AN AIRPORT CLIMATE RESILIENCE ASSESSMENT SCAN

From a theoretical concept to an operational method

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AN AIRPORT CLIMATE RESILIENCE ASSESSMENT SCAN

From a theoretical concept to an operational method

Master Thesis

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I. PREFACE

In front of you lies the thesis 'An Airport Climate Resilience Assessment Scan – From a theoretical concept to an operational method', which describes the research process and results of a master graduation project. This project was conducted to obtain the Master of Science (MSc) degree in Construction Management and Engineering (CME) at the University of Twente in Enschede, The Netherlands.

The project has been commissioned by Netherlands Airport Consultants (NACO), a Dutch airport engineering and consultancy firm. The thesis objective is to develop an Airport Climate Resilience Assessment Scan, which aims to provide an overview of the overall challenges an airport faces in the transition towards becoming a climate-resilient airport. This results in important implications for future planning and investments to enhance the climate resilience of the airport in question.

II. ACKNOWLEDGEMENTS

Ever since I was a kid, I have been fascinated by the complexity of airports. Thus, in 2007, I approached Dick Gierlings, a former pilot at the KLM Royal Dutch Airlines, and asked if I could join him on a taster day. On such a day, children are allowed to join a 'grown-up' to work. Dick showed me around the hangers and airplanes at Schipol Amsterdam Airport. I was even allowed to fly in a simulator. I want to begin by thanking Dick Gierlings for offering me such a special opportunity. Thanks to him, my amazement for the complexity of airfields, and the magnificence of the airplane still exist today.

Throughout my research, I have had great support from the people around me. Therefore, I would like to give a special word of thanks to those involved. First of all, I would like to thank my thesis committee from the University of Twente, starting with Joanne Vinke-de Kruijf. It is due to Joanne's expertise and inspiring lectures I was certain I wanted to continue learning about resilience in my master thesis. I am grateful for her supervision; both her criticism and support have been essential for the final results. My gratitude also goes to Eric Lutters, who has a huge gift for supervising students. With an indescribable sense of empathy for people and situations, he was always able to support me in a manner that was fitting of the time. I would like to also thank Robin de Graaf for his willingness to chair the committee, sharing his knowledge, providing valuable feedback, and for stepping in to aid with the project when it was needed.

At NACO I had the opportunity to develop expertise about the topic and in the industry which greatly excited me. I want to thank my supervisor at NACO, Peter Vorage. His critical mind and questions combined with understanding, sympathy and good humour motivated me to enjoy my time at NACO and get the best out of my research. I am also thankful to Max van Rest who made me feel welcome at NACO from the moment I arrived. He helped me become accustomed to the place and connected me with many colleagues, which became extremely valuable when COVID-19 began.

Finally, I want to thank my friends, including my roommates and fellow (graduate) students, for their help, good talks and laughter. And last but not least, I want to thank my parents, brother, sister and my boyfriend Tom, for their love, support in all decisions I made, and willingness to help me out if I enquired.

I sincerely hope, you enjoy reading this report and also become as enthusiastic about this industry and topic as I have.

Pleuni Verdijk
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III. SUMMARY

The background information

We are living in a turbulent world. A world that is experiencing changes in average temperature, sea level rise, increased storm intensity and many other climate change impacts. It seems that extreme weather events, which are reinforced by a changing climate, are the risks that are not only most likely to occur, but can also have a huge impact on global society. Modern society relies on the effective functioning of its critical infrastructures in which airports play a crucial role. That is because disruptions of one airport may have an immense effect on all who are relying on their effective functioning. To mitigate the consequences of extreme weather events, airports need to become more climate-resilient.

The research goal

The first step towards improving the climate resilience status of airports is assessing their current performance. Since currently no assessment method that enables to measure resilience on the airport level exists, this research aims to develop an Airport Climate Resilience Assessment Scan (AirCRAS). Here, the premise is that the AirCRAS results in a holistic overview of the strengths and weaknesses of the airport system. This AirCRAS has been developed in the commission of Netherlands Airport Consultants (NACO), a world-leading airport engineering and consultancy firm that helps to guide the future of many airports around the world. With the development of the AirCRAS, NACO aims to pre-emptively find solutions for the changing needs of their clients.

For the development of the AirCRAS, this research adopts a design science methodology. Design science aims to directly tackle the problem experienced in practice by providing a solution. In this design science methodology, three design phases are run through: the problem investigation phase, the design phase and the validation phase.

The problem investigation phase

In the problem investigation phase, the problem experienced in practice to improve the climate resilience status of airports are identified, and an overview is created of the state-of-the-art literature that can be used to design a solution for this problem.

A focus group session and interviews were conducted to provide an overview of NACO's current experience with and ambitions for improving the climate resilience of airports. The findings show that, as with the current literature regarding resilience in the air transportation system, NACO is generally focused on modelling the vulnerability to disruptive events which are mainly for the purpose of analysing the economic impact on infrastructure. This approach is technically oriented and tends to go quickly into details. It may therefore miss the identification of relevant problems in the creation of climate-resilient airports on, for example, organizational aspects. Before going into details, it is therefore important that the strengths and weaknesses of a climate resilience airport are first assessed on various aspects. This is to avoid overlooking relevant problems.

A literature study was conducted to identify the possibilities for assessing the climate resilience status of an airport on several aspects. The literature regarding this area appears to be significant, elaborating on e.g. operational frameworks, resilience principles and resilience indicators. However, air transportation is rarely mentioned in this respect. Among others, it was found that sector-specific indicators seem to be the most effective way to measure resilience. It is found that resilience indicators can help to understand and diagnose performance since they are able to offer a quick scan of the situation of a resilient system, highlighting its strengths and weaknesses. The indicators can be measured by converting them into assessment questions. Yet, presently sector-specific indicators have not been described for the aviation industry.

It can be concluded that in literature there is a lack of knowledge on how climate resilience can be measured and operationalised on the airport level. This knowledge gap is the cause of the lack of strategic guidance from airports in the transition to a climate-resilient airport. Considering these gaps, the AirCRAS aims to connect the two research fields of assessing resilience and the air transportation industry with each other and with practice. The findings from the problem investigation phase are summarized in a design brief that forms the basis for the development of the AirCRAS, which includes design requirements that the AirCRAS should comply with.

The design and validation phase
In the design phase, a prototype of the AirCRAS is developed based on the design brief. In addition, the literature was consulted again to identify climate resilience indicators. These indicators are converted into assessment questions. In the validation phase, three validation sessions were conducted, consisting of two focus group sessions and an interview. These sessions were conducted for two reasons. Firstly, to verify whether the design requirements are met. Second, to check whether the design complies with the user expectations. Feedback was received in each of these validation sessions and improvements to the design were made accordingly. The process of presenting the scan, receiving feedback and refining the design was repeated three times.

