ranges, integration of multiple sensors (airborne, ground, and sea-based), and operations in different terrains. A more detailed description of the technical aspects can be found from, e.g. Khawaja et al. (2022).

The radar system surveils the airspace by transmitting and receiving radiofrequency electromagnetic (EM) waves. The system sends the EM waves towards the area under observation and receives back the EM waves when they are reflected by an object in the area. From the received signal, the radar system determines the range, position, and velocity of the targets. Additionally, the system produces a track on the target, describing its state as a function of time. An in-depth description of radar operations can be found from, e.g. Richards et al. (2010).

The air surveillance system conducts surveillance on an AOI with the system's different sensors. The observations of the sensors are used to create an air surveillance picture (ASP) of the AOI (Shynar and Degen, 2000). The generated ASP can then be used to support the DM overseeing the air surveillance, and to assist in different air surveillance tasks. Air surveillance tasks range from general to specific. The general tasks can include providing a picture of activity in the AOI along with locating and identifying targets in flight, while a specific task may encompass providing information of the air situation on a local area (Pearson and Rocca, 2001).

Air surveillance can also be divided into long, medium, and short-range surveillance. These different ranges of surveillance fulfill different objectives, including early warning and battlefield surveillance. Early warning refers to notifying about the launch or approach of any unknown weapons or weapons carriers. Battlefield surveillance refers to the systematic observation of a battle area to provide timely information and combat intelligence (NATO, 2015).

Air surveillance consists of detecting, tracking, and identification of different targets. Multiple different factors influence the system's capability in air surveillance, such as the type and altitude of the targets, weather conditions, along with the type and placement of sensors (Pearson and Rocca, 2001). The different types of air surveillance sensors vary in their range and capabilities to detect and track targets. The placement of the sensors also affects on the capability to observe airspace, as nonuniformity of the terrain can limit their range and create blind spots. The shape and material of a target determine its reflective power, which directly affects the capability of the surveillance systems to detect it (Singh, 2022). The altitude of the target effects also the ability of the surveillance systems to detect it, since radars' capability to detect targets at low altitudes is weak. Additionally, the atmospheric and weather conditions influence the air surveillance system's performance (Pearson and Rocca, 2001).

The air surveillance system's capability to survey the AOI and fulfill different tasks depends on multiple factors. The used sensors, their placement, terrain, and the target type are all factors. Additionally, different tasks emphasize different features of radars, such as detection or tracking. Thus, making the evaluation of the capability of an air surveillance system challenging. To enable the assessment of air surveillance systems, Chapter 3 introduces an existing computational tool for calculating metrics describing the performance of the system from different aspects. Chapter 4 introduces air surveillance requirements (ASRs) that provide a formal way of describing air surveillance tasks with performance metrics. The metrics facilitate the measurement of ASRs' fulfillment. Chapters 5 and 6 discuss various measures for both single ASR and multiple ASRs.

3 Performance metrics for air surveillance systems

This chapter outlines the process of using an existing computational tool (see Lahti, 2022) to determine the performance of an air surveillance system. The computational tool assesses the system's performance by calculating location-specific performance metrics. These metrics describe different aspects of air surveillance, such as probability of detection or accuracy of track.

The computational tool is composed of sensor models and a tracker model. The sensor models are responsible for representing and quantifying the performance of various sensor types, whereas the tracker model integrates data from these sensors to estimate a track of the target. The estimated track provides information about the target's position and velocity within the airspace, relying on simulated detections generated by the sensor models.

The performance of an air surveillance system is measured in a 3D space with respect to a predefined target type. The computational tool divides the airspace into small subareas where the calculation is conducted. The tool calculates performance metrics by analyzing one target type within a specific subarea at a time and provides the average result for the performance metric within that subarea. The calculation is performed for each subarea of the airspace. This produces a 3D representation of the performance metrics within the airspace for the predefined target type.

3.1 Computational tool

The computational tool considers the following inputs when calculating the performance metrics: a specified AOI, a target type, and an air surveillance system, as shown in Figure 1. The AOI represents the 3D area where the performance metrics are calculated and is defined by a horizontal 2D zone and an altitude interval. The target type defines an air vehicle with certain flight characteristics and a radar signature. The air surveillance system is defined by a combination of different radar types used and their placement. Besides these inputs, the effect of the terrain, curvature of the earth, and other geographical information are considered, as they affect the range of the sensors.

In the computational tool, a graphical user interface is used for the definition of the air surveillance system. The system is composed of different sensors located on the earth's surface or in the air. Each sensor has a predefined type which affects its range and performance. The location, sensor type, and other parameters are set by using the graphical user interface.

The target is characterized by attributes such as type, velocity, and flight direction.

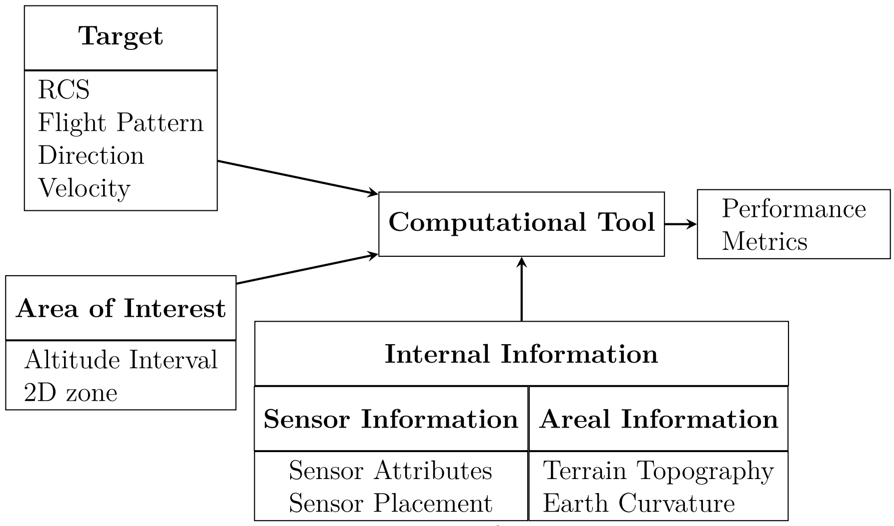

Figure 1: Inputs and outputs of the computational tool.

The size, shape, and material diminishing properties of the target are described by the target's radar cross section (RCS) model (Singh 2022, see also Väilä et al. (2017)). The RCS model represents the total reflection from the target to the observing sensor (Oh et al., 2022). Thus, it represents the target's effective size from the observing sensor's direction. The pattern, flight direction, and velocity constitute to the target's anticipated behavior and directly influence the sensor's detection capability. The target is defined via the graphical user interface of the tool.

In Figure 1, the computational tool is depicted as a 'black box'. The tool takes as input the data of the target, AOI along with internal information. The internal information consists of sensor information and areal information. The computational tool generates a matrix containing the values of the performance metrics within the AOI. Each cell of the matrix corresponds to a subarea of the AOI and contains the performance metrics of that subarea. The segmentation of the AOI into these subareas is demonstrated in Figure 2, where the AOI is divided into a 3D grid. Here, each grid cell corresponds to a matrix element. Each matrix element is the average value of the performance metrics at a subarea of the AOI. The size of the subareas is defined in the graphical user interface.

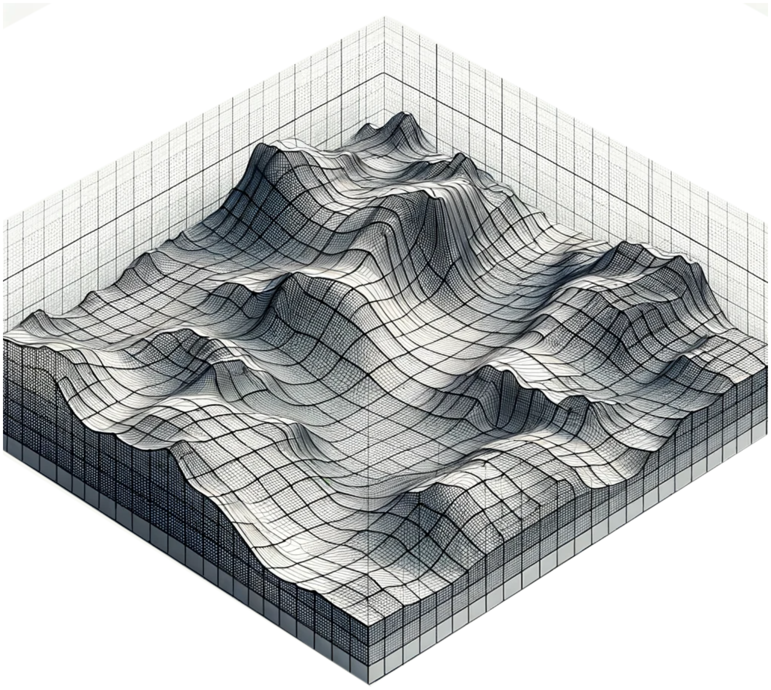

Figure 2: Segmentation of the area of interest into subareas.

3.2 Performance metrics

Examples of performance metrics for radars are presented in (Song et al., 2022) and (Ruotsalainen and Jylhä, 2017). In this thesis, the used metrics are the probability of detecting the target, the time interval between observations, and the precision of target tracking. Detailed information about the selected metrics, including their definitions and units, is provided in Table 1.

Table 1: Performance metrics of the computational tool used in this thesis.

Metric	Abbreviation	Unit	value interval	Description
Probability of detection	p_d	-	$[0, 1]$	The probability of detection of a target in a given location.
Time between observations	t_{bo}	s	$[0, \infty)$	The average time between observations of the target.
Accuracy of track	Δ_t	m	$[0, \infty)$	The average distance between the target's actual location and the estimation of the target's location.

The computational tool calculates the average value of each performance metric outlined in Table 1. The average values for the metrics in each subarea are influenced by all sensors within the subarea's range. The calculated values are utilized in the evaluation of the fulfillment of ASRs (see Chapter 4). Specific measures employed in the assessment are detailed in Chapters 5 and 6.

4 Requirements for measuring the quality of air surveillance

As discussed in Chapter 2, an air surveillance system consists of multiple sensors, which are used to observe the airspace (NATO, 2015). These observations are fused to create an air situation picture (ASP) (Shynar and Degen, 2000). The generated ASP is used to support the DM in charge of air surveillance with the required air surveillance decisions and tasks. Air surveillance consists of multiple tasks, which can be general or specific. A general task may be to provide a general situational awareness, while a specific task could be to provide sufficient surveillance to allow interception of hostile missiles. To address these varied tasks, distinct air surveillance requirements are established for the air surveillance system. These requirements can be different for each task and target. The difficulty of fulfilling the requirement is also determined by the air surveillance requirement. For further details on air surveillance tasks or requirements, see Pearson and Rocca (2001).

Multiple tasks and corresponding requirements may exist simultaneously. Additionally, the requirements may have varying levels of importance to the DM. Thus, evaluating a system's capability to fulfill multiple requirements simultaneously is challenging, as it must to take into account all of the requirements with varying importances. The evaluation of the fulfillment of all requirements concerning the system is referred to as the evaluation of the quality of air surveillance.

To define the requirements, metrics representing the performance of an air surveillance system are necessary. These metrics should also allow for the assessment of the extent to which requirements have been fulfilled. As detailed in Chapter 3, performance metrics representing the system's performance can be calculated using a computational tool. The metrics produced by the tool describe different aspects of air surveillance, thus, enabling the definement of requirements.

The objectives of the air surveillance tasks vary. Consequently, the desired value for a specific performance metric differs between tasks. For example, having a short time interval between observations is not as critical when the task's objective is detecting air vehicles far away. However, it becomes critical when the objective is to provide real-time information about airspace.

To evaluate the fulfillment of a requirement, it is essential to define desired levels for the performance metrics that describe the objectives of a task. Thus, the DM must determine appropriate values for the levels of a metric, which indicate when sufficient and insufficient performance is produced. The values describing sufficient and insufficient performance are subsequently referred to as the best and worst quality levels. Furthermore, the target type used in the computational tool affects the performance metrics, as seen in Chapter 3. Therefore, the DM may wish to define the best and worst quality levels for each target type separately.

In this thesis, the best and worst quality levels for a requirement are defined with a quality statement of performance. The quality statement is defined with a name and target type, as well as the worst and best quality levels for each performance metric. An example of a quality statement of performance is shown in Table 2. Here, two quality statements are defined. In both, the target type is 'fighter jet'. The performance metrics used are probability of detection (p_d), time between observations (t_{bo}) and accuracy of track (Δ_t). The unit of time between observations is a second and for the accuracy of track a meter. For each metric, an interval is stated where the first value defines the best quality value and the second value defines the worst quality value.

Table 2: Example of the quality statement of performance. The abbreviations p_d, t_{bo}, and Δ_t stand for the probability of detection, the time between observations, and the accuracy of track, respectively. The intervals of the performance metrics represent their best and worst quality values, denoted by [best quality value, worst quality value].

Name of the quality statement	Target	p_d	t_{bo}	Δ_t
F1	Fighter jet	[0.9, 0]	[8s,20s]	[150m, 400m]
F2	Fighter jet	[1, 0]	[2s,20s]	[40m, 400m]

To evaluate the fulfillment of a requirement, other aspects of a task besides the quality statement must also be accounted for, such as the surveillance zone and the priority of the task. Therefore, in this thesis, air surveillance requirements (ASRs) are defined with a surveillance zone, target type, quality statement, and priority. The surveillance zone refers to a 3D area concerning the ASR, specified by a 2D zone and an altitude interval. The target type refers to an air vehicle and is determined by its RCS, velocity, and flight direction. The priority depicts the relative importance of the task. ASRs are defined for each task and target type separately.

An ASR and its components are presented in Figure 3. The ASR describes a single air surveillance task and is used to measure its fulfillment. The fulfillment of a single ASR is measured with a spatial value function which is derived in Chapter 5. The chapter also introduces a realization level function that measures the area where the performance metrics exceed a minimum threshold level. Additionally, the chapter introduces other measures that allow for the visualization of both the fulfillment of an ASR and the realization level. These measures enable a more in-depth analysis of the fulfillment of an ASR. In Chapter 6, a measure for the air surveillance quality is detailed. The quality is evaluated with an air surveillance quality function by aggregating the fulfillment of individual ASRs. In the aggregation, the relative importance of ASRs is taken into account. In the chapter, a total realization level function is also derived, which capacitates the measurement of the average area where the threshold level is exceeded in multiple ASRs simultaneously. Moreover, measures enabling the visualization of the quality of air surveillance and total realization level are discussed.

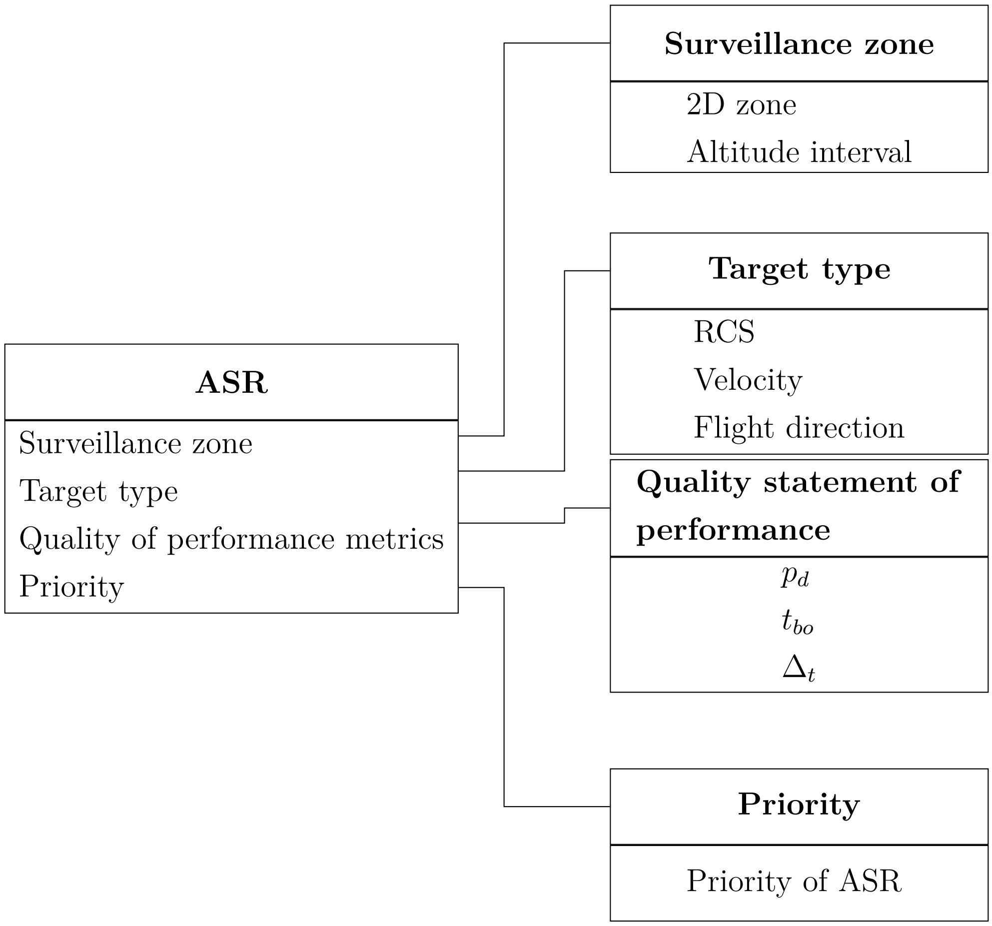

Figure 3: Definition of air surveillance requirement. The abbreviations p_d, t_{bo} and Δ_t stand for the probability of detection, time between observations and accuracy of track, respectively.