The AirCRAS that results from applying this iterative process, is a digital tool. The users of the AirCRAS are experts from NACO. Together with the experts from the airport, they form an expert panel that jointly goes through the AirCRAS in a workshop at the start of a project. In the AirCRAS, the expert panel answers a set of assessment questions. It takes about half a day to complete the AirCRAS. The AirCRAS consists of four phases:

1. The first stage of the AirCRAS is intended to align expectations regarding the relevance of performing the AirCRAS and the process which the expert panel will go through. Also, this stage elaborates on the sources that have been used for its development;
2. In the second stage, the users must choose what climate vectors they consider relevant for the airport in question. Choosing relevant climate vectors for their specific airport is necessary because the assessment questions to be answered in the third phase depend on those climate vectors. For example, for an airport located in Central Africa, it is irrelevant to answer questions related to sea level rise;
3. In this stage, the assessment questions have to be answered. These questions are divided into three categories: organisation, operations and infrastructure. The assessment questions must be answered on a scale from A (representing the best) to E (representing the worst);
4. Finally, the fourth stage presents the results in a rose diagram. Also, it provides discussion points that facilitate dialogues concerning, among others, the challenges the airport experiences in their transition towards becoming a climate-resilient airport. The outcome of the discussion results in priorities and/or constraints that might be used for a future in-depth resilience study.

The conclusion
This research presents the first Airport Climate Resilience Assessment Scan. By having applied a design science method, we were able to transform the theoretical concept of resilience into an operational assessment method. The AirCRAS provides an overview of the overall challenges an airport faces in the transition towards becoming a climate-resilient airport. This results in important implications for future planning and investments to enhance the climate resilience of the airport in question.

The recommendations
In closing, recommendations for future research and practical purposes are formulated. First of all, it is recommended to further explore *if* actions are taken to prepare for extreme weather events, and *what* they entail. It is recommended to identify airports' motifs for acting or not acting to prepare for the impacts of climate change.

Second, the AirCRAS is currently only suitable for the individual assessment of airports. The meaning of the labels assigned to an indicator is subjective. For the sharing of lessons-learned between airports, it is recommended to further develop the AirCRAS into a benchmark method.

Third, it is recommended to explore the possibilities of developing the AirCRAS into an evaluation tool. It may be interesting to use the AirCRAS in the end-stage of the project to validate whether (the correct) changes are made.

Currently, the resilience of airports is considered at the airport-level. It is recommended to consider airports as a part of the complete transportation system. In that context, the possibilities of collaboration between air transport and high-speed rail to increase the resilience of the overall transportation system can be explored.

Practical recommendations relate to, firstly, support the further development of this area of expertise within NACO. Among other things, this concerns the appointment of someone who is responsible for the implementation and further development of the AirCRAS. It is also recommended to develop a model that calculates which of NACO's customers are at greatest risk of extreme weather conditions. This information can be used to actively approach airports for the acquisition of new projects aimed at improving the climate resilience of airports.

IV. SAMENVATTING

Achtergrondinformatie
De wereld waarin wij leven is aan klimaatverandering onderhevig. Zo stijgt de zeespiegel, neemt de temperatuur van de aarde toe en verschuiven neerslagpatronen. Onderzoek toont aan dat extreme weersomstandigheden risico's vormen die niet alleen met de grootste waarschijnlijkheid zullen optreden, maar die ook een enorme impact kunnen hebben op de samenleving op wereldniveau. De moderne samenleving is afhankelijk van het effectief functioneren van haar kritieke infrastructuren. Hierin spelen luchthavens een cruciale rol. De verstoring van één luchthaven heeft namelijk een enorm effect op iedereen die van hen afhankelijk is. Om de gevolgen van extreme weersomstandigheden te mitigeren, moeten luchthavens klimaat-resilient* worden.

Het onderzoeksdoel
De eerste stap om de klimaat resilience van luchthavens te verbeteren, is het beoordelen van hun huidige prestaties. Aangezien er momenteel geen beoordelingsmethode bestaat waarmee klimaat resilience op luchthavenniveau kan worden gemeten, is het doel van dit onderzoek om een klimaat resilience scan voor luchthavens te ontwikkelen. Deze scan wordt de AirCRAS ("Airport Climate Resilience Assessment Scan") genoemd. De AirCRAS moet na gebruik een overzicht bieden van de sterke en zwakke punten van een vliegveld op dit gebied. De scan is ontwikkeld in opdracht van Netherlands Airport Consultants (NACO), een wereldwijd toonaangevend ingenieurs- en adviesbureau voor luchthavens over de hele wereld. Met het ontwikkelen van deze scan beoogt NACO te voorzien in de veranderende behoeften van hun klanten.

Voor het ontwikkelen van de scan volgt dit onderzoek een ontwerpgerichte onderzoeksmethode. Deze methode beoogt het in de praktijk ervaren probleem direct aan te pakken door een oplossing te bieden. De ontwerpgerichte onderzoeksmethode bestaat uit drie fases: de probleemanalyse, de ontwerpfase en de validatiefase.

De probleemanalyse
In de probleemanalyse zijn de problemen die worden ervaren in de praktijk bij het verbeteren van de klimaat-resilience van vliegvelden geïdentificeerd, en is gezocht naar de 'state-of-the-art' literatuur die gebruikt kan worden voor het ontwerpen van een oplossing.

Middels een focusgroep sessie en interviews is NACO's huidige kennis en ervaring met betrekking tot het creëren van klimaat-resilient vliegvelden in kaart gebracht. De bevindingen laten zien dat NACO zich in het algemeen richt op het modelleren van de kwetsbaarheid van verstorende gebeurtenissen. Dit is vooral bedoeld om de economische impact op infrastructuur te analyseren. Deze benadering is technisch georiënteerd en treedt snel in details. Het mist daardoor mogelijk de identificatie van relevante problemen bij het creëren van klimaat-resilient vliegvelden op, bijvoorbeeld, organisatorische aspecten. Alvorens in details wordt getreden is het daarom van belang dat eerst de sterke en zwakke punten van een klimaat resilience luchthaven worden beoordeeld op meerdere aspecten. Hierdoor behoedt men zich ervoor relevante problemen over het hoofd te zien.

Om in kaart te brengen welke mogelijkheden er bestaan rondom het beoordelen van de klimaat resilience status van een luchthaven op meerdere aspecten, is literatuuronderzoek verricht. De literatuur op dit gebied blijkt zeer uitgebreid. Het gaat in op bijvoorbeeld resilience indicatoren, principes, en operationele kaders. Het heeft echter zelden betrekking op de luchtvaartindustrie. Het blijkt dat sectorspecifieke resilience indicatoren een effectieve manier zijn om resilience te meten. Ze kunnen helpen bij het begrijpen en diagnosticeren van prestaties. Ze benoemen wat de meest kritieke problemen lijken te zijn, en helpen om kansen te identificeren. De indicatoren kunnen worden gemeten door ze te om te zetten naar assessment vragen. Sectorspecifieke indicatoren zijn niet beschreven voor de luchtvaartindustrie.

Hieruit kan worden geconcludeerd dat er in de literatuur een lacune bestaat over hoe resilience gemeten en geoperationaliseerd kan worden op luchthavenniveau. Deze kenniskloof is de oorzaak van het gebrek aan strategische begeleiding van luchthavens bij de transitie naar een klimaat-resilient luchthaven. Gezien deze lacune, beoogt de scan de onderzoeksgebieden van klimaat resilience en de luchttransportindustrie met elkaar én met de praktijk te verbinden. De bevindingen uit de probleemonderzoeksfase zijn samengevat in een ontwerpopdracht die

* Klimaat-resilient en klimaat resilience zijn Engelse termen die in het Nederlands worden vertaald met veerkracht. Deze Nederlandse term dekt de lading niet. Daarom is ervoor gekozen om de Engelse term "resilience" te gebruiken in deze Nederlandse samenvatting.

de basis vormt voor de ontwikkeling van de AirCRAS, waarin ontwerpeisen voor de AirCRAS zijn opgenomen.