5 Assessing the fulfillment of an air surveillance requirement

This chapter introduces the spatial multi-criteria decision analysis (SMCDA) framework which is applied to assess the fulfillment of an ASR (see Chapter 4). The fulfillment of an ASR is evaluated based on the DM's preferences, facilitating a comparative analysis and subsequent ranking of various air surveillance system alternatives.

Within the SMCDA framework, different air surveillance system alternatives are evaluated using a spatial value function (Harju et al., 2019; Simon et al., 2014). The spatial value function evaluates the capabilities of each alternative and produces a commensurable value representing the extent to which the alternatives fulfill an ASR. Additionally, the SMCDA framework incorporates a spatial measure that aids in the assessment of air surveillance systems. The spatial measure enhances the evaluation process by providing location-specific insight into the fulfillment of an ASR.

The fulfillment of ASR measures how well the performance metrics produced by the air surveillance system fulfill the best quality levels for each performance metric. However, significant variations might exist between the metrics. Thus, the fulfillment of the ASR may seem sufficient to the DM despite some of the metrics having low values. This kind of shortcoming from the system is undesired. Thus, a measure is derived to evaluate the area where a minimum threshold level for each metric is exceeded. This measure is referred to as the realization level.

5.1 Fulfillment measure of an air surveillance requirement

In the SMCDA framework, an additive spatial value function is used for evaluating the capabilities of air surveillance systems to fulfill ASRs. The spatial value function is founded on the principles of an additive multi-criteria value function (Harju et al., 2019). In the evaluation, the spatial value function takes into account the preferences of the DM. It generates a commensurable value, enabling the comparison of different air surveillance alternatives. This value is referred to as the fulfillment value of a single ASR. The metrics derived from the computational tool, as detailed in Chapter 3, serve as the attribute values for the spatial value function.

The evaluation of the air surveillance system is considered within a specified surveillance zone which the DM determines. The surveillance zone is defined as a 3D space which the computational tool represents as a matrix. Each element in this matrix corresponds to the average values of the performance metrics in a specified 3D subarea of the surveillance zone.

The DM plays a critical role in the evaluation by directing it with her preferences and defining the ASR (see Chapter 4). The ASR outlines the conditions under which each performance metric reaches its best and worst quality levels for a given target type within the 3D surveillance zone. Consequently, it enables the assessment of its fulfillment.

The air surveillance systems' capability to fulfill ASRs is evaluated for each ASR separately. The air surveillance system alternatives are denoted with z_i, where i stands for ith system. The total number of alternatives is described with I and $i = 1, ..., I$. The 3D surveillance zone of the ASR is denoted with S and the target type with t. The 3D subareas of the surveillance zone are indicated by $s \in S$. The performance metric from the computational tool for the target t in subarea s is denoted by $z_i^t(s)^k$, where $k = 1, ..., K$ and K corresponds to the number of the performance metrics under consideration. The spatial value function $V(z_i^t)$ evaluates the alternative's z_i capability to fulfill the ASR within the surveillance zone S.

The spatial value function is defined as

$$V(z_i^t) = \sum_{s \in S} w_s \sum_{k=1}^{K} h_k u_k(z_i^t(s)^k), \tag{1}$$

where

- $z_i^t(s)^k$ are the consequences of the alternative z_i for target type t for performance metric k at 3D subarea s,
- u_k are the consequence value functions (CVFs),
- h_k are the criterion weights for the CVFs,
- w_s is the spatial weight for the 3D subarea $s \in S$.

The consequence value function (CVF) $u_k : \mathbb{R} \to [0, 1]$ represents the DM's judgment for a consequence $z_i^t(s)^k$, i.e., the value of performance metric k within a subarea s for a system z_i. Each of the metrics k has a unique CVF. The CVF maps the consequence to a unit interval reflecting the DM's preferences (Malczewski and Rinner, 2015). The unit interval denotes the desirability of the consequence for the DM on a commensurable value scale, where the value zero represents the least-desirable outcome and one the most-desirable outcome. The resulting values from the CVFs are called consequence values.

The shape of the CVF is defined by DM's preferences. The preferences are monotonic in the sense that improving a consequence for a metric in a subarea of the surveillance zone cannot make it less preferable (Harju et al., 2019). The shape of the CVF is defined by the DM for each ASR and metric separately, as each air surveillance task has different objectives. The CVF can be decreasing or increasing.

The number of performance metrics determines the amount of consequence values. In cases, where more than one performance metric is used the consequence values are aggregated to attain a value for the fulfillment of the ASR in a single subarea. This value belongs to the interval $[0, 1]$. The values one and zero represent the best and worst-case scenarios, where every consequence value in the subarea is one or zero. In the aggregation, weights h_k are used for CVFs. The weights represent the relative importance of performance metrics. They are non-negative and sum up to one.

The relative importance between subareas of the surveillance zone may vary for the DM. To account for this, spatial weights w_s are used, which allow for the consideration of geography-related preferences. All weights belong to the unit interval and sum up to one.

The output of the spatial value function $V(z_i^t)$ is called the fulfillment value of an ASR. It is a value from the interval $[0, 1]$ and represents how well the ASR is met. Value zero indicates that the air surveillance system does not yield any kind of fulfillment with respect to the ASR in the whole surveillance zone. Value 1 indicates that the ASR is fully met in the whole surveillance zone.

5.2 Visualization of the fulfillment of an air surveillance requirement

As explained in Section 5.1, the fulfillment of an ASR is measured with the spatial value function in Equation 1 which yields 'the fulfillment value of an ASR' from the interval $[0, 1]$. This measure describes the fulfillment of an ASR on the whole surveillance zone, but it does not describe the fulfillment spatially. Thus, in cases where the fulfillment value is not adequate for the DM, it does not assist in finding the subareas where the ASR's fulfillment is weak. Also, the fulfillment value of an ASR is not adequate for interpreting the distribution of the ASR fulfillment. Thus, a measure that takes into account the spatial elements is needed. The spatial measure introduced here is derived from the spatial value function and allows the DM to interpret the fulfillment of the ASR visually and locate the areas where the fulfillment is inadequate.

To visualize the fulfillment of an ASR a spatial measure named the 2D fulfillment value of an ASR is derived. The 2D fulfillment value is evaluated with the 2D value function. The 2D value function presents the ASR's fulfillment in 2D, thus allowing spatial interpretation of the fulfillment. The 2D value function is of form

$$V_{2D}(z_i^t, \hat{S}) = \sum_{s \in \hat{S}} \hat{w}_s \sum_{k=1}^{K} h_k u_k(z_i^t(s)^k), \tag{2}$$

where

- $\hat{S} \subset S$ is the set of 3D subareas located on the same horizontal location on the altitude interval,
- $\hat{w}_s$ are the normalized weights of the subareas $s \in \hat{S}$.

The 2D value function (2) takes as inputs the air surveillance system z_i^t and the set of 3D subareas $\hat{S}$. The subareas $s \in \hat{S}$ are aligned horizontally but vary vertically, hence forming a column through the surveillance zone's altitude interval. The measure outputs a '2D fulfillment value of a single ASR' on the unit interval which depicts the average fulfillment of the ASR over the altitude interval. The value is calculated by taking a weighted average of the fulfillment of individual subareas over the altitude interval. This may be carried out for the whole surveillance zone, yielding a 2D horizontal representation of the ASR's fulfillment. This allows interpretation of the fulfillment of the ASR in different areas of the surveillance zone.

Figure 4 shows an example of the 2D fulfillment values of a single ASR provided by the 2D value function overlaid on a map. The edges of the surveillance zone are illustrated with a red line. The radars are marked with green squares on the map. The 2D fulfillment values are color-coded such that the colors represent how well the ASR is fulfilled. Green corresponds with the 2D fulfillment value equaling one and grey with the 2D fulfillment value being zero. The figure illustrates that the ASR fulfillment diminishes with increasing distance from the radar system. Furthermore, the use of the 2D value function facilitates the identification of radar placements that are affected by visual obstruction due to the terrain. Such a phenomenon can be seen in the area marked by an orange square. The 2D fulfillment values drop to zero much closer to the radars within the area marked by the orange square, when compared to the other areas of the surveillance zone.

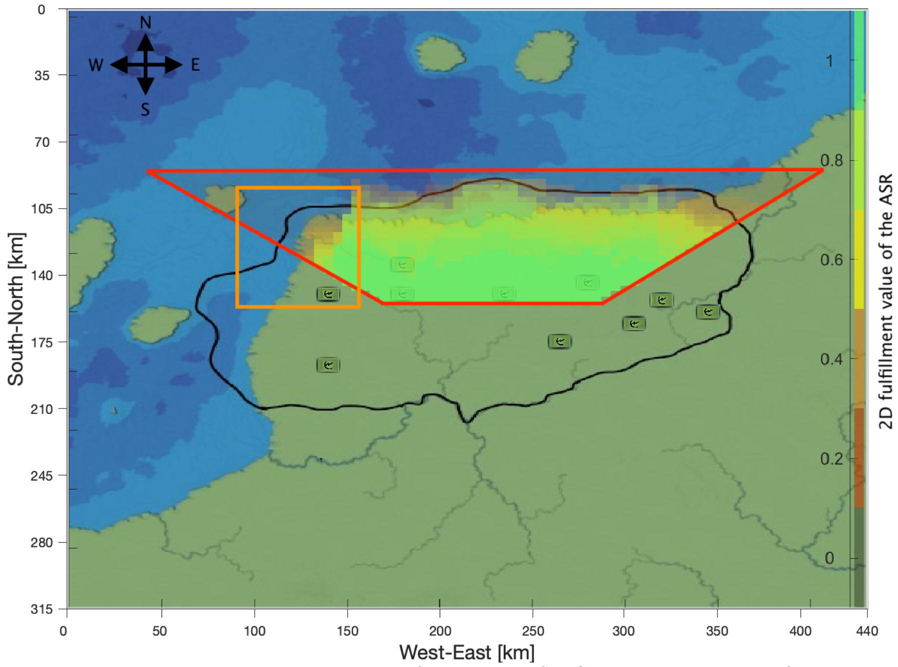

Figure 4: Example visualization of the 2D fulfillment value of a single ASR.

5.3 Realization level measures for an air surveillance requirement

The fulfillment value of an ASR provided by the function (1) and the spatial measure described in Section 5.2 evaluate the average fulfillment of the ASR. These measures describe how well the performance metrics of the system fulfill the best quality levels fixed in the ASR. However, there might exist significant variations between the consequence values of the performance metrics within a subarea. The variation may be significant even when the DM concludes the fulfillment of the ASR to be sufficient. This is because the fulfillment of the ASR is evaluated as a weighted average of the consequence values. Thus, even with a consequence value of zero for one metric, the fulfillment of the ASR may be adequate if the other consequence values are good. This kind of shortcoming in the fulfillment of the ASR is not desirable, as each metric describes a specific aspect of air surveillance. Thus, the information on the percentage of subareas exceeding a certain minimum threshold level for every performance metric is valuable for the DM.

To evaluate what percentage of subareas in the surveillance zone exceed a minimum threshold level, a realization level function is derived. The threshold level is denoted with δ. The function yields the realization level value that is the percentage of subareas s within the surveillance zone S where every performance metrics' consequence value exceeds the threshold level δ. The realization level function is of the form

$$r(z_i^t, \delta) = \frac{1}{N} \sum_{s \in S} \prod_{k=1}^{K} 1_{>\delta}(u_k(z_i^t(s)^k)), \tag{3}$$

where N is the number of subareas in the surveillance zone and $1_{>\delta}(u_k(z_i^t(s)^k))$ is an indicator function

$$1_{>\delta}(u_k(z_i^t(s)^k)) = \begin{cases} 1 & , \textit{if } (u_k(z_i^t(s)^k) \geq \delta \\ 0 & , \textit{else} \end{cases}. \tag{4}$$

Equation 3 depends on the air surveillance system z_i^t, the target type t, the surveillance zone S, and the threshold level δ. The chosen δ affects the realization level values considerably. When $\delta = 0$, the realization level value is one as even subareas that are out of the radars range have a consequence value of zero for each metric. The realization level value falls as δ increases. When the threshold level is equal to one, the realization level value is the percentage of subareas for which the quality of performance metrics are fully met.

The relationship between the realization level value and the threshold level δ is illustrated in Figure 5. The realization level is plotted as a function of δ. At $\delta = 0$, the realization level equals one. When δ is a small value greater than zero, the realization level value represents a percentage of the surveillance zone within range of the radars. In Figure 5, this value is approximately 0.58. As δ increases the realization level falls until $\delta = 1$ where it is approximately 0.18. Thus, approximately 18 percent of the surveillance zone fulfills the ASR completely.

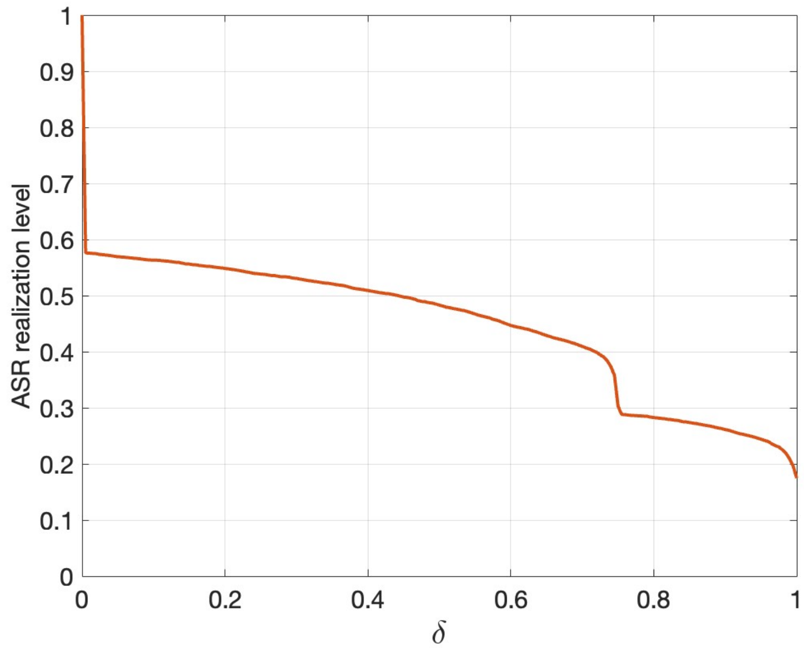

Figure 5: Example of the realization level value as a function of the threshold level δ.

The realization level informs the DM about the existence of subareas where the threshold level is not met, but it does not help the DM to locate these subareas. Hence, a spatial measure is derived to pinpoint such subareas. This spatial measure is called the 2D realization level value and is derived with the 2D realization level function. It enables the visualization of the realization level by creating a 2D representation of the realization level values. The 2D realization level values can be overlaid on a map in a similar manner to how the 2D value function depicts the ASR fulfillment.

The 2D realization level function is

$$r_{2D}(z_i^t, \delta, \hat{S}) = \frac{1}{N_{\hat{S}}} \sum_{s \in \hat{S}} \prod_{k=1}^{K} 1_{>\delta}(u_k(z_i^t(s)^k)), \tag{5}$$

where $N_{\hat{S}}$ is the number of subareas under consideration. The other symbols used in the equation are defined in Equations 2 and 3. The 2D realization level value represents the percentage of subareas $s \in \hat{S}$ where every performance metric exceeds the threshold level δ. The 2D realization value can be calculated for the entire surveillance zone and then overlaid on a map.

An example of the 2D realization level values for $\delta = 1$ is presented in Figure 6. The edges of the surveillance zone are indicated with a red line. The radars of the air surveillance system are described with green squares. The 2D realization level values are color-coded similarly to the 2D fulfillment values. Green corresponds with the best possible 2D realization level value and grey with the worst one. Thus, using the visualization, one can identify areas where the threshold level δ is achieved.

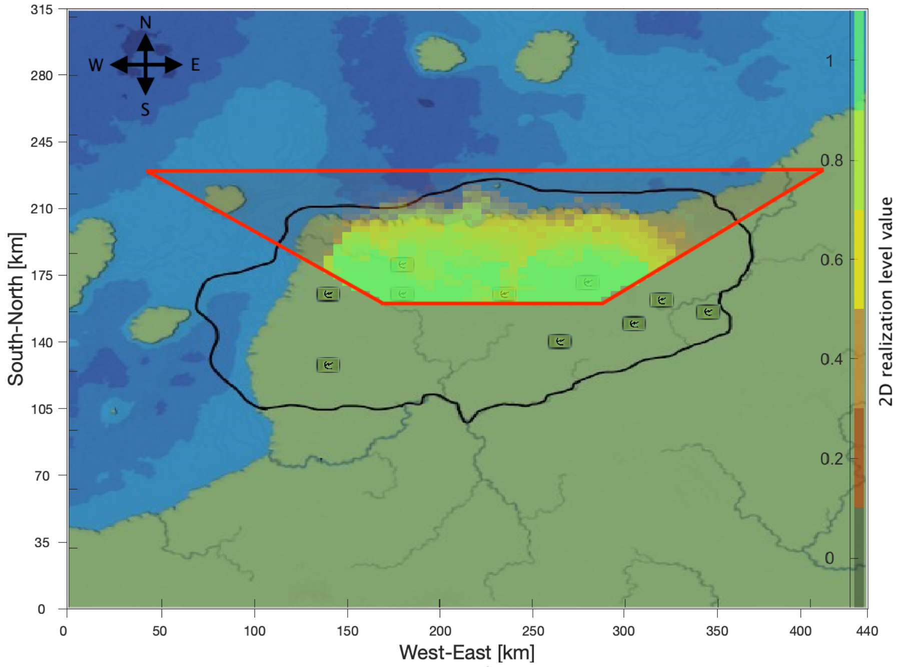

Figure 6: Example visualization of the 2D realization level values.

6 Assessing the fulfillment of multiple air surveillance requirements

Chapter 5 presented the SMCDA framework's measures related to a single ASR. However, DMs are not concerned only with a single ASR, as often multiple air surveillance tasks with different objectives are ongoing simultaneously. Thus, combining multiple ASRs is necessary for the DM to get a complete view of the quality of air surveillance. In this chapter, the framework's measures for evaluating the quality of air surveillance and the realization level of multiple ASRs simultaneously are derived. Additionally, visualization of these measures in 2D is discussed.

6.1 Relative importance of air surveillance requirements

The air surveillance systems must be capable of fulfilling multiple ASRs. However, the DM may not see all of the ASRs as equally important. Thus, the relative importance of ASRs must be taken into account in the evaluation. The relative importance of the ASRs are described with weights. There are multiple elicitation techniques for the weights, such as Swing, tradeoffs, or pairwise comparison (see, e.g., Pöyhönen and Hämäläinen, 2001).

The form of ASRs used in this thesis contains priorities describing their ordinal importance. Thus, an ordinal weighting method should be used. In this thesis, the weights are derived with the centroid weights method (see, e.g., Ahn, 2011). This method derives weights for the ASRs based on their ordinal importance. The weight of the ith most important ASR is

$$m_i = \frac{1}{I}\sum_{j=i}^{I}\frac{1}{j}, \tag{6}$$

where

- I is the number of ASRs,
- m_i is the weight of the ith ASR in the importance rank.

In cases where there are multiple ASRs with the same priority, they must have equal weights. The weights for such ASRs are derived by first taking a sum of the values yielded by Equation 6 for the ASRs. This sum is then divided by the number of ASRs with the same priority.

The weights derived with Equation 6 belong to the unit interval and sum up to one.

The ASR with the highest priority has the largest weight. The ASR with the lowest priority has the smallest weight.

6.2 Quality measure of air surveillance

The DM planning an air surveillance system may be concerned with multiple ASRs with differing importance. Thus, when evaluating the quality of the air surveillance system, the ASRs with their relative importance must be accounted for. To evaluate an air surveillance system with respect to multiple ASRs, an additive value function (AVF) is used (see, e.g., Keeney and Raiffa, 1993). The AVF is referred to as the air surveillance quality function. The ASRs represent attributes of the AVF and the spatial value function (1) serves as the attribute-specific value function. The attribute weights are derived from the ASR's priorities with Equation 6. The quality function yields the air surveillance quality value which is one of the SMCDA frameworks' measures.

The air surveillance quality function is

$$V_{total}(z_i) = \sum_{S \in A} m_S V(z_i^{t_S}, S), \tag{7}$$

where

- A is a set consisting of the 3D surveillance zones S defined by the ASRs under consideration,
- m_S are the weights of the ASRs given by Equation 6,
- t_S is the target type of the ASR under consideration in the surveillance zone S,
- $V(z_i^t, S)$ is the spatial value function (1) evaluated with air surveillance system z_i, target type t_S and surveillance zone S.

Equation 7 yields the air surveillance quality value from the unit interval. The air surveillance quality value represents how well the ASRs are fulfilled. Value one depicts a situation where all of the ASRs are fully met, and value zero portrays a situation where the fulfillment of every ASR is zero.

6.3 Realization level measures for multiple air surveillance requirements

As explained above, the quality measure of air surveillance is determined by aggregating the fulfillment values of multiple ASRs. This air surveillance quality value describes the average fulfillment over all of the ASRs. Inside these ASRs, there may be significant fluctuation between the consequence values for the air surveillance performance metrics. The realization level function and the corresponding value presented in Section 5.3, can be used to measure the percentage of subareas in the surveillance zone which exceed a threshold level δ set for consequence values. The realization level concept can be extended to measure how the threshold level is exceeded in multiple ASRs. The resulting measure is called the total realization level value and it is obtained with the total realization level function.

The total realization level is calculated by taking the weighted average of the realization level functions as well as realization level values for individual ASRs. Here, the threshold level δ remains the same for every ASR. The total realization level function is

$$R(z_i, \delta) = \sum_{S \in A} m_S r(z_i^{t_S}, \delta, S), \tag{8}$$

where

- m_s are the weights of the ASRs given by Equation 6,
- $r(z_i^{t_S}, \delta, S)$ is the realization level function (3) for air surveillance system z_i, target type t_S on surveillance zone S and threshold level δ.

The function (8) yields the total realization level value on the unit interval $[0, 1]$. The value zero represents the worst-case scenario where the realization level for every ASR is zero. The value one depicts the best-case scenario where the consequence values of every subarea of every ASR exceed δ. Similar to the realization level value of a single ASR, the total realization level can be plotted as a function of the threshold level δ. This allows the DM to examine the total realization level value for different threshold levels δ.

In Figure 7, the total realization level value is presented as a function of δ for given ASRs and their weights. The realization level is 0.7 when δ is close to zero. It declines gradually to nearly zero as δ approaches 1. Thus, there exist practically no subareas where any ASR is fully met, i.e., $\delta = 1$. Additionally, there is a steep drop in the total realization level value at $\delta \approx 0.67$. This drop indicates that the realization level value of multiple ASRs drops significantly when $\delta \approx 0.67$.

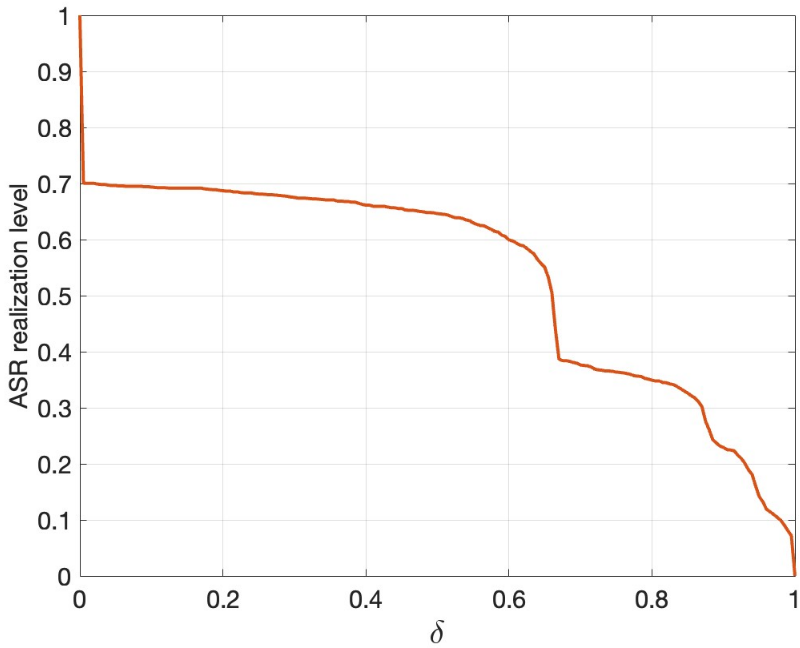

Figure 7: Example of the total realization level value as a function of the threshold level δ.

6.4 Visualization of the fulfillment of multiple air surveillance requirements

Equations 7 and 8 describe the quality of air surveillance and the total realization level with respect to multiple ASRs. These measures allow the DM to interpret the fulfillment of multiple ASRs and potential undesirable outcomes in the fulfillment. However, they do not provide a spatial depiction of the measures. The fulfillment of ASRs may considerably differ between the ASRs and their respective subareas. Similarly, the total realization level does not inform the DM about the exact location where the deficiency in fulfillment occurs. Therefore, spatial measures are necessary to enable the DM to interpret the ASRs' fulfillment and identify the areas where it is inadequate.

The air surveillance quality value can be visualized in a manner similar to the fulfillment of a single ASR. The idea is now that the 2D value functions as well as corresponding 2D fulfillment values for individual ASRs are averaged. This yields a measure called a 2D air surveillance quality value that can be visualized in 2D while taking into account all of the ASRs. The 2D quality value is obtained with the 2D air surveillance quality function. The evaluation is done over the altitude interval for one horizontal location at a time. In the evaluation, an average is taken over the subareas located on the AOI's altitude interval. For subareas that belong to multiple ASRs' surveillance zones, an average is also taken over the 2D fulfillment values.

The 2D air surveillance quality function is formally

$$V_{total2D}(z_i, \dot{S}) = \frac{1}{n} \sum_{\substack{\hat{S} \subset S \in A \\ \hat{S} \subset \dot{S}}} V_{2D}(z_i^{t_S}, \hat{S}), \tag{9}$$

where

- $\dot{S}$ is a set of 3D subareas of the AOI located on the altitude interval on the same horizontal location,
- $\hat{S} \subset S$ is the set of subareas of an ASR's surveillance zone which also belong to the set $\dot{S}$,
- A is the collection of the surveillance zones of the ASRs under consideration,
- $\hat{S} \subset S \in$ and $\hat{S} \subset \dot{S}$ is the set of subareas $\hat{S}$ of an ASR's surveillance zone S which also belong to the set of subareas under consideration $\dot{S}$,
- n is the number of ASRs with surveillance zones that intersect with $\dot{S}$,
- $V_{2D}(z_i^{t_S})$ is the 2D value function (2) for air surveillance system alternative z_t, target type t_S and 3D subareas $\hat{S} \subset S$.

In Figure 8, an example illustration of multiple ASRs simultaneously is presented. The AOI's borders are described with blue lines. The radars are presented with green boxes. The visualization allows the DM to interpret multiple ASRs simultaneously and detect areas where little or no fulfillment for an ASR or ASRs exist. The orange quadrangle represents an area where the fulfillment of ASRs is weak. Inside the area, the 2D air surveillance quality values are near zero, as seen by the color-coding of the results.

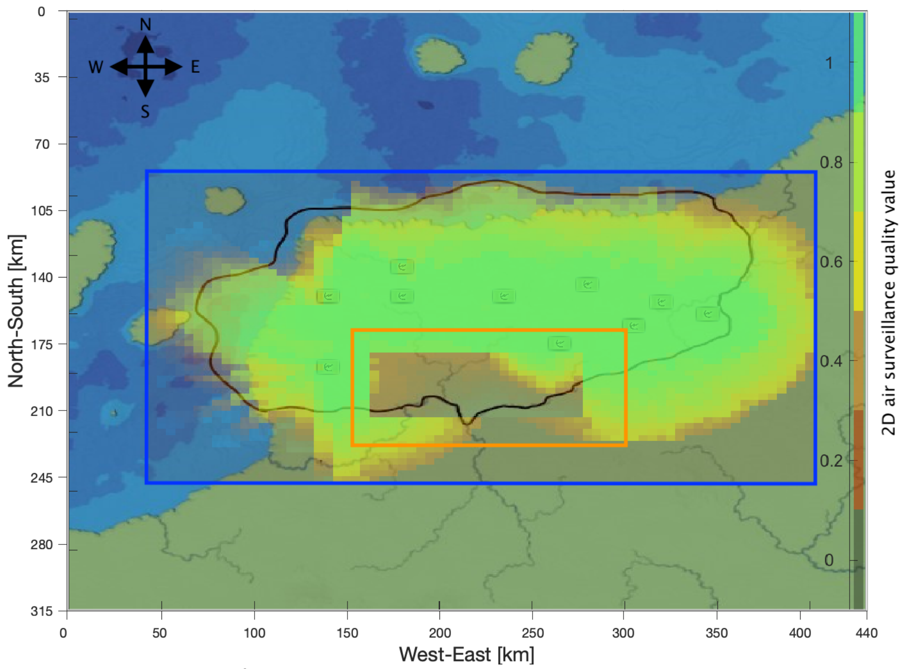

Figure 8: Visualization of the 2D air surveillance quality value taking into account multiple ASRs simultaneously.

The total realization level value can be represented in 2D similarly to the air surveillance quality value. The 2D visualizations of the total realization level values are referred to as the 2D total realization level values. These values can be derived with a modified version of Equation 9 where the 2D realization level function (5) is used instead of the 2D value function $V_{2D}(z_i^{ts})$. The 2D total realization level values can be visualized similarly to Figure 8.

6.5 Summary of measures for air surveillance requirements

Chapters 5 and 6 introduce various measures included in the SMCDA framework related to the fulfillment of ASRs. Some measures are associated with a single ASR, while others relate to multiple ASRs. Furthermore, some measures are averaged over the 3D surveillance zone, while others allow the evaluation to be presented in 2D. In addition, the measures can be classified based on whether they evaluate the fulfillment of an ASR or the area where the threshold level for an ASR is met. The variety of the measures ensures that the capabilities of an air surveillance system can be evaluated comprehensively and from multiple perspectives. A summary of these measures is provided in Table 3.

Table 3: Air surveillance measures of the SMCDA framework.

Function	**Measure**	**Description**
Spatial value function (1)	Fulfillment value of an ASR	Measures the fulfillment of the single ASR within the surveillance zone.
2D value function (2)	2D fulfillment value of an ASR	Depicts the fulfillment value of an ASR in 2D.
Realization level function (3)	Realization level value	Describes the percentage of subareas where every consequence value exceeds a minimum threshold level.
2D realization level function (5)	2D realization level value	Visualizes the realization level value in 2D.
Air surveillance quality function (7)	Quality value of air surveillance	Calculates a weighted average of the fulfillment of multiple ASRs under consideration.
2D air surveillance quality function (9)	2D air surveillance quality value	Enables the visualization of multiple ASRs in 2D.
Total realization level function (8)	Total realization level value	Measures the average realization level value of ASRs under consideration.

7 An example air surveillance planning problem

In this chapter, the SMCDA framework presented in Chapters 5 and 6 is used to solve an example air surveillance planning problem. The objective of this example is to demonstrate and validate the framework's use in the planning of air surveillance. Additionally, the practicality and relevance of the framework in a real-world context are discussed. In a real-world scenario, a DM is responsible for planning an air surveillance system. The framework is intended to facilitate the planning process by supporting the tasks and problem solving of the DM who is in charge of air surveillance.

7.1 Air surveillance system alternatives

In this example, an air surveillance planning problem of a country is tackled with the SMCDA framework. The imaginary country and its borders are presented in Figure 9. The borders are marked by a black line. The area depicted in the figure is of size 315 km x 440km.

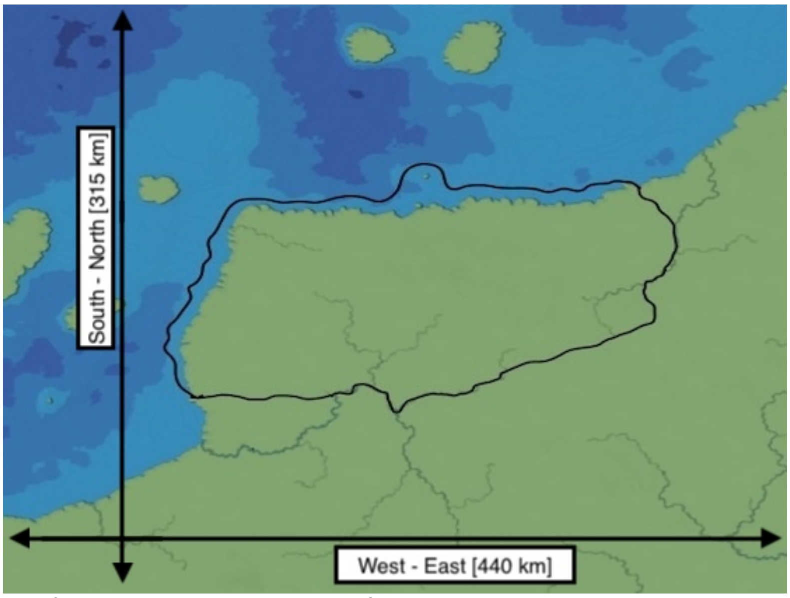

Figure 9: Map of the area in question for the surveillance problem. The country's border is depicted by a black line.

The country has 10 radar sensors with a limited number of feasible placement options. Based on these constraints, three air surveillance system alternatives – 'West', 'Neutral', and 'East' – have been designed. The alternatives differ in their radar placement. The air surveillance quality of the alternatives must be assessed to reveal which alternative is most capable of surveilling the airspace. The alternatives are evaluated and compared by their capability to fulfill ASRs. The ASRs used in this example are presented in Section 7.2.

The air surveillance system alternatives are presented in Figure 10. Each alternative consists of ten radars. Placements of radars are illustrated with colored boxes. The color of each box indicates the system to which the radar belongs. The air surveillance systems monitor the AOI. However, the alternatives differ in their focus inside the AOI. The difference in the focus affects the radar placement. The alternative 'West' emphasizes the west side of the AOI. It has five radar sensors on the west side of the country. These radars are indicated by red, yellow, and pink boxes in Figure 10. Alternatives 'Neutral' and 'East' have four and two radars on the western side of the country. These radars are indicated by blue, yellow, and pink boxes. Conversely, the alternative 'East' emphasizes the east side of the AOI. It has five radars on the east side of the country. These radars are indicated by green, yellow, and grey boxes. Alternatives 'Neutral' and 'West' have four and two radars on the country's western side. These radars are indicated by blue, grey, and red boxes. The alternative 'Neutral' is a balanced version of the other two alternatives and does not focus on either side of the country.