De ontwerp- en validatiefase
In de ontwerpfase wordt een prototype van de AirCRAS ontwikkeld op basis van de ontwerpopdracht. Daarnaast is de literatuur opnieuw geraadpleegd voor het identificeren van klimaat resilience indicatoren. Voor de gevonden indicatoren zijn bijpassende assessment vragen geformuleerd. In de validatiefase zijn drie validatiesessies gehouden, bestaande uit twee focusgroep sessies en een interview. Deze sessies zijn om twee redenen gehouden. Ten eerste om te verifiëren of aan de ontwerpeisen is voldaan. Ten tweede om te controleren of het ontwerp voldoet aan de gebruikersverwachtingen. In elk van deze validatiesessies is feedback ontvangen en zijn dienovereenkomstig verbeteringen aangebracht aan het ontwerp. Om die reden zijn de ontwerpfase en validatiefase sterk met elkaar verweven. Het proces van het presenteren van de scan, het ontvangen van feedback en het verfijnen van het ontwerp is drie keer herhaald.

De AirCRAS is een digitale tool. De gebruikers van de AirCRAS zijn experts van NACO. Samen met de experts van de luchthaven vormen zij een expertpanel dat gezamenlijk het AirCRAS doorloopt in een workshop aan het begin van een project. In de AirCRAS beantwoordt het expertpanel een set assessment vragen. Het doorlopen van de AirCRAS duurt ongeveer een halve dag. De AirCRAS bestaat uit vier fases:

1. De eerste fase van de AirCRAS is bedoeld om de verwachtingen af te stemmen op de experts met betrekking tot de relevantie van het uitvoeren van de AirCRAS en het proces dat het expertpanel zal doorlopen. Hierbij is een tijdsindicatie gegeven over hoelang het duurt om de AirCRAS te doorlopen. Ook gaat deze fase in op de bronnen die zijn gebruikt voor de ontwikkeling ervan. Dit is nodig om de expert panel te overtuigen van de betrouwbaarheid van de informatie;
2. In de tweede fase bepalen de gebruikers welke klimaatvectoren ze relevant achten voor de luchthaven in kwestie. Het kiezen van relevante klimaatvectoren voor hun specifieke luchthaven is nodig omdat de assessment vragen die in de derde fase beantwoordt moeten worden, afhankelijk zijn van die klimaatvectoren. Voor een vliegveld in Midden-Afrika is het bijvoorbeeld irrelevant om vragen te beantwoorden met betrekking tot zeespiegelstijging. Door deze vragen buiten beschouwing te laten, verhoogt de efficiëntie van het proces;
3. De selectie van assessment vragen die worden beantwoord in deze fase, zijn onderverdeeld in drie categorieën: organisatie, operatie en infrastructuur. De vragen moeten worden beantwoord op een schaal van A (vertegenwoordigt het beste antwoord) tot E (vertegenwoordigt het slechtste antwoord);
4. In de vierde fase worden de resultaten gepresenteerd in een roos diagram. Ook zijn discussiepunten gegeven die dialogen op gang moeten brengen over, onder meer, de uitdagingen die de luchthaven ervaart in hun transitie naar een klimaat-resilient luchthaven. De uitkomst van de discussie resulteert in prioriteiten en/of beperkingen die richting geven aan een vervolgstudie die de knelpunten meer gedetailleerd onder de aandacht brengt.

De conclusie
Dit onderzoek presenteert de eerste klimaat resilience assessment scan (AirCRAS) voor luchthavens. Door een ontwerpgerichte onderzoeksmethode toe te passen is het theoretische concept omgezet in een operationele scan. De scan geeft een overzicht van de algemene uitdagingen van een luchthaven bij de transitie naar een klimaat-resilient luchthaven. Dit heeft belangrijke gevolgen voor planning en investeringen om de resilience van de betreffende luchthaven te vergroten.

De aanbevelingen
Tot slot zijn vier aanbevelingen voor toekomstig onderzoek en twee aanbevelingen voor de praktijk geformuleerd. Allereerst wordt aanbevolen om verder te onderzoeken óf en welke acties luchthavens over de hele wereld nemen om zich voor te bereiden op extreme weersomstandigheden. Er wordt aanbevolen om motieven van luchthavens te identificeren voor het wel of niet handelen ter voorbereiding op de gevolgen van klimaatverandering.

De AirCRAS is op dit moment alleen geschikt voor de individuele beoordeling van luchthavens. De betekenis van de labels die worden toegekend aan een indicator, is namelijk subjectief. Voor het uitwisselen van kennis en ideeën tussen luchthavens, is het aanbevolen om de AirCRAS verder door te ontwikkelen naar een benchmark methode. Hierin moeten labels dezelfde betekenis hebben.

Ten derde is het aanbevolen om onderzoek te doen naar het verder ontwikkelen van de AirCRAS naar een evaluatie tool. Het kan interessant zijn om de AirCRAS te gebruiken na afloop van het project, om te valideren of (de juiste) veranderingen hebben plaatsvonden.

Op dit moment wordt er alleen gekeken naar de resilience van luchthavens op luchthavenniveau. Er wordt aanbevolen luchthavens te bekijken als onderdeel van de infrastructuur in een gebied. In dat kader kunnen de mogelijkheden van samenwerken tussen luchtvervoer en hogesnelheidstreinen worden verkend om de resilience van het totale transportsysteem te vergroten.

Praktische aanbevelingen hebben betrekking tot, ten eerste, het ondersteunen van verdere ontwikkeling van dit expertisegebied binnen NACO. Dit betreft, onder andere, het aanstellen van iemand die verantwoordelijk is voor de implementatie en verdere ontwikkeling van de AirCRAS. Ook wordt geadviseerd om een model te ontwikkelen dat berekent welke van de klanten van NACO het grootste risico lopen op extreme weersomstandigheden. Deze informatie kan worden gebruikt om luchthavens actief te benaderen voor het verwerven van nieuwe projecten gericht op het verbeteren van de klimaat resilience van luchthavens.