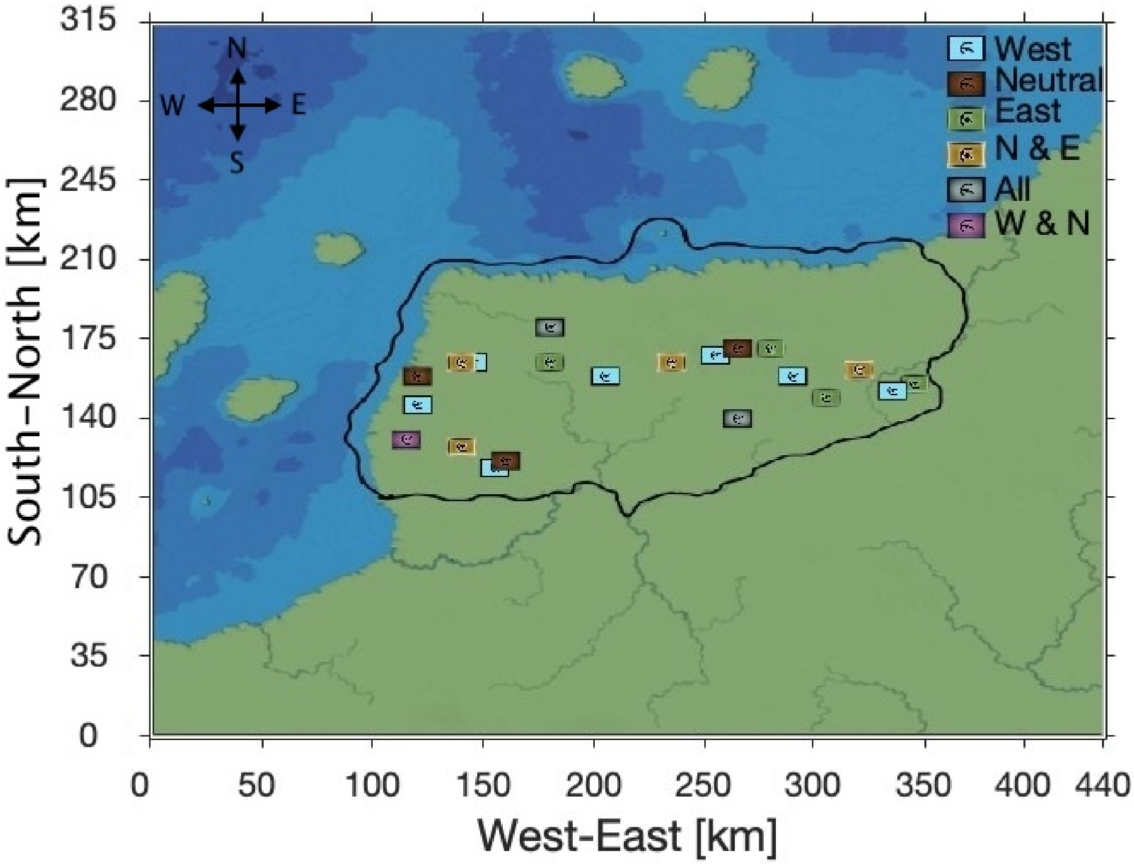

Figure 10: Radar placements of air surveillance system alternatives. The radars are depicted by colored squares. The radar's color depicts which system or systems it belongs to.

7.2 Air surveillance requirements

The air surveillance system alternatives are evaluated by their capability to fulfill multiple ASRs. In this example 11 ASRs are used and they are presented in Table 4. In the table, the ASR's name, 2D zone, altitude interval, target type, quality statement of performance, and priority are listed. The ASR's surveillance zone is defined by its 2D zone and altitude interval. The 2D zones are presented in Section 7.2.1.

There are three target types used in the ASRs: 'airliner', 'fighter jet', and 'helicopter'. The DM's preferences concerning the performance metrics are described with the quality statements of performance which are presented in Section 7.2.2. The priority refers to the ordinal ranking of the ASRs and is used to derive the weights of the ASRs. An ASR with a priority of 1 is the most important, and an ASR with a priority of 7 is the least important. The weights derived from the priorities are shown in Section 7.2.2.

Table 4: Air surveillance requirements.

Air surveillance requirements					
Name of ASR	**2D zone**	**Altitude interval**	**Target type**	**Quality statement of performance**	**Prio-rity**
North Airliner	North	7-13 km	Airliner	A1	7
North Fighter jet	North	1-15 km	Fighter jet	F1	6
East Fighter jet	East	1-15km	Fighter jet	F1	4
East Airliner	East	5-13 km	Airliner	A2	5
South Airliner	South	7-13 km	Airliner	A2	2
South Fighter jet	South	1-15 km	Fighter jet	F2	1
West Fighter jet	West	1-15 km	Fighter jet	F1	4
West Airliner	West	2-10 km	Airliner	A1	5
Central Fighter jet	Central	1-6 km	Fighter jet	F3	1
Central Helicopter	Central	100-1000 m	Helicopter	H1	2
Central Fighter jet 2	Central	100-1000 m	Fighter jet	F3	3

7.2.1 Area of interest and surveillance zones

The AOI considered in this example is presented in Figure 11 in 2D. The AOI's borders are described with blue lines. The AOI is divided into five surveillance zones which are used for defining ASRs. The altitude intervals which are used with the surveillance zones to define ASRs are presented in Table 4. Four of the zones focus on the different directions, and the fifth zone focuses on the center of the AOI. Some of the zones overlap. The zones are presented on a map in Figures 12 – 16, where their borders are illustrated with a red line. Figure 12 shows the northern zone. In Figures 13, 14 and 15, the eastern, southern, and western zones are presented. In Figure 16, the central zone which focuses on the center of the AOI is depicted.

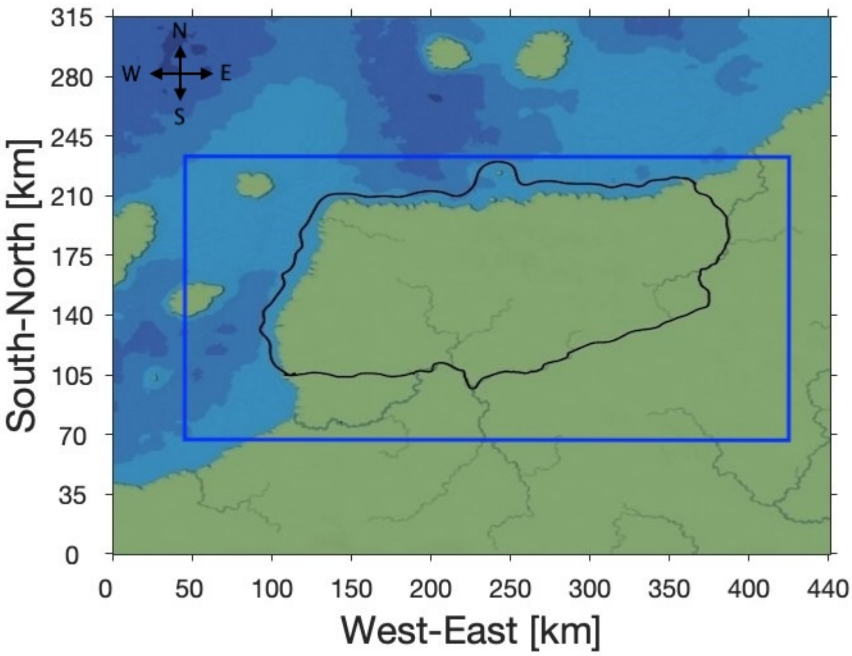

Figure 11: AOI depicted with a blue line.

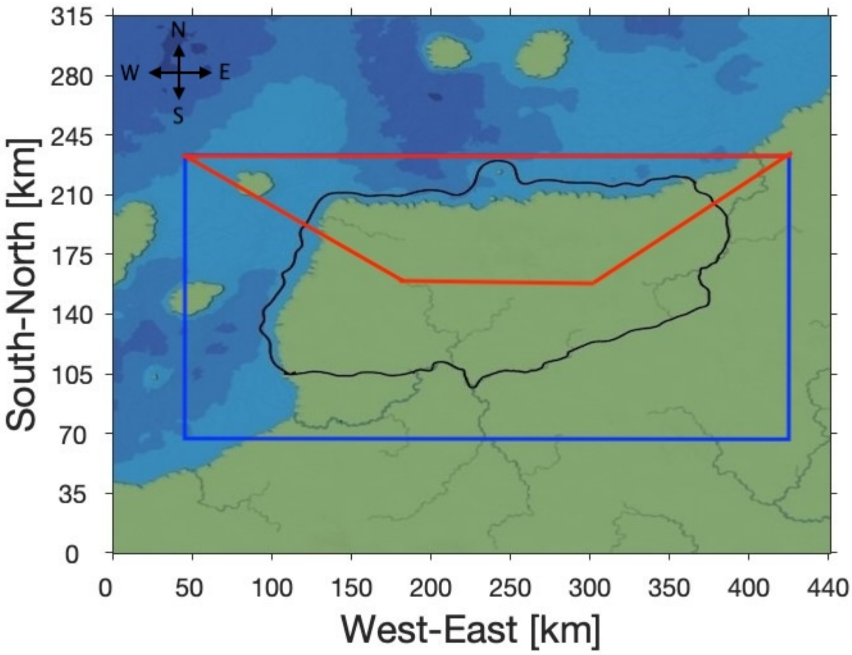

Figure 12: Borders of the northern zone are depicted with a red line. The AOI is depicted with a blue line.

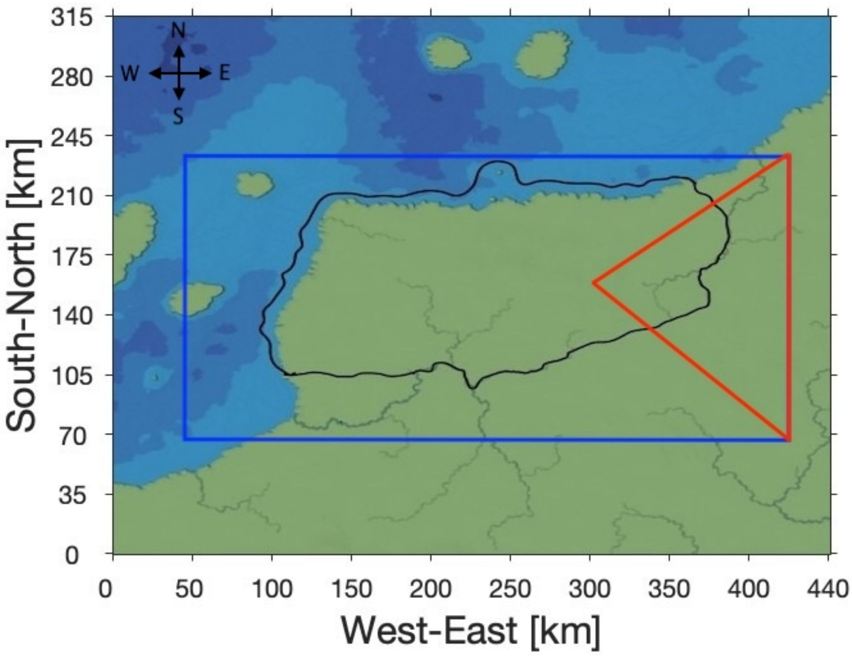

Figure 13: Borders of the eastern zone are depicted with a red line. The AOI is depicted with a blue line.

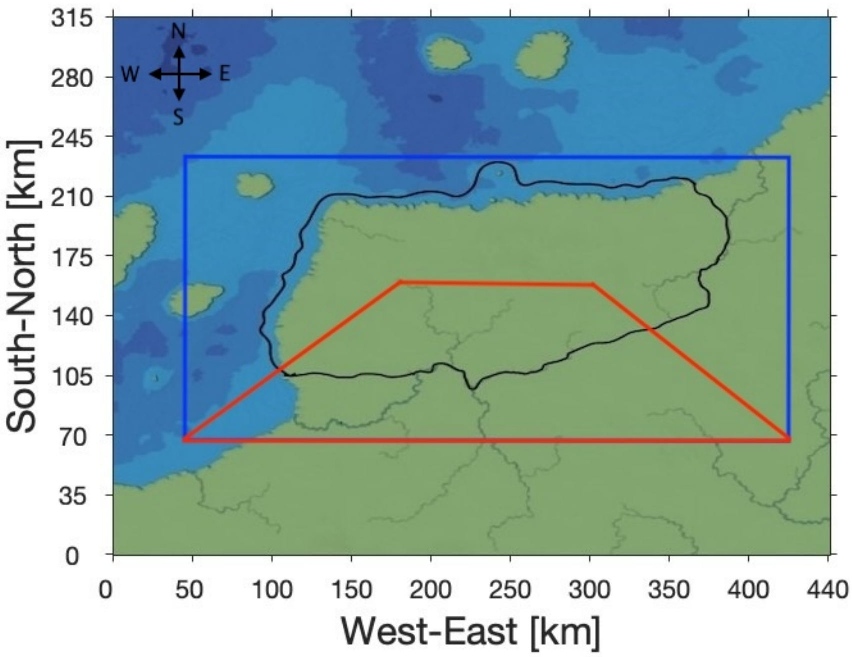

Figure 14: Borders of the southern zone are depicted with a red line. The AOI is depicted with a blue line.

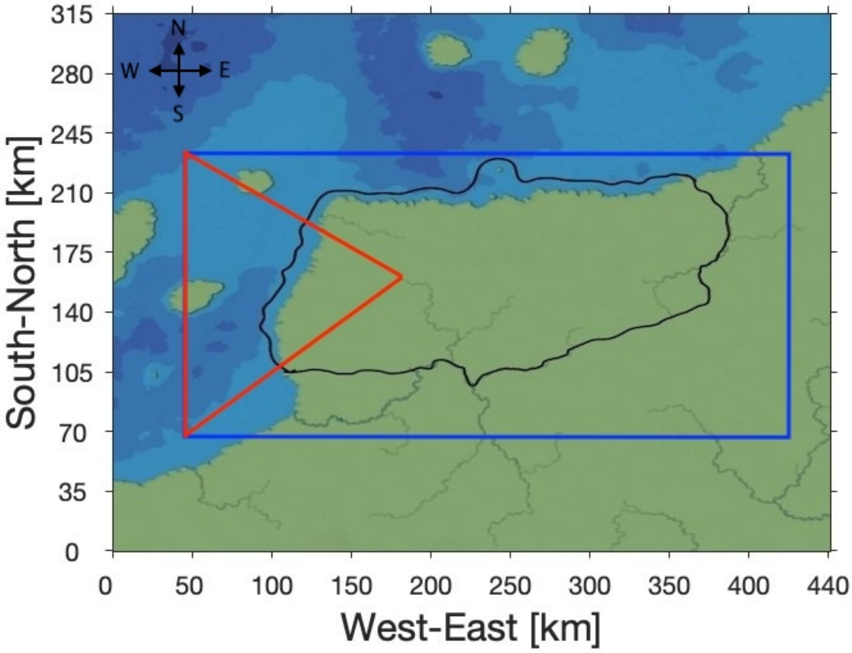

Figure 15: Borders of the western zone are depicted with a red line. The AOI is depicted with a blue line.

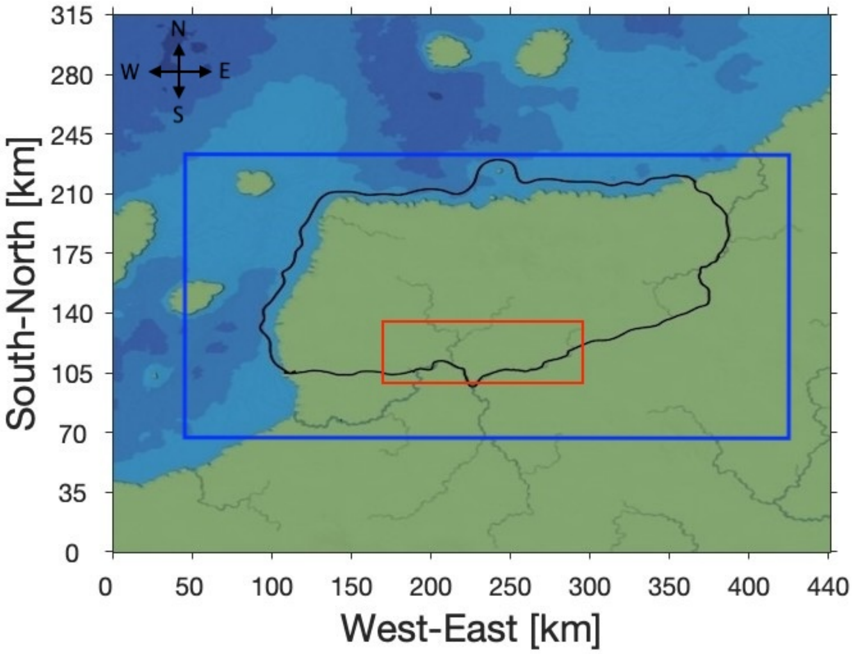

Figure 16: Area of the central zone is depicted with a red line. The AOI is depicted with a blue line.

7.2.2 Consequence value functions and weights

This chapter presents the quality statements of performance and the weights for ASRs. The quality statements are used to derive CVFs. These statements describe the values for each performance metric where the best and worst consequence value is attained.

These values are called the best and worst quality levels. The statements are defined for each target type separately. A target type may have multiple quality statements as objectives between ASRs differ.

In Table 5, the quality statements, denoted by F1, F2 and F3, for target type 'fighter jet' are presented. The best quality level defined in F2 for each performance metric is higher than in F1. The same applies to each performance metric of F3 when compared to F2. The quality statements for target types 'airliner' and 'helicopter' are shown in Tables 6 and 7. The target type 'airliner' has two quality statements named A1 and A2. The best quality level for every performance metric in A2 is higher than in A1. The target type 'helicopter' has one quality statement H1.

Table 5: Quality statements of performance for the target type 'fighter jet'. The abbreviations p_d, t_{bo} and Δ_t stand for the probability of detection, time between observations, and the accuracy of track, respectively.

Name of the quality statement	Target	p_d	t_{bo}	Δ_t
F1	Fighter jet	[0.9, 0]	[8s,20s]	[150m, 400m]
F2	Fighter jet	[0.95, 0]	[6s,20s]	[100m,400m]
F3	Fighter jet	[1.0, 0]	[2s,20s]	[40m, 400m]

Table 6: Quality statements of performance for the target type 'airliner'. The abbreviations p_d, t_{bo}, and Δ_t stand for the probability of detection, time between observations, and the accuracy of track, respectively.