V. TABLE OF CONTENT

VI. LIST OF TABLES

VII. LIST OF FIGURES

VIII. LIST OF EXAMPLES

IX. LIST OF ACRONYMS

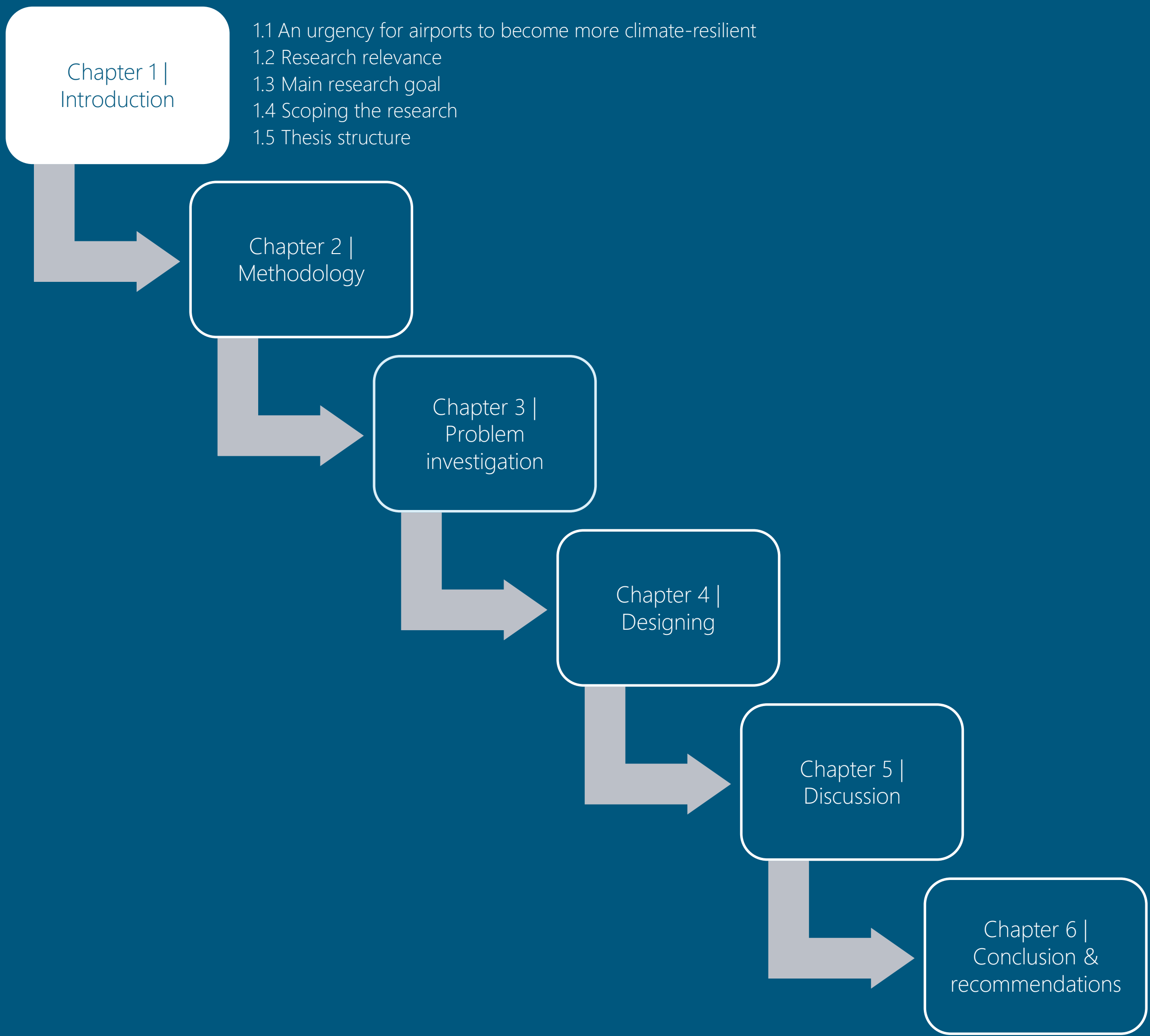
A-CDM	Airport Collaborative Decision Making
ACI	Airport Council International
ACRP	Airport Cooperative Research Program
AirCRAS	Airport Climate Resilience Assessment Scan
ATC	Air Traffic Control
ATS	Air Transportation System
DFW	Dallas/Fort Worth International Airport
FAA	Federal Aviation Administration
GTAA	Greater Toronto Airports Authority
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
IPCC	Intergovernmental Panel on Climate Change
ISO	The International Organisation for Standardisation
NACO	Netherlands Airport Consultants


C7

CHAPTER 1 | INTRODUCTION

Airports are complex, interdependent and critical systems, that are vulnerable to the impacts of extreme weather events, which are reinforced by climate change. To mitigate the consequences of extreme weather events, airports need to become more climate-resilient. The first step towards improving the climate resilience status of airports is assessing their current performance. Since currently no assessment method that enables to measure resilience on the airport level exists, this research aims to develop an Airport Climate Resilience Assessment Scan (AirCRAS).

The first chapter starts with an elaboration on the background of the research topic, which emphasizes the urgency for airports to become more climate-resilient. Section 1.2 continues with a description of the research relevance for both science and practice. From both the background information (Section 1.1) and the research relevance (Section 1.2) the main research goal results, and is presented in Section 1.3. Section 1.4 describes what is and what is not included within the boundaries of this research. Finally, the thesis structure is given in Section 1.5.



1.1 An urgency for airports to become more climate-resilient

A changing climate

We are living in a turbulent world. A world that is experiencing changes in average temperature, sea level rise, increased storm intensity and many other climate change impacts (ICAO 2018). Large areas of inhabited land, alongside their infrastructure, are projected to be flooded every year, and many other extreme weather events have been developing and will continue to do so into the following decades (United Nations 2019). The World Economic Forum (2019) states in their Global Risk Report that extreme weather events, natural disasters, and the failure of climate change mitigation and adaptation, are the risks having the highest likelihood and highest impact for society on a global scale. It appears that the consequences of extreme weather events, which are reinforced by a changing climate, are inevitably putting pressure on many aspects of society.

Airports as critical infrastructure in modern society

Modern society relies on the effective functioning of its critical infrastructures. Airports are considered critical infrastructure because interruptions not only influence the airports but due to the interconnectedness of the aviation system, loss of functionality of one airport may have ripple-effects across a wide geographical area (Ali and Jones 2013; Arsenault 2017; Shapira et al. 2019). For example, In April 2010 an ice-capped volcano in Iceland roused from a 187-year slumber. European aviation authorities grew concerned as the ash cloud drifted toward the continent and the UK. If an aircraft flew throughout the ash cloud, the ash could damage the plane's engines, sandblast the cockpit windows, and damage aircraft instruments. As a precaution, civil aviation authorities shut down major hubs for cargo such as Heathrow, Amsterdam, Paris, and Frankfurt, which were closed for six days (Hennessy 2010). Companies, however, weren't prepared for such an event. Although some airfreight might not be particularly time-sensitive (e.g. jewellery), many categories of freight are dependent on a tight schedule (e.g., perishable foods, vaccines, emergency spare parts, and surgical instruments). During these six days, thousands of tons of Kenyan fresh flowers rotted in storage units and warehouses, representing a loss to the Kenyan economy of $3.8 million per day (B. Lee, Preston, and Green 2012), which representants about 3 per cent of Kenya's daily GDP (Central Intelligence Agency 2010). A Swiss supermarket chain, noted disruptions in supplies from the United States (green asparagus), Iceland (cod), and Southeast Asia (tuna). Italian exporters of mozzarella and fresh fruits lost about $14 million each day that flights were grounded (Ibid.). The Federation of Hong Kong Industries said hotels and restaurants in Hong Kong had shortages of French cheese, Belgian chocolates, and Dutch fresh-cut flowers (B. Lee, Preston, and Green 2012). On top of that, the volcano crisis had a tremendous impact on global air traffic and led to 48% of cancelled flights. This corresponds to 10 million stranded passengers and a loss of approximately $1.5 – 2.5 billion for the airlines in just a few days (Schmitt and Kuenz 2015; Bye 2011). The example illustrates that the global interconnectedness caused by the aviation industry can bring huge damages to the whole of society. Moreover, airports are widely used as the main logistical hubs for incoming relief supplies, and provide in this way a lifeline to affected communities after a disaster (Walle 2018) This emphasises the need of well-functioning of airports during disaster periods.