Name of the quality statement	Target	p_d	t_{bo}	Δ_t
A1	Airliner	[0.85, 0]	[12s,20s]	[200m, 400m]
A2	Airliner	[0.90,0]	[4s,20s]	[80m,400m]

Table 7: Quality statement of performance for the target type 'helicopter'. The abbreviations p_d, t_{bo}, and Δ_t stand for the probability of detection, time between observations, and the accuracy of track, respectively.

Name of the quality statement	Target	p_d	t_{bo}	Δ_t
H1	Helicopter	[0.95, 0]	[4s,20s]	[80m, 400m]

CVFs describe the consequence value of a performance metric for an ASR. The CVFs used in this example are linear. Defining a non-linear or piecewise linear CVF would require more in-depth knowledge of air surveillance and radar technology. Since the CVFs are linear, the best and worst quality levels define the shape of the CVF. The definition of the CVF by quality statements is demonstrated for the target type 'fighter jet'. The quality statements used are F1 and F3. The CVFs obtained with other quality statements are not presented, but they are linear and the performance metric values for which the CVFs yield one and zero are determined according to the quality statements in Tables 5, 6 and 7. Figures 17-19 present the CVFs for all the performance metrics defined by the quality statements F1 and F3 given in Table 5.

In Figure 17, the CVFs defined by the quality statements F1 and F3 for the performance metric p_d are plotted over interval $[0, 1]$. For both CVFs, the worst quality level is the same, i.e., $p_d = 0$. The best quality level is set in F1 as $p_d = 0.9$. This is lower than the best quality level $p_d = 1.0$ specified in F3. The lower best quality level of F1 results in a sharper slope for the CVF when compared to the CVF defined by F3. Thus, the CVF determined by F3 requires a higher performance metric value to attain the same consequence value as compared to the CVF defined by F1.

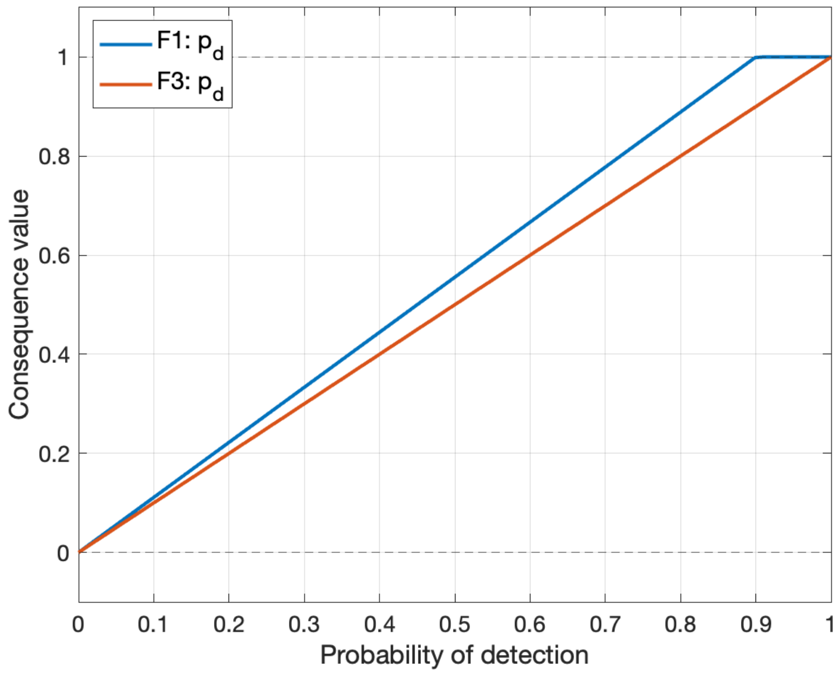

Figure 17: CVFs for the probability of detection defined by quality statements F1 and F3.

In Figure 18, the CVFs defined by quality statements F1 and F3 for time between observations are plotted over interval $[0s, 30s]$. The worst quality level is associated with $t_{ob} = 20s$ in both F1 and F3. The best quality level is obtained with $t_{ob} = 8s$ in F1 and $t_{ob} = 2s$ in F3. Thus, the slope of the CVF described by F1 is sharper than that of F3.

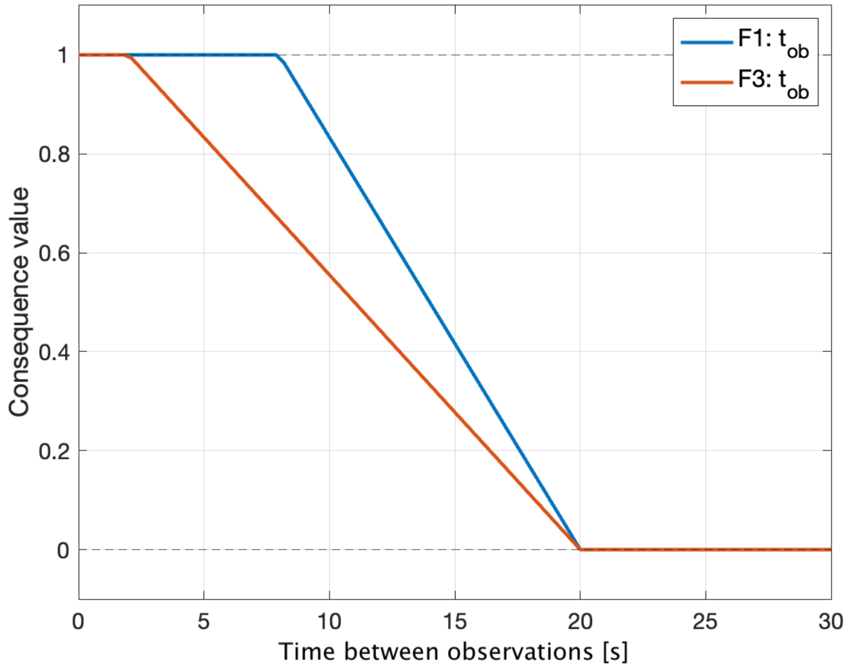

Figure 18: CVFs for the time between observations defined by the quality statements F1 and F3.

The CVFs determined by the quality statements F1 and F3 for the accuracy of track are illustrated in Figure 19. The CVFs are plotted over interval $[0m, 500m]$. The worst quality level is set as $\Delta_t = 400$m in both F1 and F3. The best quality level is specified as $\Delta_t = 150$m in F1 and $\Delta_t = 40$m in F1. The slope of the CVF determined by F1 is steeper than that of F3, as the best quality level of F3 is more demanding.

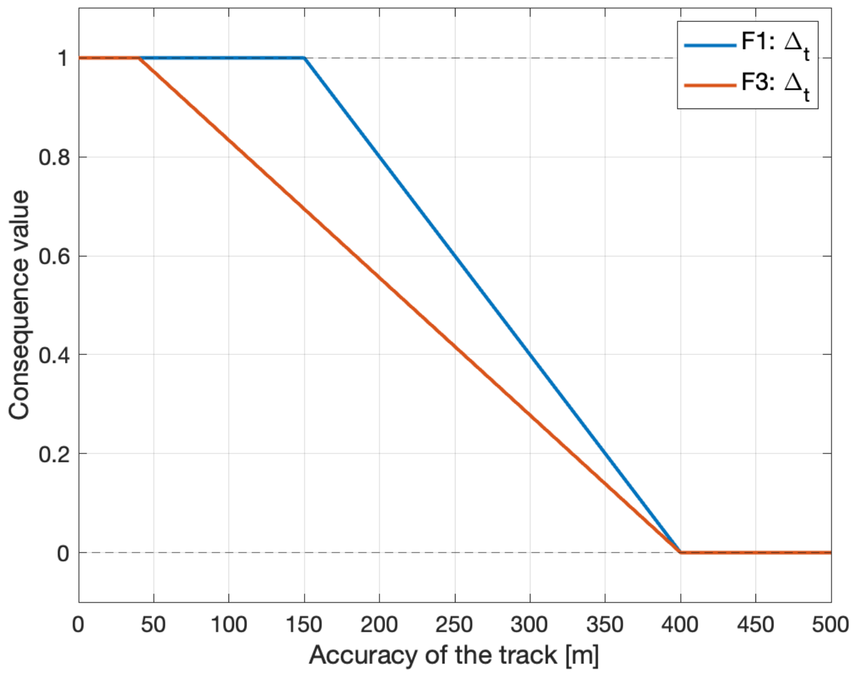

Figure 19: CVFs for the accuracy of the track defined by the quality statements F1 and F3.

In this example, the weights used for the CVFs are uniform. The spatial weights used within the ASRs' surveillance zones are also uniform. The only non-uniform weights are the weights representing the priorities of the ASRs. In Table 8, the priorities and weights are presented. The priorities represent the ordinal importance of the ASR defined by the DM in the ASRs. ASRs with the same priority are seen as equally important. The weights for the ASRs are derived with the centroid weights method which was introduced in Section 6.2.

Table 8: Weights used for the ASRs.

Name of ASR	Priority	Weight
North Airliner	7	0.0083
North Fighter jet	6	0.0174
East Fighter jet	4	0.0594
East Airliner	5	0.0331
South Airliner	2	0.1230
South Fighter jet	1	0.2291
West Fighter jet	4	0.0594
West Airliner	5	0.0331
Central Fighter jet	1	0.2291
Central Helicopter	2	0.1230
Central Fighter jet 2	3	0.0851

7.3 Comparison of the air surveillance systems

In this chapter, the air surveillance system alternatives are evaluated and compared with the SMCDA framework. The first subsection focuses on evaluating the alternatives' capability to fulfill ASRs. The second subsection deals with the realization level values of the alternatives and how they relate to the fulfillment values.

7.3.1 Air surveillance systems' capability to fulfill air surveillance requirements

The air surveillance system alternatives are evaluated by assessing their fulfillment values of ASRs. The ASRs are presented in Table 4. The evaluation is carried out with Equations 7 and 1. The performance metrics for the alternatives are calculated by a computational tool presented in Chapter 3. The weights representing ASRs' ordinal importance are presented in Table 8.

Table 9 presents the air surveillance quality values of the air surveillance system alternatives. The values indicate that the best alternative is 'Neutral'. The system 'West' has also a good quality value, with only a minuscule difference from the alternative 'Neutral'. Conversely, the system 'East' is the worst alternative, with its quality value being significantly lower than others. Thus, the alternative 'West' seems to be best suited for the air surveillance planning problem out of the alternatives.

Table 9: Air surveillance quality values of the air surveillance system alternatives.

Air surveillance system	West	Neutral	East
Quality value of air surveillance	0.5479	0.5563	0.4772

Results in Table 9 describe the alternatives' quality of air surveillance, but they do not indicate what factors contributed to the differences between the quality values. One way to depict the differences between the alternatives is to visualize the air surveillance quality. In Figures 20-22, 2D air surveillance quality values are presented for each alternative. Areas where significant differences are noticeable are marked with red, orange, and blue quadrangles. The areas are located on the western side of the AOI or within the western side of the central zone. The alternative 'Neutral' has better 2D quality values than the other alternatives on the northwest side of the AOI. This area is indicated by the blue quadrangle. The alternative 'East' is worse than the other alternatives in the area defined by the red quadrangle. The alternative 'West' has a better 2D quality value compared to the other alternatives on the west side of the central zone, as highlighted by the orange quadrangle.

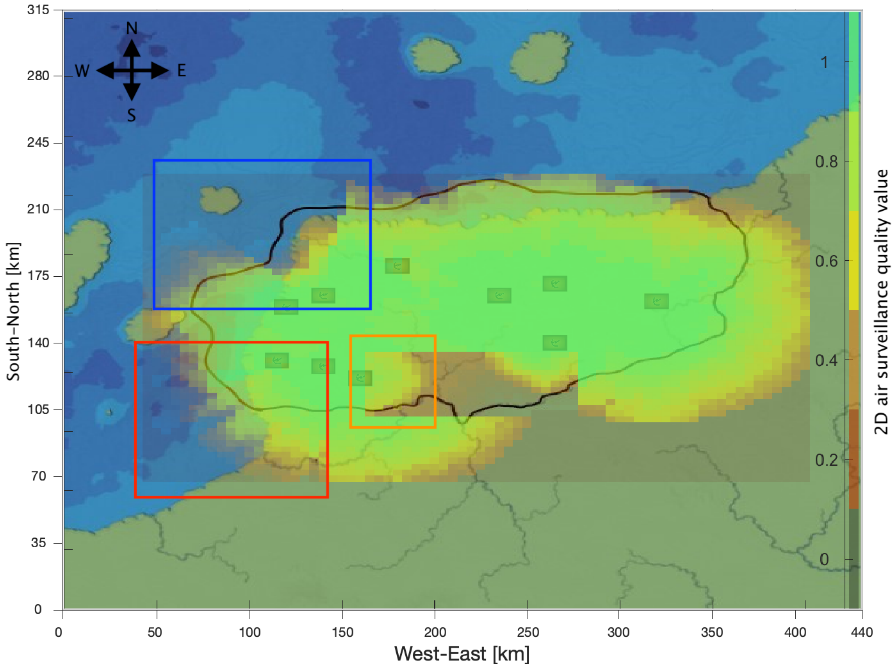

Figure 20: 2D air surveillance quality value for the alternative 'West'. The areas where significant differences between the alternatives are noticeable are marked with red, orange and blue squares.

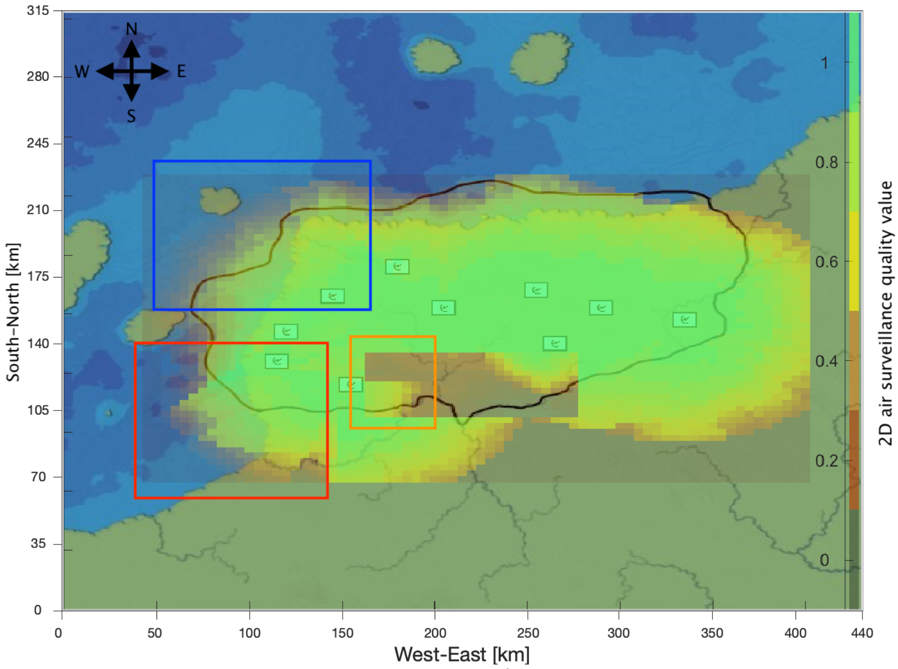

Figure 21: 2D air surveillance quality value for the alternative 'Neutral'. The areas where significant differences between the alternatives are noticeable are marked with red, orange and blue squares.

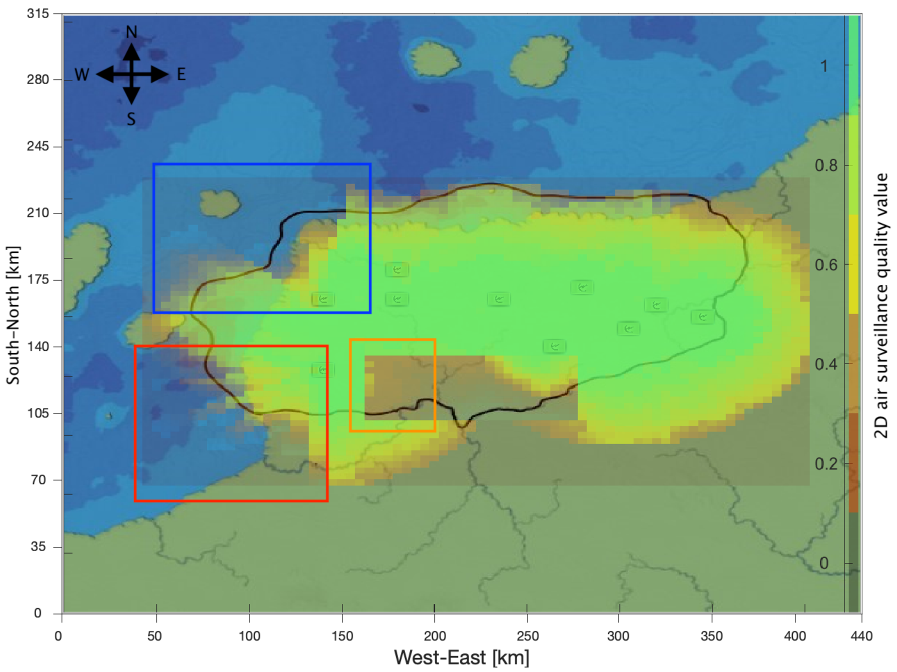

Figure 22: 2D air surveillance quality value for the alternative 'East'. The areas where significant differences between the alternatives are noticeable are marked with red, orange and blue squares.

The 2D quality values of the air surveillance systems are a fast way to describe differences between the alternatives in an easily interpretable way. The 2D visualizations provide a good understanding of the alternative's quality of air surveillance inside the

AOI, but some information is lost in the 2D visualization since ASRs concerning the same horizontal location are aggregated together. These ASRs may have different targets, quality statements of performance, or concern different altitude intervals, which complicates the interpretations of the 2D measure. Thus, examining the alternative's fulfillment of individual ASRs is required to gain a more comprehensive understanding of the differences.