Airports' vulnerability to extreme weather events

Nowadays, these interconnected and essential airports are experiencing the consequences of climate change (ICAO 2018). For example, Don Muang airport in Bangkok has experienced extreme rainfall in 2011, resulting in a shutdown of the airport for a year to repair the damages and to ensure airport operations could resume. Also, the hurricanes Katrina and Sandy that hit the USA have caused the shutdown of many airport operations (Vorage 2018). Besides, the world's busiest airports are often located close to the coast and near major cities. However, coastal areas are exposed to fierce winds, storm surges, large waves and tsunamis that expend their destructive energy when they reach the coastline, which creates potentially catastrophic losses and makes these airports extremely vulnerable to extreme weather events (Kron 2013).

An urgency to create climate-resilient airports

To conclude, airports are complex, interconnected and highly essential systems that are vulnerable to extreme weather events. The probability of occurrence of these extreme weather events is increasing due to climate change. Also, the impact of such events is reinforced by climate change and can become immense not only for airports themselves but also for all who are relying on their effective functioning. Therefore, to mitigate the consequences of the impacts of extreme weather events, airports need to become more climate-resilient.

1.2 Research relevance

To support clarity in further reading, the definition of a 'climate-resilient airport' is given. This definition is based on the three resilience capacities as identified by Francis and Bekera (2014). It is formulated for this particular research:

*A **climate-resilient airport** is an airport that can absorb impacts of extreme weather events, recover from disruptions caused by them and adapt to the changing conditions.*

The origin of the definition is detailly explained in the problem investigation (Chapter 3).

Practical relevance
The project has been commissioned by Netherlands Airport Consultants (NACO), which is part of Royal HaskoningDHV (RHDHV). NACO is a world-leading airport engineering and consultancy firm with over 70 years' experience working in the aviation and air transportation industry. From the largest of international hubs to regional and domestic airports, NACO has helped to guide the future of over 600 airports in more than 100 countries around the world (NACO 2020a). NACO is focused on ensuring that airports will continue to function for decades to come. Therefore, contributing to the sustainable airport evolution is right at the heart of their mission (NACO 2020c).

In 2018, the European Organisation for the Safety of Air Navigation (EUROCONTROL) launched a survey to determine to what extent the European aviation sector considered the potential impacts of climate change to be of concern. Also, they aimed to identify whether or not organisations within the sector have been taking action to adapt to those impacts (EUROCONTROL 2018). Responses were from a range of aviation stakeholders including air navigation service providers, airport operators, airlines, civil aviation authorities and manufacturers. The survey revealed that 86% per cent out of 80 respondents expect that adaptation to the impacts of climate will be necessary now or in the future. However, only 52% of the respondents are initiating planning for the impacts of climate change. The main reason for not acting was a lack of information about how to do so (Ibid.). Even though data regarding how many airports worldwide expect to be impacted by climate change is limited, similar results are expected. This lack of knowledge provides an opportunity for NACO to further develop their expertise on climate-resilient airports, to pre-emptively find solutions for the changing stakeholder needs.

NACO's current experience regarding improving the climate resilience of airports is limited. So far NACO has conducted one extensively documented Climate Resilience Study, for Singapore Changi Airport. In this study, the Civil Aviation Authority of Singapore (CAAS) and NACO developed a methodology to map and mitigate airport climate change risks (Dolman and Vorage 2019). According to NACO's experts, their current stepwise approach is generally focused on modelling the vulnerability to disruptive events which are mainly for the purpose of analysing the economic impact on infrastructure. This approach is technically oriented and tends to go quickly into details. It may therefore miss the identification of relevant problems in the creation of climate-resilient airports on, for example, organizational aspects. Before going into details, it is therefore important that the strengths and weaknesses of a climate resilience airport are first assessed on various aspects. This is to avoid overlooking relevant problems.

Scientific contribution
Literature was consulted to explore the possibilities for creating a holistic overview of the climate resilience status of airports. It is found that a resilience assessment method can help to create an overview of the performance of a system (Alshehri, Rezgui, and Li 2015; Lopez 2016). Most of the research regarding resilience assessment methods focus on urban areas or disaster risk management (Cutter, Burton, and Emrich 2010; Alshehri, Rezgui, and Li 2015; Silva, Kernaghan, and Luque 2012; Tyler and Moench 2012). Within these contexts, researchers introduce resilience principles (Kim and Lim 2016), while others use resilience characteristics or qualities (Tyler and Moench 2012) as a mechanism to measure resilience. However, resilience principles, characteristics or qualities (e.g., flexibility or redundancy) are rather broad aspects that need to be more specifically formulated to be of any use for practice. Besides, Cariolet, Vuillet, and Diab (2019) emphasize that indicators as developed in a specific context, should not be applied systematically to other contexts as resilience is a context-dependent concept.

Lisa, Schipper, and Langston (2015) suggest that sector-specific indicators may be the most effective mechanism to measure resilience because they can provide enough context by asking detailed questions. An indicator is a quantitative or qualitative measure derived from observed factors that have the potential to simplify complex real-world phenomena into information that is easier to communicate (European Environment Agency 2003; Freudenberg 2003; Molle and Mollinga 2003). Resilience indicators can help to understand and diagnose performance since they are able to offer a quick scan of the situation of a resilient system, highlighting its strengths and weaknesses (Cutter, Burton, and Emrich 2010). They appoint what seems to be the most critical issues and contribute to the enhanced problem formulation (Jensen and Wu 2018). Therefore, indicators are often used as a mechanism to communicate performance with stakeholders (Øien, Bodsberg, and Jovanović 2018). These functions signify the important role of resilience indicators as building blocks of any assessment system (Ilmola 2016). To enable resilience improvements to be tracked over time, specific indicators would need to be established. These findings show that the use of indicators for measuring the climate resilience status of airports offer a great opportunity. Yet, at present there is no set of indicators that enables measurement of climate resilience on the level of airports.

Research on the resilience of air transport networks has generally been focused on analysing and modelling their dynamics (indirect connectivity and passenger dynamics, air traffic jams, and epidemic spreading) and vulnerability to disruptive events (Cardillo et al. 2013). Little attention has been devoted to the qualitative analysis of airports under disruptive situations, such as extreme weather events. Within this context, most literature analysis the impacts of climate change, resilience, and adaptation (Ferrulli 2016; NATS 2011; EUROCONTROL 2013; ACRP 2012; ICAO 2018b; 2018a; Pendakur 2017; ICAO 2016a; GTAA 2014; ACI 2018). However, it remains unclear what factors affect airport resiliency performance (Zhou and Chen 2020). More importantly, no assessment scan providing insight into the overall overview of the strengths and weaknesses of airport regarding the climate resilience status, exist.

It can be concluded that in literature there is a lack of knowledge on how climate resilience can be measured and operationalised on the airport level. This knowledge gap is the cause of the lack of strategic guidance from airports in the transition to a climate-resilient airport. Considering these gaps, the AirCRAS aims to connect the two research fields of assessing resilience and the air transportation industry with each other, and with practice.

1.3 The research goal

Resulting from the background information (Section 1.1.) and the research relevance (Section 1.2.) this research aims to:

> *Design an Airport Climate Resilience Assessment Scan (AirCRAS) that can be used by airport engineering and/or consultancy companies to create a holistic overview of the climate resilience status of an airport.*

A holistic overview of the climate resilience status of an airport should prevent engineers from rapidly delving into technical details. The premise is that this overview will stimulate discussion about the challenges that the airport faces in the transition towards becoming a more climate-resilient airport, and facilitates dialogues about the level of risk the airport is willing to accept. This provides priorities and constraints for the follow-up in-depth resilience study, and will finally result in important implications for future planning and investments to enhance the climate resilience of the airport in question.