Table 10 displays the fulfillment values of the ASRs for each air surveillance system. The differences in the fulfillment values of individual ASRs between the alternatives are quite small. The largest variations between the alternatives for an ASR are slightly over 0.1. Thus, the differences in the alternatives' quality values primarily arise from the ASRs with the highest priorities. Additionally, the results in the table indicate that the alternative 'East' is dominated by the alternative 'Neutral', as the fulfillment value of every ASR is higher for 'Neutral' than for 'East'. This is illustrated in Figure 23, where the fulfillment values are plotted over the ASRs for every alternative. The alternative 'Neutral' performs better than the alternative 'East' on every ASR. Hence, the alternative 'Neutral' is a better choice for the example problem than the alternative 'East' no matter what the priorities of the ASRs are.

Table 10: Fulfillment values of individual ASRs for each surveillance system alternative.

	Air surveillance system		
Name of ASR	**West**	**Neutral**	**East**
North Airliner	0.726	0.786	0.700
North Fighter jet	0.601	0.619	0.575
East Fighter jet	0.633	0.723	0.681
East Airliner	0.753	0.830	0.777
South Airliner	0.714	0.764	0.650
South Fighter jet	0.591	0.637	0.540
West Fighter jet	0.517	0.516	0.462
West Airliner	0.503	0.534	0.448
Central Fighter jet	0.661	0.621	0.542
Central Helicopter	0.232	0.186	0.122
Central Fighter jet 2	0.218	0.175	0.117

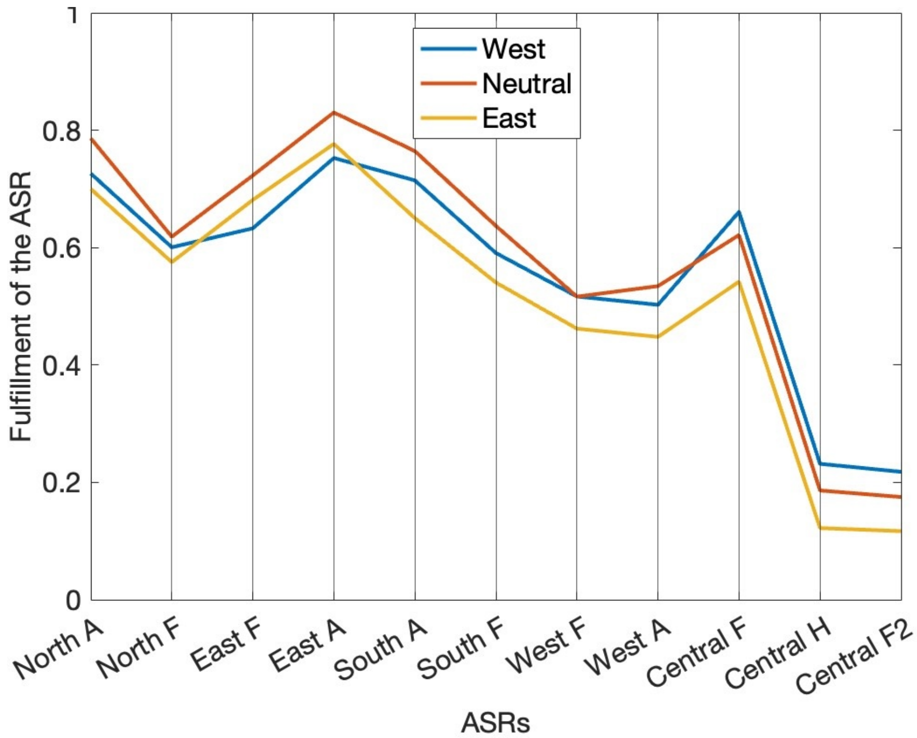

Figure 23: Fulfillment of the ASRs for the air surveillance systems. The abbreviations 'F', 'A', and 'H' stand for 'Fighter jet', 'Airliner', and 'Helicopter', respectively.

The main differences in the quality values of the alternatives stem from the ASRs with the highest priorities, which are located in the central and southern zones. To gain a deeper understanding of what factors cause the variations between the alternatives, a closer examination of one ASR from both the central and southern zones is next conducted.

The differences in the fulfillment values of the ASR between the air surveillance systems may be caused by several factors. An alternative may have more radars located near the ASR's surveillance zone which increases the fulfillment of the ASR. Another factor is the placement of radars. The radar's placement can affect the radar's range, as it can be limited by terrain. Both of these factors contribute to differences between the alternatives in the central and southern zones.

In Figures 24-26, the 2D fulfillment values of the ASR 'Central Helicopter' for each alternative are presented. The surveillance zone's altitude interval is 100-1000m. Due to the low altitude interval, the impact of wrong kind of placement of radars is strong. At low altitudes, the influence of terrain on radars is significant because the area within the radar's range is small, and only a few radars can observe a single location. Therefore, if the terrain limits the range of a single radar the effect on the fulfillment is more significant than on higher altitudes. In the figures, an area where significant differences between the alternatives exists is marked with a red line. The worse 2D fulfillment value of the ASR of the alternative 'East' in the area is caused by its radar placement. None of its radars are located within range of the area. The worse radar placement is evident when comparing the number of radars inside the red quadrangle between the alternatives. The alternative 'East' is the only one with no radars inside the red quadrangle. The difference between the systems 'West' and 'Neutral' can be explained by better radar placement of the alternative 'West'. The difference in the radar placement between the systems is small inside the red quadrangle. Still, the alternative 'Neutral' is unable to produce any fulfillment on the northeast side of the red quadrangle. However, the system 'West' is capable of producing fulfillment in this area. The difference between the alternatives' 2D fulfillment values indicates that the terrain partially obstructs the radar of the alternative 'Neutral'.

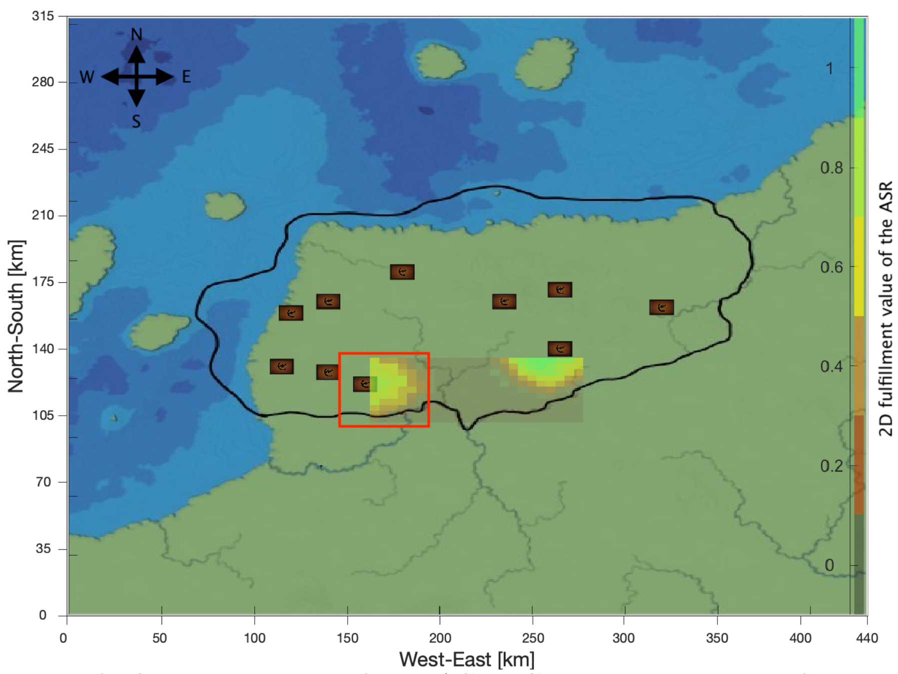

Figure 24: 2D fulfillment values of the ASR 'Central Helicopter' for the alternative 'West'. The area where significant differences between the alternatives exist is marked with a red line.

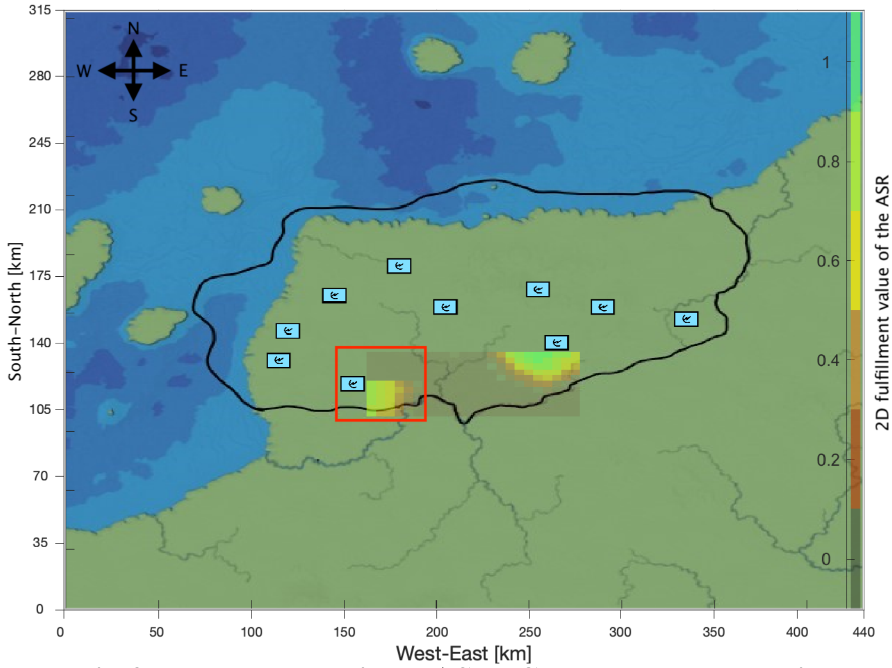

Figure 25: 2D fulfillment values of the ASR 'Central Helicopter' for the alternative 'Neutral'. The area where significant differences between the alternatives exist is marked with a red line.

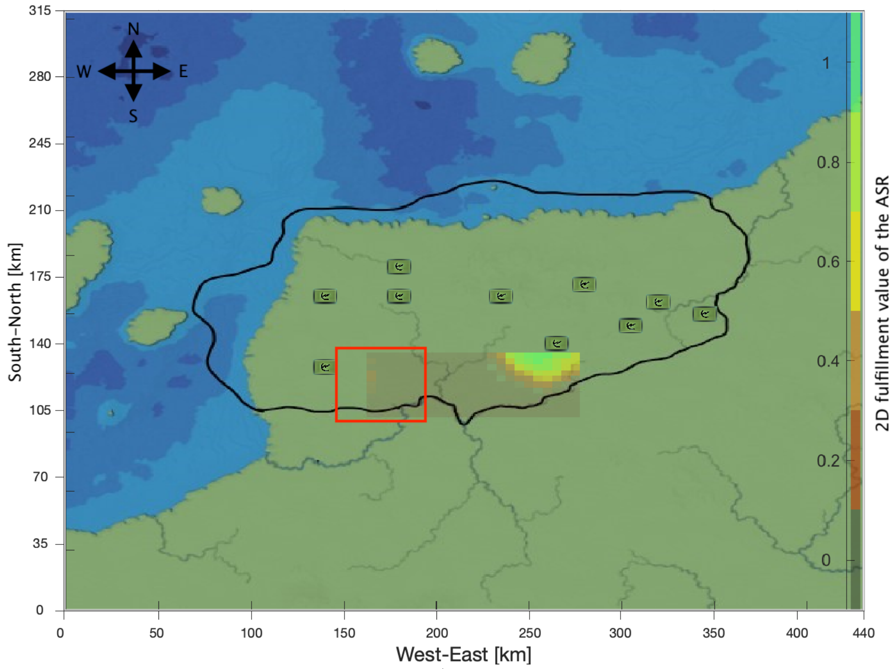

Figure 26: 2D fulfillment values of the ASR 'Central Helicopter' for the alternative 'East'. The area where significant differences between the alternatives exist is marked with a red line.

In Figures 27-29, the alternatives' 2D fulfillment values of the ASR 'South Airliner' are displayed. Areas with significant differences in the 2D fulfillment values are marked with red and orange quadrangles. The 2D fulfillment values for the alternative 'East' are significantly weaker inside the area marked with an orange quadrangle when compared to the other systems. The worse 2D fulfillment of the ASR seems to stem from the alternative 'East' having fewer radars in the range of the area when compared to the other alternatives. Additionally, the terrain seems to be limiting the radars' range. The alternative 'East' has only one radar inside the orange quadrangle compared to the two and three radars of the systems 'Neutral' and 'East'. The radar of the alternative 'East' is also partially obstructed by the terrain. This is evident from the shape of the 2D fulfillment values inside the orange quadrangle. The fulfillment values are near one on the southeast side of the quadrangle. However, despite being closer to the radar, the fulfillment drops to zero in the middle of the quadrangle. Moreover, the 2D fulfillment of the ASR 'South Airliner' for the alternative 'West' is significantly weaker inside the red quadrangle, when compared to the other alternatives. The weaker 2D fulfillment values within the area are the results of there being fewer radars in range compared to the other alternatives. Therefore, the alternatives 'East' and 'Neutral' are able to produce better 2D fulfillment inside the area.

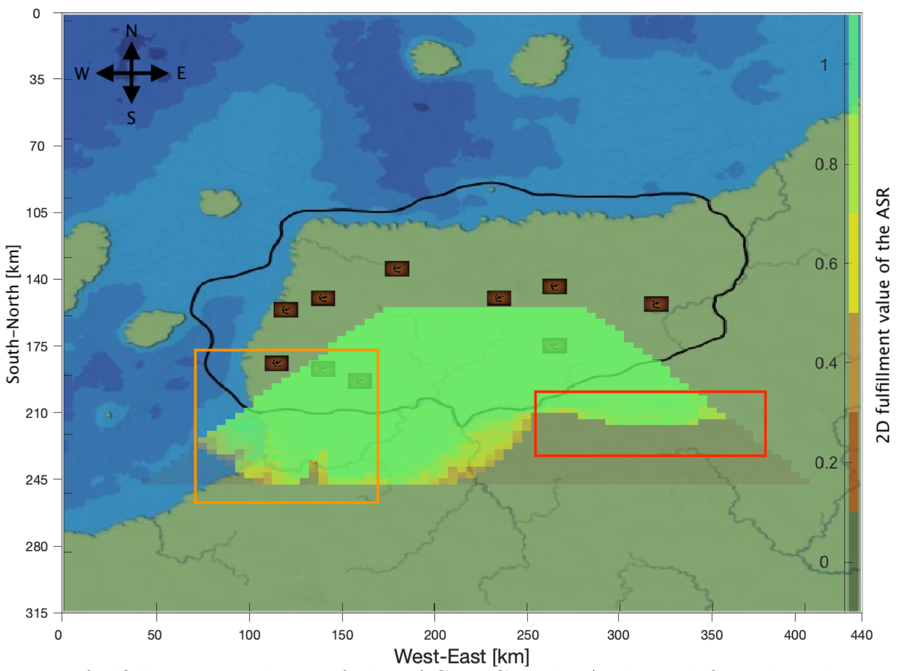

Figure 27: 2D fulfillment values of the ASR 'South Airliner' for the alternative 'West'. The areas with significant differences in the 2D fulfillment values between the alternatives are marked with red and orange quadrangles.

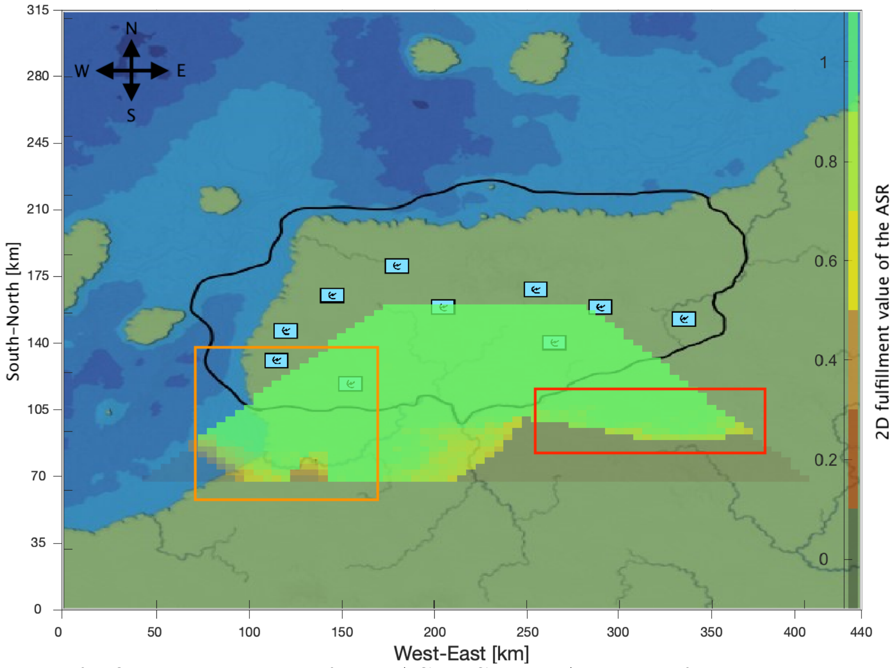

Figure 28: 2D fulfillment values of the ASR 'South Airliner' for the alternative 'Neutral'. The areas with significant differences in the 2D fulfillment values between the alternatives are marked with red and orange quadrangles.