This research adopted a design science methodology to achieve the research goal. Three design phases and various design activities were conducted. These are detailly explained in the Methodology (Chapter 2).

1.4 Scoping the research

As previously stated, in this research the climate resilience status of airports for extreme weather events will be discussed. This excludes the airports' level of resilience to any other disaster. So, excluding e.g., terrorist attacks, chemical leaks, cyber-attacks, pandemics and political crisis.

Extreme weather events can be regarded as shocks (fast-moving variables) or stressors (slow-moving variables) (Ernstson et al. 2010; Maru 2010). This research differentiates between seven climate vectors (being aspects of the climate that are known to affect the airport in question). These climate vectors categorise the impact of climate change on the airport and can be considered both climate shocks and climate stressors. Therefore, this research takes into account both aspects. The seven climate vectors are examined in this research, are the following: 1) sea level rise, 2) increased intensity of storms, 3) temperature change, 4) changing precipitation, 5) changing icing conditions, 6) changing wind and 7) desertification. Section 4.1, describes how these climate vectors are established and elaborates on what each of these climate vectors entails.

As explained in Section 0, the AirCRAS aims to provide a holistic overview of the climate resilience status of an airport, which are governed by airport authorities. Aspects that are in hands of, for example, airlines or air traffic management do not fall within the responsibilities of the airport authority and therefore, are not included in the creation of a holistic overview of the climate resilience status. These aspects are considered outside the scope of this research.

The AirCRAS is based on climate resilience indicators and variables. However, this research does not aim to deliver a complete set of indicators and variables since providing quick insight into the strengths and weaknesses does not necessitate such. Besides, delivering a complete set of indicators and variables is not possible in the fast-changing world in which we live today. Instead, the indicators and variables that are developed to form a starting point for measuring the climate resilience of airports.

1.5 Thesis structure

This report guides the reader through six sequential chapters.

Whereas this first chapter introduced the research background, its relevance and its goal, Chapter 2 elaborates upon the design science methodology that was adopted to achieve the research goal. Chapter 2 explains why this approach is suitable for this research and elaborates on the design activities that are run through. Additionally, the chapter explains what data collection methods are used to gather data that is needed to conduct the design activities. This design science project consists of three phases: the problem investigation phase (phase A), the design phase (phase B), and the validation phase (phase C).

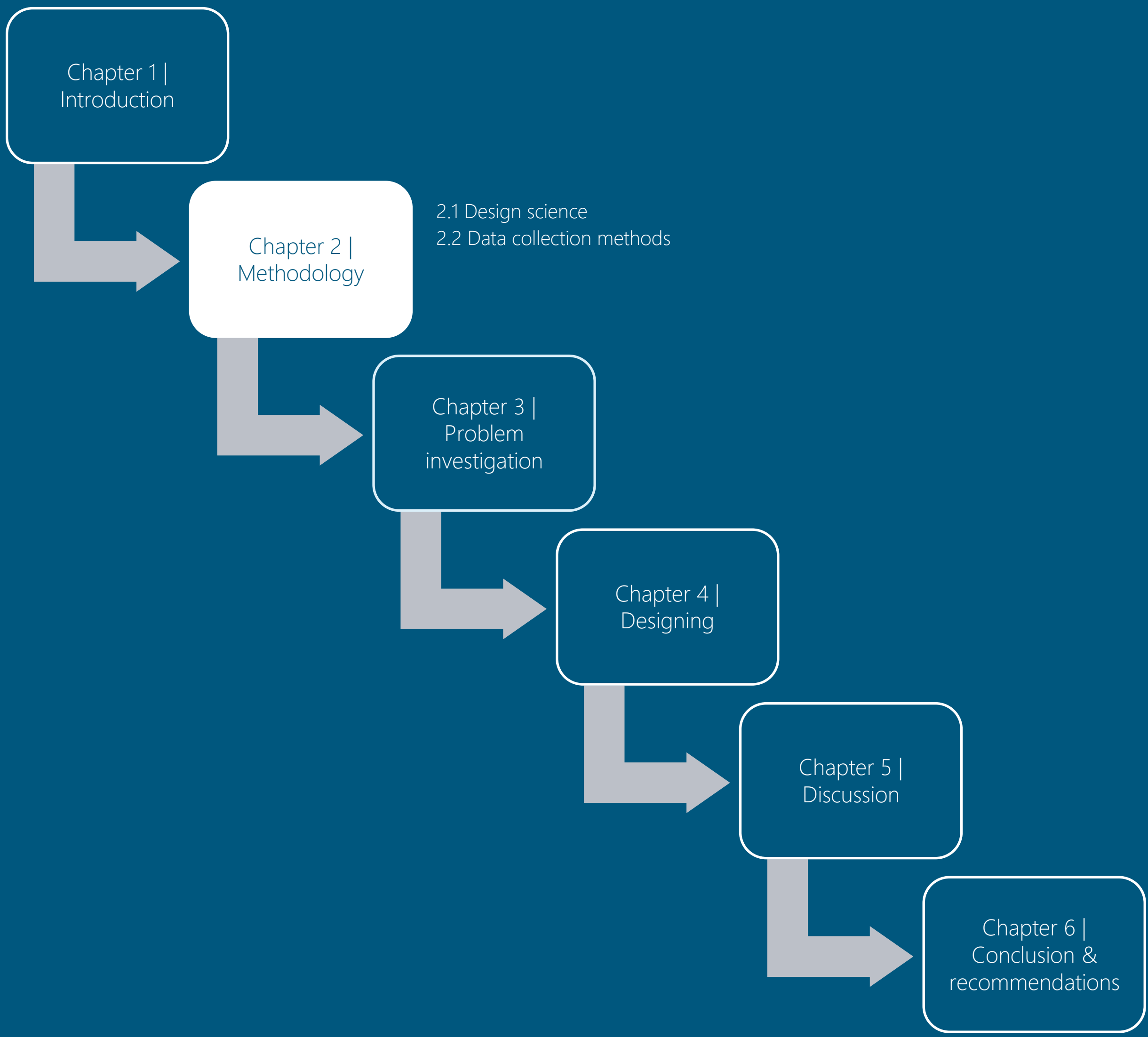
Chapter 3 presents the problem investigation phase (phase A). This chapter This chapter aims to identify the problem that is experienced in practice to improve the climate resilience status of airports, and creates an overview of the state-of-the-art literature that can be used to design a solution for this problem. By doing so, the design goal becomes evident. The chapter synthesis the information into a design brief which forms a basis for the development of the AirCRAS.

The design phase (phase B) and validation phase (phase C) are intertwined. To clarify, in the design phase a prototype of the AirCRAS is developed. In the validation phase, three validation sessions were conducted to gain feedback and improve the AirCRAS accordingly. Hence, the process of presenting the AirCRAS, receiving feedback and refining the design accordingly, is iterated three times. Chapter 4 firstly offers some insight into the iterative process that was run through towards the validated AirCRAS. Next, the validated AirCRAS is presented in more details. The chapter closes by verifying whether the design requirements as summarized in the design brief, are met.