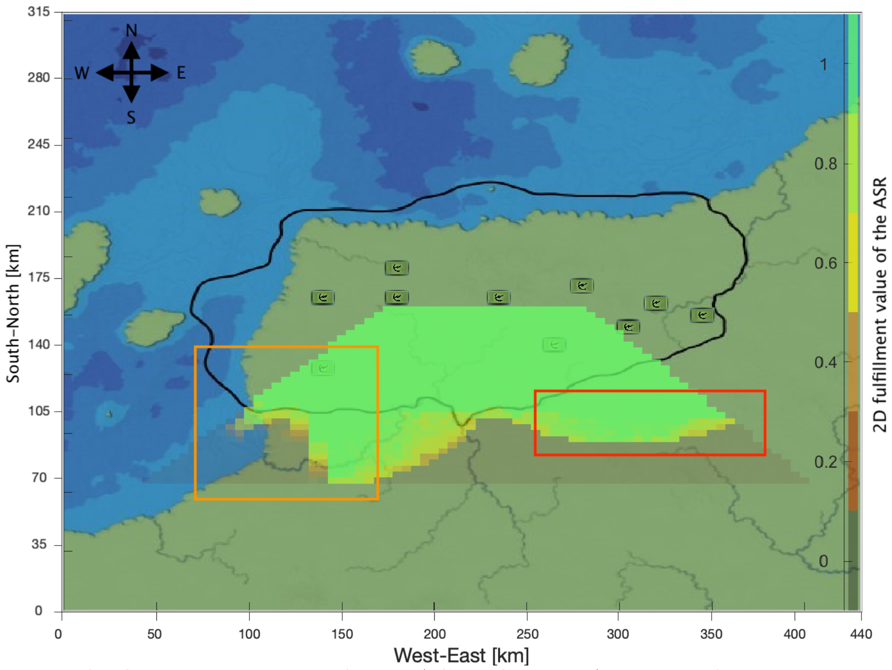

Figure 29: 2D fulfillment values of the ASR 'South Airliner' for the alternative 'East'. The areas with significant differences in the 2D fulfillment values between the alternatives are marked with red and orange quadrangles.

7.3.2 Realization levels of the air surveillance system alternatives

In the previous subsection, the air surveillance systems were compared and ranked according to their fulfillment values of the ASRs. The fulfillment value is measured by aggregating consequence values. The aggregation of these values means that the fulfillment value of an ASR may be deemed adequate by the DM even when one of the consequence values is zero. This kind of deviation of the consequence values is undesired as every performance metric describes a specific aspect of air surveillance. Thus, it is important to verify and compare how the consequence values vary inside the surveillance zones. This analysis is conducted with the realization level function and the total realization level function (cf. Sections 5.3 and 6.3).

In Table 11, the alternatives' total realization level values for threshold levels 1.0, 0.5, and 0.2 are presented. The value δ represents the threshold level for every performance metric. The alternative 'Neutral' performs best across all the threshold values δ. The total realization level value of the alternative 'West' ranks second for each value of *delta*, and the total realization level value of the alternative 'East' is the worst. Thus, the alternative 'Neutral' is the best alternative for the air surveillance planning problem as it has the highest air surveillance quality value and the highest total realization level values.

Table 11: Total realization level values for the air surveillance system alternatives.

	Realization level		
Air surveillance system	$\delta = 1.0$	$\delta = 0.5$	$\delta = 0.2$
West	0.2549	0.5286	0.5570
Neutral	0.2606	0.5353	0.5659
East	0.2436	0.4548	0.4832

The total realization level values presented in Table 11 detail the total realization levels for the surveillance alternatives but do not specify the ASRs causing the differences. Thus, the realization levels for individual ASRs must be examined to pinpoint which ASRs cause the deviations. In Table 12, each ASR's realization level value for $\delta = 1$ is given for each alternative. The alternative 'Neutral' has the highest realization level value for two ASRs despite having the highest total realization level value, when $\delta = 1$. The alternative 'Neutral' has the highest total realization level value, since its realization level values for every ASR are adequate. It is the worst alternative with respect to only one ASR. Additionally, it has the highest realization level value for the ASR 'South Airliner' and the second highest for the ASR 'South Fighter jet'. These requirements are the only priority one or two ASRs where the alternatives' realization level values deviate from zero significantly. Thus, they have a significant influence on the total realization level value. Moreover, the difference between the alternatives 'West' and 'Neutral' is larger for the ASRs in the eastern zone, than the ASRs in the western zone. The ASRs in the western and eastern zones have priorities four and five. Thus, the impact of these ASRs on the total realization level value is the same.

Table 12: Realization level values of the air surveillance system alternatives for $\delta = 1$.

	Air surveillance system		
ASR	**West**	**Neutral**	**East**
North Airliner	0.678	0.666	0.636
North Fighter jet	0.498	0.453	0.437
East Fighter jet	0.255	0.443	0.518
East Airliner	0.503	0.648	0.663
South Airliner	0.619	0.668	0.568
South Fighter jet	0.461	0.435	0.400
West Fighter jet	0.295	0.197	0.205
West Airliner	0.290	0.175	0.125
Central Fighter jet	0	0	0
Central Helicopter	0	0.00316	0.00158
Central Fighter jet 2	0	0	0

The alternative 'Neutral' has the highest fulfillment value of most ASRs which is shown in Table 10. Additionally, the alternative 'East' is dominated by the alternative 'Neutral', since 'Neutral' has a higher fulfillment value for every ASR, see Figure 23. However, the alternative 'East' is not dominated when the alternatives' realization level values are compared for individual ASRs with $\delta = 1$. In Figure 30, the realization level value for $\delta = 1$ is plotted as a function of the ASRs for each alternative. The realization level values of the alternative 'East' are higher than the values of the alternatives 'Neutral' and 'West' for multiple ASRs.

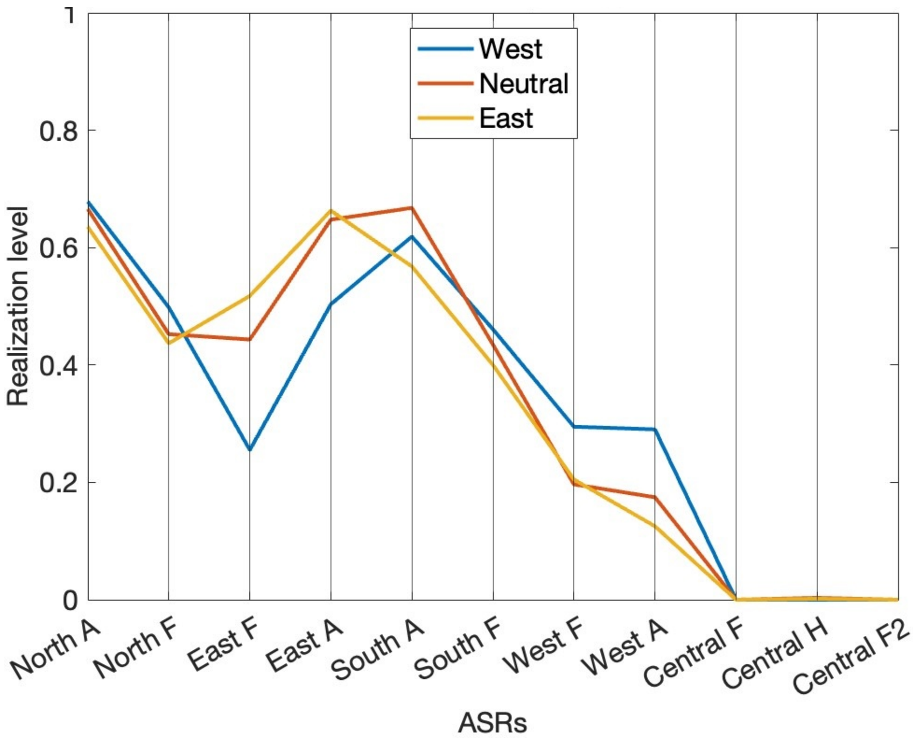

Figure 30: Realization level for the air surveillance systems when $\delta = 1$. The abbreviations 'F', 'A', and 'H' stand for 'Fighter jet', 'Airliner', and 'Helicopter', respectively.

The ordering of the alternatives changes between the fulfillment values of the ASRs and the realization level values for $\delta = 1$. This change is mainly caused by the size of the area where a moderate realization level is achieved. Such a moderate realization level refers to the realization level when $\delta = 0.5$. In Table 13, the alternatives' realization level values for each ASR with $\delta = 0.5$ are presented. A lower δ causes changes in the alternatives' ordering when compared to the order of the alternatives in Table 12 where $\delta = 1$. The ranking of the alternative 'East' is worse for several ASRs when $\delta = 0.5$, while the ranking of the alternative 'Neutral' is better for multiple ASRs. Additionally, the alternative 'East' is now dominated by the alternative 'Neutral' because 'Neutral' has a higher realization level value for each ASR when $\delta = 0.5$. The dominance is shown in Figure 31 where the realization level value for $\delta = 0.5$ is plotted as a function of the ASRs for each alternative.

Table 13: Realization values of the air surveillance system alternatives for $\delta = 0.5$.

	Air surveillance system		
ASR	**West**	**Neutral**	**East**
North Airliner	0.718	0.764	0.692
North Fighter jet	0.579	0.556	0.549
East Fighter jet	0.558	0.669	0.646
East Airliner	0.689	0.782	0.741
South Airliner	0.688	0.738	0.625
South Fighter jet	0.551	0.603	0.510
West Fighter jet	0.441	0.394	0.383
West Airliner	0.477	0.483	0.428
Central Fighter jet	0.681	0.646	0.538
Central Helicopter	0.229	0.178	0.109
Central Fighter jet 2	0.230	0.181	0.109

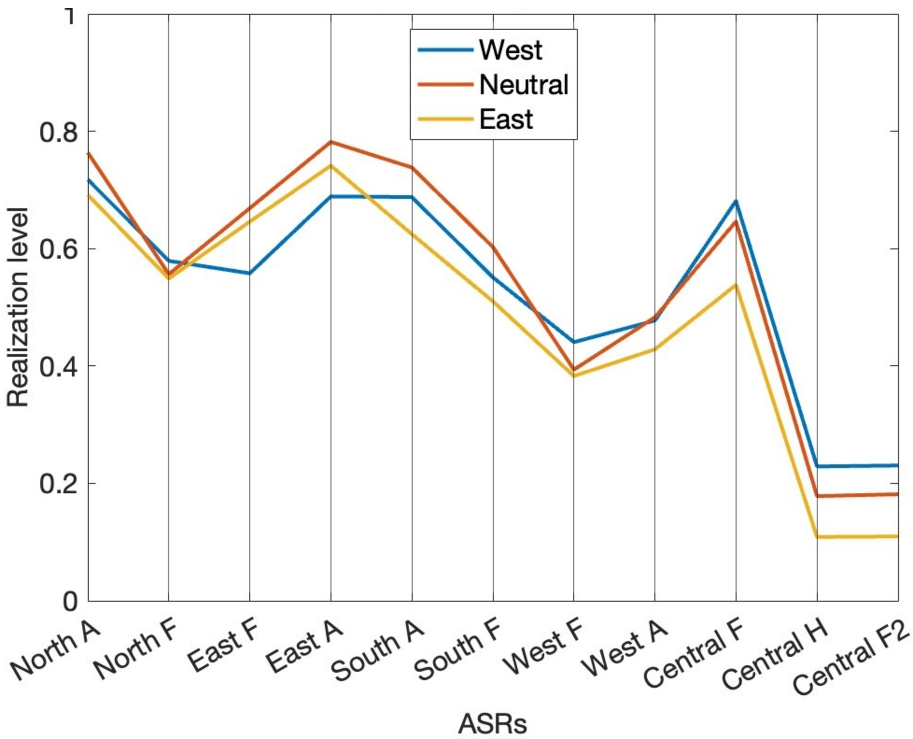

Figure 31: Realization level for the air surveillance systems when $\delta = 0.5$. The abbreviations 'F', 'A', and 'H' refer to 'Fighter jet', 'Airliner', and 'Helicopter', respectively.

The realization level values for $\delta = 0.5$ in Table 13 indicate that the area where a moderate realization level is achieved is larger on every ASR for the alternative 'Neutral' when compared to the alternative 'East'. Furthermore, 'Neutral' outperforms 'West' by attaining a reasonable realization level over a broader area on multiple ASRs.

The difference in the ordering of the alternatives 'West' and 'Neutral' based on their realization level values for the threshold levels $\delta = 1$ and $\delta = 0.5$ can be also verified visually with 2D realization level values. Additionally, the 2D realization values enable the detection of subareas where the alternatives' 2D values vary.

Figures 32 and 33 show the 2D realization level values for the alternatives 'West' and 'Neutral' for the ASR 'West Airliner' when $\delta = 1$. The area where the alternative 'Neutral' can exceed the threshold level $\delta = 1$, is smaller than the corresponding area of the alternative 'West'. Figures 34 and 35 display the 2D realization level values for the ASR 'West Airliner' when $\delta = 0.5$ for the alternative 'West' and 'Neutral'. The area where the alternative 'Neutral' can exceed the threshold level is now slightly larger than the corresponding area of the alternative 'West'. This demonstrates that despite having a lower realization level value for $\delta = 1$, the system 'Neutral' is capable of achieving a reasonable realization level over a wider area compared to the alternative 'West'.

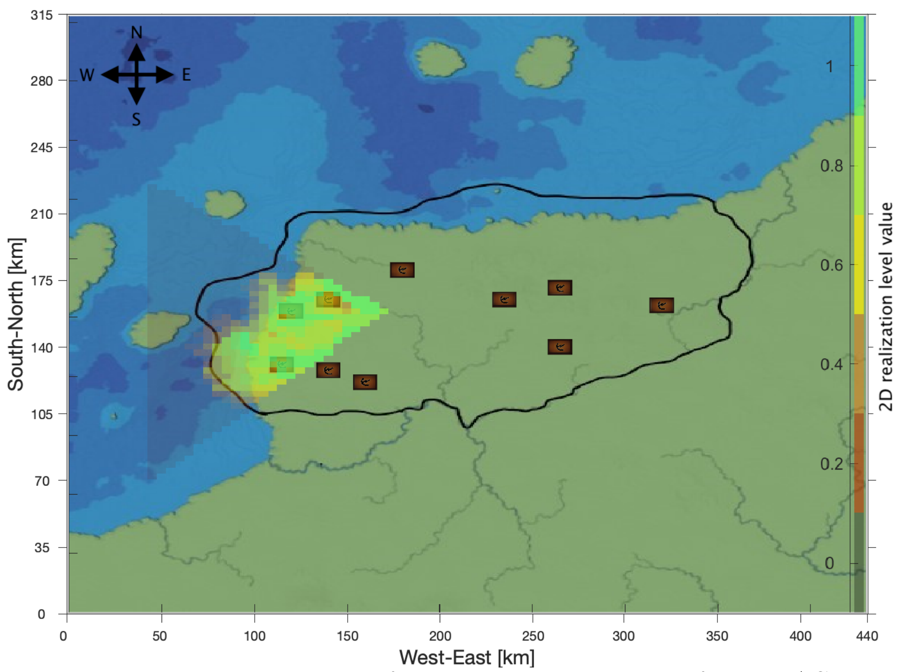

Figure 32: 2D realization level value of the alternative 'West' for the ASR 'West Airliner' when $\delta = 1$.

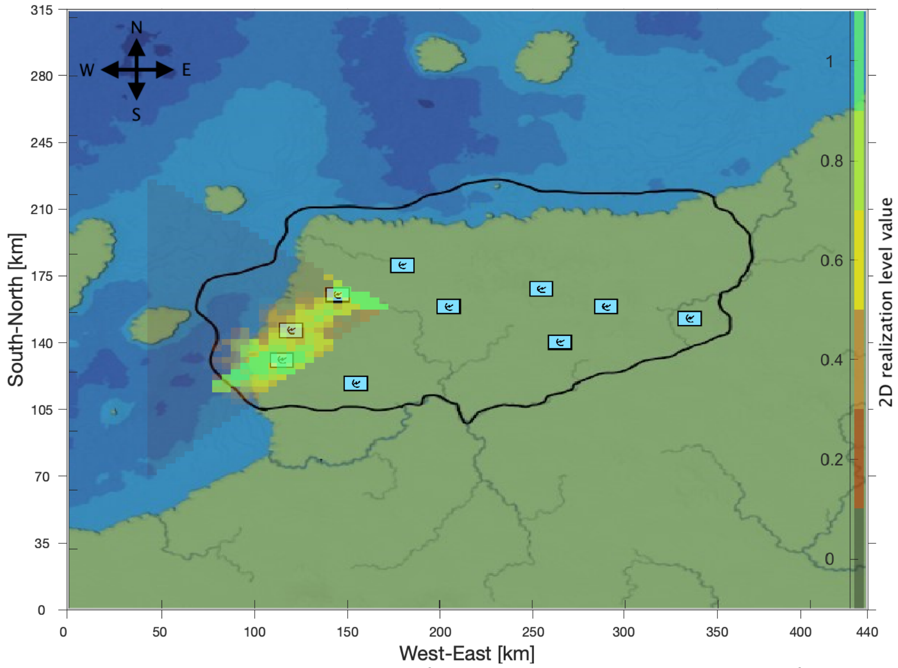

Figure 33: 2D realization level value of the alternative 'Neutral' for the ASR 'West Airliner' when $\delta = 1$.