Chapter 5 discusses the reliability and validity of the research, and elaborates on the added value to literature. Finally, Chapter 6 concludes and provides recommendations for future research and practical purposes.

CHAPTER 2 | METHODOLOGY

This chapter elaborates on the design science methodology that is adopted in this research. Section 2.1 introduces the design science methodology by describing the relevance of applying it, and by presenting the design activities that are run through in this design science project. Section 2.2 describes the data collection methods that are used to gather data that is needed to conduct the design activities.



2.1 Design science

Resilience does not translate easily into practice (Sellberg, Wilkinson, and Peterson 2015). As Martin-Breen and Anderies (2011) stated: *"Resilience is not visible, it is a theoretical construct that relates to an individual's or system's response to future events."* (p.52). Design science, in contrast to more traditional research approaches, aims to directly tackle the problem experienced in practice by providing a solution. Therefore, design science forms the designated research approach for the sake of coping with the challenge of translating a theoretical construct into practice, in particular within a given amount of time.

Design science, as described by Van Aken (2007), has been developed because of discontent about existing academic research approaches. According to the author, such approaches have been strongly academized. These can be used to describe, explain, and criticize. Nonetheless, such approaches do not actually design solutions for problems experienced in practice (ScienceGuide 2008; Higgs and Rowland 2000). As a consequence, an increasing separation arises between theory and practice (Bunker, Alban, and Lewicki 2004; Rynes, Bartunek, and Daft 2001). Design science aims to resolve these deficiencies by (re)designing an artefact so that it effectively contributes to the achievement of the stakeholder's goal (Wieringa 2014). Design science addresses the aforementioned limitations by focussing strongly on the desired outcome and being holistic- and client-orientated (Van Aken 2007).

Design science combines academic research and designing. Since these concepts are contradictory regarding many aspects (see Figure 1) it has to be noted that we cannot simultaneously do both to the full extent. As Fällman (2005) stated: *"It might simply be too much to both do a good design, with a happy client – answering to all the real-world challenges one will face – and do a good research, with happy peers, i.e., answering to being true over being real"* (p.5). Instead, forces are joined to, as systematically as possible, deliver a design which is as useful as possible for practice.

Figure 1 provides insight into how the approaches are integrated into this particular research.

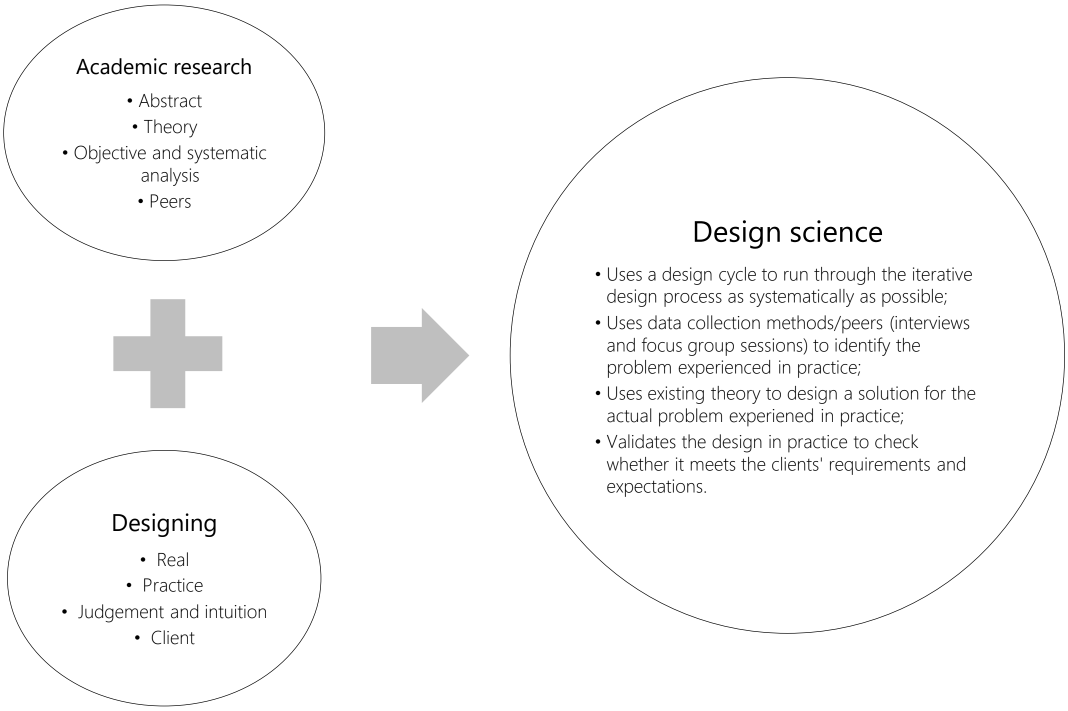


Figure 1: *A rough representation of how design science combines academic research and designing to close the gap between theory and practice, adapted from Fällman (2005).*

Wieringa's design science methodology

According to Wieringa (2014), a design science project consists of three phases: the problem investigation phase (phase A), the design phase (phase B), and the validation phase (phase C). Since a design science project iterates many times over these phases, the set of phases is called the 'design cycle' (Wieringa 2014).

The design cycle is part of the larger 'engineering cycle'. In the engineering cycle, the result of the design cycle (which is a validated design) is transferred to the real world, used, and evaluated (Ibid.). However, this research runs through the design cycle only.

Figure 2 illustrates the design cycle which is established and outlined by Wieringa (2014), and adapted to fit the purpose of this research. The activities that are conducted in each phase are introduced next. Also, the data collection methods that were used to gather the required data are introduced next, and further elaborated on in Section 2.2.