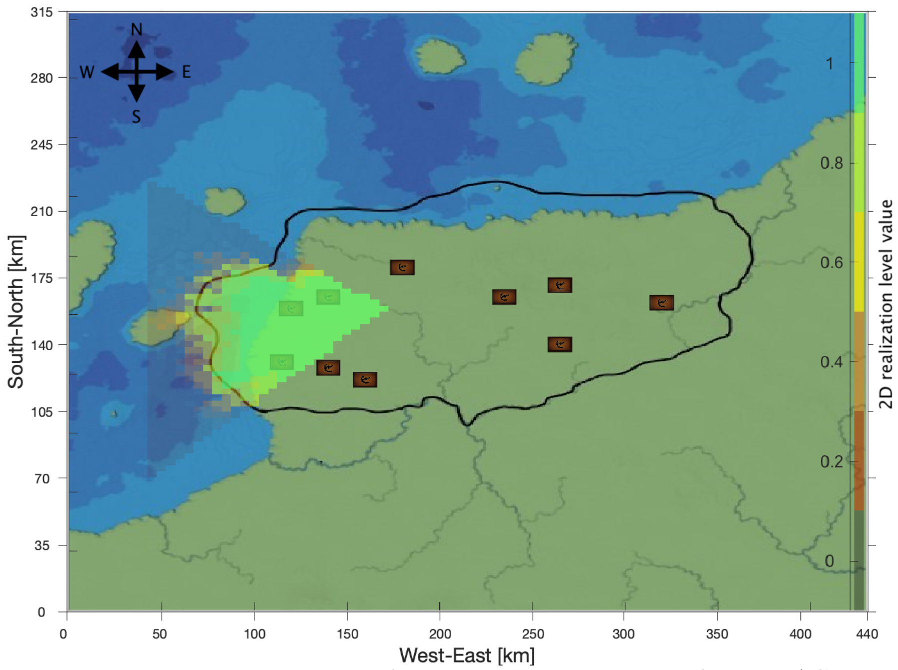

Figure 34: 2D realization level value of the alternative 'West' for the ASR 'West Airliner' when $\delta = 0.5$.

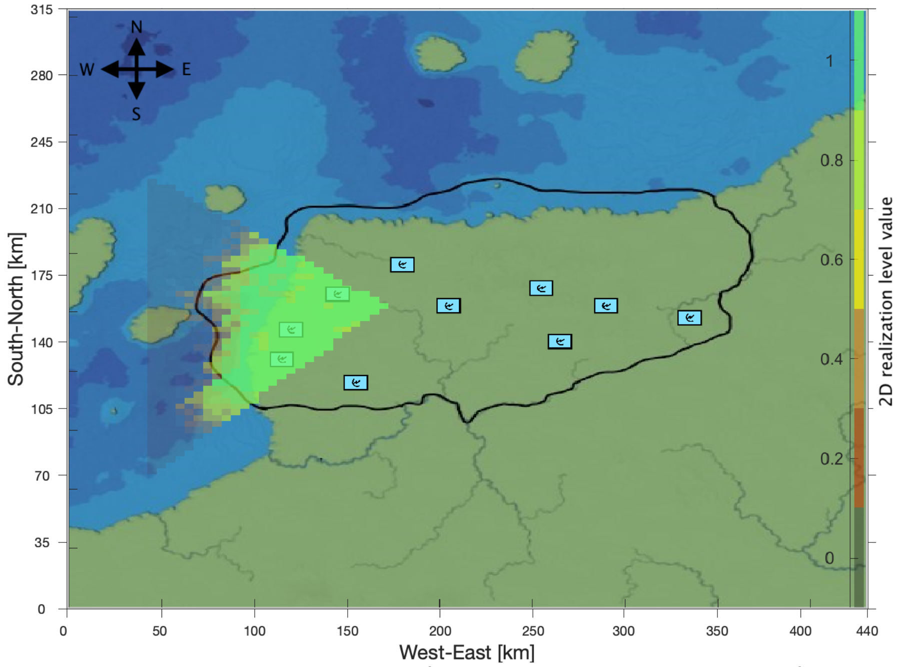

Figure 35: 2D realization level value of the alternative 'Neutral' for the ASR 'West Airliner' when $\delta = 0.5$.

The realization level values do not fully explain the fulfillment values of an ASR. There are multiple factors affecting the fulfillment value. The fulfillment value of an ASR can be reasonable despite the realization level value being low. In Figure 36, the alternatives' realization level values for the ASR 'West Fighter jet' are plotted as a function of δ. The realization level value of the alternative 'Neutral' is worse than the value of the system 'West' for all the threshold levels δ. Despite the differences in the realization level values, there is only a 0.001 difference in the fulfillment values of the ASR 'West Fighter jet' between the alternatives as shown in Table 10. Thus, there exists a significant variation between the consequence values of the alternative 'Neutral'. The variation of these values means that the alternative 'West' is preferred to the alternative 'Neutral' for the ASR as the fulfillment value for both alternatives is the same but the realization level values of 'West' are better for every threshold level. This result underscores the importance of evaluating the realization level values of the alternatives.

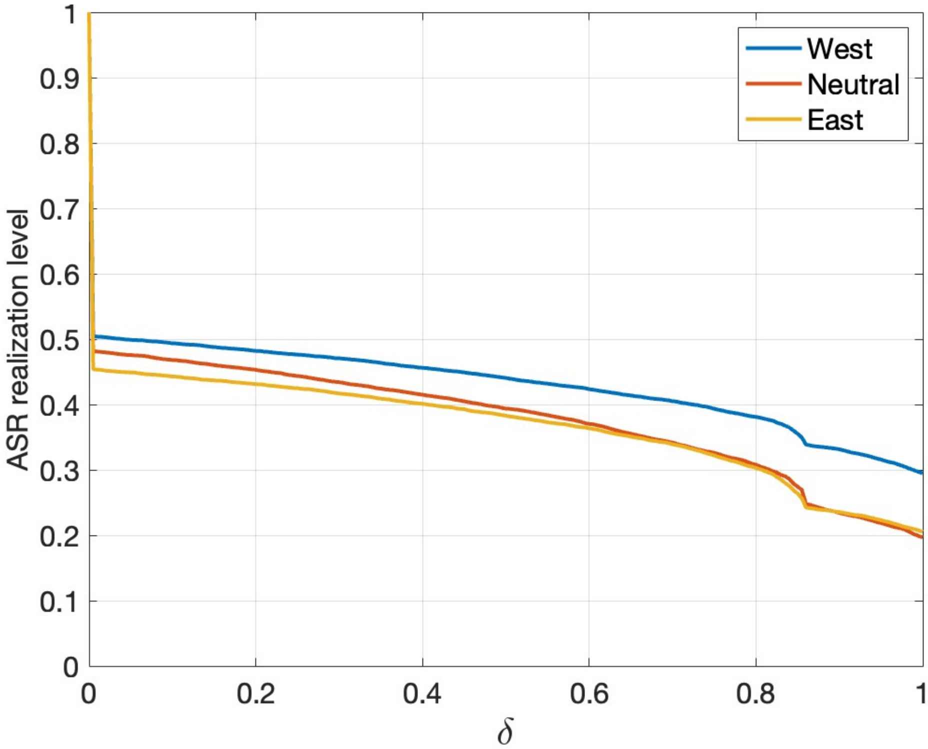

Figure 36: Realization level value as a function of the threshold level δ for each alternative with the ASR 'West Fighter jet'.

7.4 Summary

The example air surveillance planning problem was used to demonstrate how the quality of air surveillance provided by an air surveillance system can be evaluated with the SMCDA framework introduced in this thesis. The example illustrated the comparison and ranking of system alternatives while taking into account the preferences of a DM responsible for planning air surveillance. The alternatives are evaluated based on how well they fulfill different ASRs dictated by the DM. Additionally, the use of spatial measures was illustrated when identifying factors that cause differences in the systems' fulfillment values of ASRs. The 2D value function was applied to detect limitations in the range of radars caused by terrain. Moreover, the realization level function was utilized to identify shortcomings in the systems' capability to fulfill ASRs.

In the planning example, the air surveillance system 'Neutral' had the highest air surveillance quality value out of the alternatives. It had the highest fulfillment value on most of the ASRs. The total realization level value for the alternative 'Neutral' was also highest for the threshold levels 1, 0.5, and 0.2. Thus, the alternative 'Neutral' was the best solution for the air surveillance planning problem under consideration. The quality value of the alternative 'West' was the second highest. Additionally, it had the highest fulfillment value for all ASRs in the central surveillance zone. Moreover, the total realization level value for the alternative 'West' was the second highest for the threshold levels assessed. Thus, it is the second choice out of the alternatives. The alternative 'East' had the worst quality value and total realization level value across all considered threshold levels. Furthermore, the alternative 'East' was dominated by the alternative 'Neutral' for the fulfillment of the ASRs, as the alternative 'East' had a worse fulfillment value on every ASR. The alternative 'Neutral' also dominated alternative 'East' for the realization level values when $\delta = 0.5$, since the realization level value of 'Neutral' was higher on every ASR. Hence, the alternative 'East' was the worst alternative for the planning problem. It should be noted that in this chapter the evaluation of a single ASR was demonstrated only on a few ASRs presented in Table 4. A similar analysis could have been conducted for every ASR.

The example demonstrated that the SMCDA framework is already capable of being used in the planning of air surveillance. However, the framework can be developed in several ways. Different spatial weights could be applied within surveillance zones to give higher importance to certain altitudes or subareas of a surveillance zone. Additionally, in this thesis, weights of ASRs were derived with the centroid weights method. However, there are plenty of other elicitation methods to determine the weights, such as Swing, SMART, or pairwise comparisons (see, e.g., Pöyhönen and Hämäläinen, 2001). Thus, in a real-life scenario, using multiple methods to obtain the weights is a sensible idea to ensure that the weights represent the DM's preferences in a valid way.

The weights used for CVFs were uniform in the example. However, using non-uniform weights with the CVFs for some ASRs may represent the DM's preferences more accurately. Additionally, the CVFs used were linear. However, non-linear or piece-wise linear CVFs could represent the DM's preferences better. The use of elicitation methods, such as the bisection method (see, e.g., Keeney and Raiffa, 1993), could be applied to define more accurate CVFs.

Weights of ASRs - or other weights in the SMCDA framework - could be elicited by taking into account incomplete preference information on the importance of different elements of the framework. In these elicitation methods, the DM gives preference statements which result in the weights being presented as intervals (see, e.g., Harju et al., 2019; Salo and Hämäläinen, 2010). This approach leads to the fulfillment values of ASRs, air surveillance quality values, and realization level values being described with intervals. These intervals contain the feasible values of each measure in respect to the interval constraints of the weights. The alternatives can then be ranked into dominated and non-dominated alternatives using dominance rules (see, e.g., Salo and Hämäläinen, 2010). Additional preference information can be given which narrows the intervals of the weights which in turn narrows the intervals of the measures and reduces the number of non-dominated alternatives.

Another area for development could be applying sensitivity analysis to the SMCDA framework (see, e.g., Wieckowski and Sałabun, 2023). Sensitivity analysis describes how changes in parameters of the framework considering preferences of the DM or the computation of performance metrics impact the evaluation of air surveillance systems. Thus, informing how sensitive the ranking of system alternatives is to changes in the parameters. Notably, if the ordering of the alternatives changes because of small variations in weights or quality statements of ASRs, additional focus should be given to the elicitation of these parameters. Moreover, If minor adjustments in performance metrics result in changes in the systems' ranking, one should pay attention to the accuracy of the parameter values of the computational tool used for calculating the metrics. These parameters include a surveillance zone, the size of subareas, and a target type, see Chapter 3. Additionally, sensitivity analysis allows the identification of performance metrics with the most influence on the ranking of surveillance systems when these systems are evaluated based on their capability to fulfill the ASRs.

8 Concluding remarks

In this thesis, the evaluation of the quality of air surveillance when using ground-based air surveillance systems consisting of radars was studied. Such systems must be capable of fulfilling multiple air surveillance tasks simultaneously. The objectives of these tasks may concern the entire area of interest (AOI) or a specific subarea of an AOI. The objective may vary in importance for the decision maker (DM) who is in charge of air surveillance. The tasks are also often contradictory, as enhancing a system to fulfill one objective better can diminish the fulfillment of another one. The main goal of this thesis was to develop a spatial multi-criteria decision analysis (SMCDA) framework for the evaluation, comparison and ranking of air surveillance systems in a way that takes into account the objectives of the tasks and the preferences of the DM regarding air surveillance.

In the SMCDA framework, a new way to represent objectives of air surveillance tasks was established. The framework represented objectives with air surveillance requirements (ASRs). ASRs were defined with a surveillance zone, the type of a target, quality statements of performance of air surveillance, and ASRs' priorities. The surveillance zone was represented as a 3D area. The target type referred to the characteristics of an aircraft used in the task. The quality statement of performance described the task with performance metrics. These metrics depicted different aspects of air surveillance and were calculated with an existing computational tool. The ordinal importance of the ASRs was depicted with their priorities.

The DM's role in the evaluation was vital. The DM was responsible for defining the ASRs and determining the consequence value functions (CVFs) which quantified the desirability of values of each performance metric. Moreover, the DM was required to assign weights that reflect the importance of each CVF and spatial weights which depicted the relative importance of different subareas within the surveillance zone.

The framework evaluated the fulfillment of a single ASR with a spatial value function. The spatial value function yielded a fulfillment value of the ASR which described the extent to which the ASR could be fulfilled within the surveillance zone. The framework also enabled the visualization of the fulfillment of the ASR with a 2D value function. The 2D fulfillment value allowed pinpointing areas where the fulfillment was weak. Additionally, the framework allowed the detection of shortcomings in the fulfillment with the realization level function. The function evaluated the percentage of the surveillance zone of the ASR where the consequence values of the performance metrics exceed a minimum threshold. This percentage was referred to as the realization level value. The visualization of this value was enabled with the 2D realization level function.

The fulfillment of multiple ASRs was assessed with an air surveillance quality function. The evaluation was conducted by aggregating the fulfillment values of individual ASRs which yielded the air surveillance quality value. The ordinal importance of the ASRs was taken into account in the aggregation with the weights of the ASRs which were derived from the ASRs' priorities. The framework also enabled the 2D visualization of the quality value. Additionally, a measure called the total realization level value was derived to analyze the average realization level value of the ASRs.

The use of the framework was demonstrated by solving an example air surveillance planning problem where three air surveillance system alternatives were considered. The alternatives were compared by their ability to fulfill ASRs. The demonstration illustrated that variations in the fulfillment values of the ASR could be found between the systems. The fulfillment values revealed such variations even in cases where the location of systems' radars differed only by a small amount. The 2D fulfillment values provided more details about the deviations between the systems by pinpointing the subareas of the surveillance zone where the fulfillment differed. Additionally, the 2D values enabled the detection of radars that were partially obstructed by terrain. The ability of the framework to compare and rank systems and explain the differences between them indicated that it is a capable tool for supporting the planning of air surveillance.

To solve the planning problem, the alternatives were ranked based on the air surveillance quality values. These values enabled the DM to quickly detect which alternative best fulfilled the ASRs and what differences existed between the systems. Using the visualizations of the quality values, it was possible to compare areas where the alternatives' fulfillment deviated. The realization level values produced a more detailed picture of the ASR's fulfillment compared to its fulfillment value. Utilizing this measure, the area within the range of the systems and the area where an ASR was completely fulfilled could be assessed. Thus, one was able to compare the systems when their fulfillment values of an ASR were equivalent.

Based on the solution of the example problem, the measures of the framework appeared to be valid. The quality values enabled the ranking of the system alternatives in an order where the fulfillment of the ASRs and their ordinal importance were taken into account. The system with most radars located near the surveillance zone had, in most cases, the highest fulfillment and realization level values. When this was not the case, inefficient placement of radars could be identified as the cause of the worse ranking of the system. Additionally, the framework was capable of identifying dominated alternatives in respect to both the fulfillment and realization level values of the ASRs. Overall, the framework provided a holistic view of the capabilities of the air surveillance systems with regard to the ASRs associated with different air surveillance tasks.

The SMCDA framework, as demonstrated in this thesis, can already be used to support air surveillance design. Objectives of air surveillance can vary from, e.g., detecting airspace violations to facilitating civil air traffic control. Thus, the surveillance system most capable of achieving these potentially conflicting objectives should be identified. However, if military readiness is raised, the focus can shift to early warning capability in strategically important areas. In conflict conditions (e.g., Mansikka et al. 2021a; Mansikka et al. 2021b), a system that is able to track targets in certain geographical areas is preferred. Additionally, systems could be designed so that they allow fast changes in the focus of air surveillance.

In this thesis, air surveillance systems analyzed with the SMCDA framework consisted of ground-based radars. In the future, more advanced sensors, such as passive sensors or AESA radars (see, e.g., van Bezouwen et al., 2010; Kuschel et al., 2019), could be included in the evaluation. This extension would require the addition of models of these advanced sensors to the computational tool used for determining performance metrics. Moreover, new measures for the fulfillment of ASRs would also be needed. For example, passive sensors do not emit radio waves which is not currently taken into account in the framework. Additionally, air-based sensors could be considered.

The combat sustainability of air surveillance systems could be taken into account in the SMCDA framework. In a combat scenario, there is a possibility of radars being destroyed by anti-radiation missiles (ARMs) which detect the EM radiation of the radars (see, e.g., Czeszejko, 2013; Mattila et al., 2014). Thus, minimizing the radiation in certain areas of the surveillance zone may be beneficial. This would lower the system's capability to observe the airspace but would additionally lower the risk of the radars being destroyed. Performance measures could be derived to evaluate the benefits of means of increasing the combat sustainability of an air surveillance system. It should also be noted that the approach discussed is also appropriate for addressing other types of radiation-detecting threats than ARMs.

In the existing literature, the performance of radars and air surveillance systems has been typically analyzed by assessing a predefined system in a 3D area. This thesis presented a novel approach absent from the existing literature for the planning of air surveillance. A 3D area and ASRs are fixed and a system best suited for these requirements is then identified. The formal form of the ASRs is pragmatic in the sense that a designer who is unfamiliar with technical details of an air surveillance system can define them. The framework ensures that air surveillance systems can be designed in a transparent and well-justified manner. It contains several new ways to measure the quality of air surveillance. These measures are easily interpreted by the DM responsible for the planning of air surveillance. The measures can also be visualized, thus helping to justify results of the planning problem plainly and pragmatically. The existing literature lacks the application of SMCDA methods in the area of air surveillance. Thus, this thesis extends the existing literature with the framework for supporting the design of air surveillance systems.

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