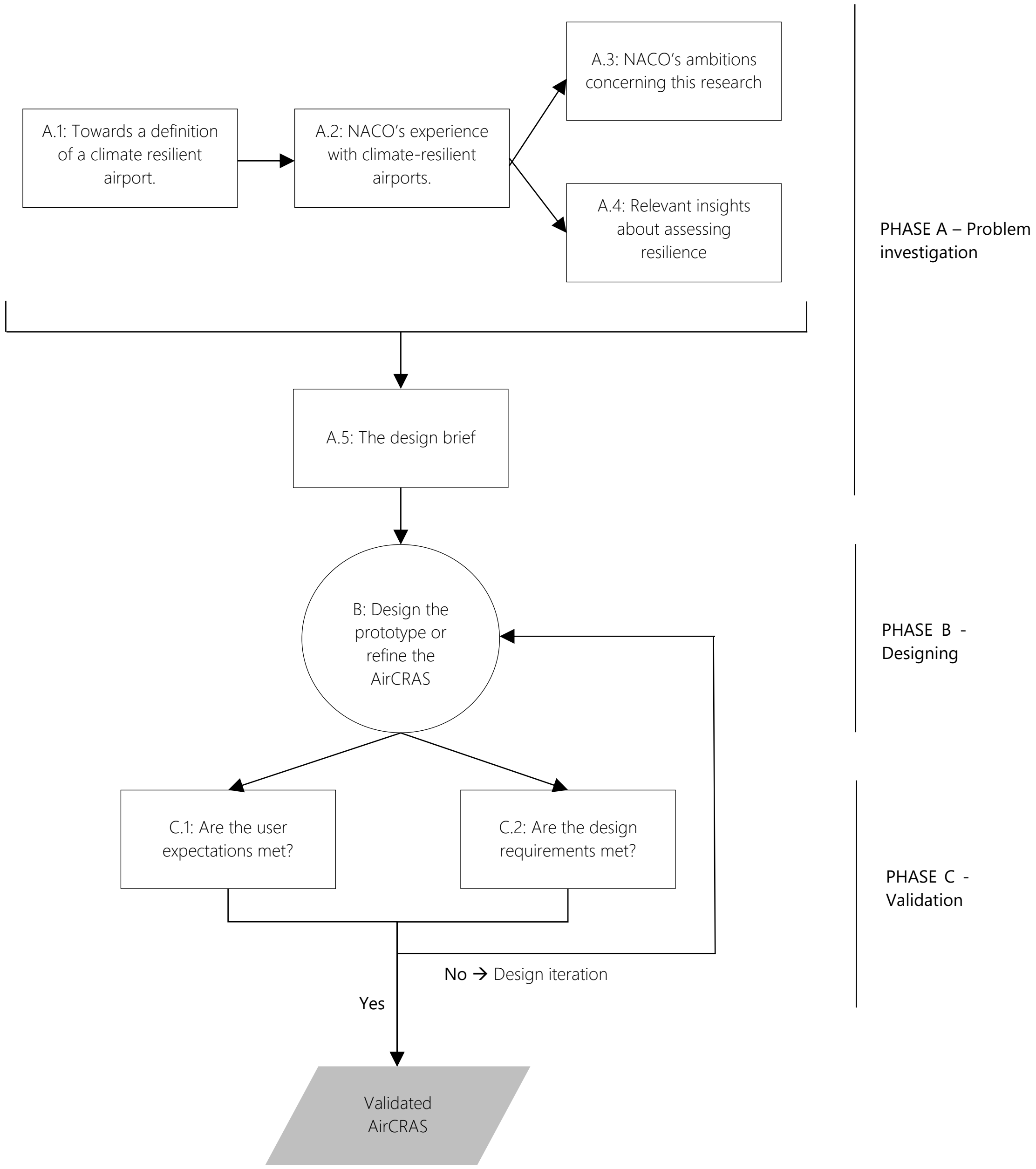


Figure 2: The tailor-made design activities per design phase, adapted from Wieringa (2014).

The problem investigation (phase A) aims to identify the problem that is experienced in practice to improve the climate resilience status of airports, and creates an overview of the state-of-the-art literature that can be used to design a solution for this problem. The phase starts with establishing the definition of a climate-resilient airport. Once the meaning of a climate-resilient airport is clear, the current stepwise approach that NACO runs through for improving the climate resilience of airports will be described. Based on the limitations of the current stepwise approach, NACO's ambitions for improving the existing stepwise approach have been formulated next. Since some of these ambitions are related to assessing resilience, in the following step literature is consulted to identify the possibilities that assessing resilience brings along. Furthermore, literature is reviewed to identify what knowledge regarding climate resilience of airports is available, and how this information can be used in response to NACO's ambitions. All this information is synthesised into a design brief which, among others, describes the goal of designing an AirCRAS, elaborates how the information in literature can be used as a mechanism to comply with NACO's ambitions and summarizes design requirements the AirCRAS has to meet. The design brief forms the starting point of development of the AirCRAS.

The **design phase (phase B)** and **validation phase (phase C)** are intertwined due to the iterative nature of the design process. In the design phase a prototype of the AirCRAS is developed, based on the design brief. For the identification of climate resilience categories, indicators, and variables, again, literature was consulted, and documents have been analysed. From this, a prototype of the AirCRAS resulted. Three validation sessions were conducted to refine the prototype. These sessions were conducted for two reasons, first, to verify whether the design requirements are met (with that, the validation phase includes a ***verification*** element) and second, to check whether the design complies with the user expectations. In each of these validation sessions, feedback and improvements were made accordingly. Hence, the process of presenting the AirCRAS, receiving feedback and refining the design accordingly, is iterated three times. In the third validation session the AirCRAS was applied to the particular project of Singapore Changi Airport to validate whether the results of the AirCRAS are in line with the results of the pre-existing resilience study. After the last validation session, it was decided to not conduct further validation sessions, since all design requirements were either met or substantially met and no new user expectations arose. Besides, the feedback as acquired in the last validation session, was of a very fine level of detail, mainly regarding the formulation of the assessment questions.

2.2 Data collection methods

In this research, literature was reviewed, documents have been analysed, four interviews have been conducted and three focus group sessions were organised. Table 1 summarizes the data collection method that were used to conduct a design activity. The following section more detailly elaborates on each of these data collection methods.

Table 1: Summary of the data collection methods used in each of the design phases.

Activities of the design cycle	Data collection method
PHASE A – Problem investigation	
A.1: Towards a definition of a climate-resilient airport	• Literature review • Document analysis
A.2: NACO's experience with climate-resilient airports	• Document analysis
A.3: NACO's ambitions concerning this research	• First focus group session (FS1) • Feedback as obtained in interviews (I1, I2 and I3)
A.4: Relevant insights about assessing resilience	• Literature review
A.5: Design brief	• Synthesis of previous information
PHASE B – Designing	
B: Design (or refine) the AirCRAS	• Design brief (activity A.5) • Literature review • Document analysis • Feedback as obtained in FS2, FS3 and I4
PHASE C - Validation	
C.1 Are the design requirements met?	• Second focus group session (FS2) • Third focus group session (FS3) • Interview (I4)
C.2 Are user expectations met?	• Second focus group session (FS2) • Third focus group session (FS3) • Interview (I4)

Table 2 presents the participants of the interviews and focus group sessions. Table 8 in Appendix A, describes each of the participants' backgrounds and presents the questions that have guided the discussion in both the interviews and focus group sessions.

The same participants were approached repeatedly since it allows to build upon previously acquired information and validate whether feedback has been correctly interpreted and integrated into the design and prevents the research from diverging into many different directions. To prevent bias in acquired information, in the second and third focus group session (FS2 and FS3) two new participants were invited and one out of the three participants did take part for the second time.

A recording device has been used to collect the data in both the interviews and focus group sessions. Based on the recordings, transcripts have been made and sent back to the respondents. Data was processed so that anonymity is ensured. Only from the participants who had indicated so at the beginning of an interview, their name and contact information will be recorded, serving as a means of contact in future participation and providing feedback. The information was not shared with third parties. The raw data will only be accessible by the researcher and her direct supervisors.

Table 2: Participants per data collection method.

Data collection method	Reference to participants
PHASE A – Problem investigation	
First focus group session (FS1)	NACO expert 1
	NACO expert 3
	NACO expert 4
First interview (I1)	RHDHV expert 1
Second interview (I2)	NACO expert 1
Third interview (I3)	NACO expert 2
PHASE C - Validation	
Second focus group session (FS2)	RHDHV expert 1
	NACO expert 5
	EUROCONTROL expert 1
Third focus group session (FS3)	NACO expert 3
	RHDHV expert 2
	NACO expert 6
Fourth interview (I4)	NACO expert 3

Next, we will elaborate on each of the data collection that was used to conduct a design activity.

PHASE A – Problem investigation

In **activity A.1** literature was reviewed to identify the meaning of a climate-resilient airport. To ensure that all potential literature was selected, specific search operators were used to select the relevant articles regarding climate-resilient airports in the Scopus library. Appendix B provides detailed information about these search operators and describes each of the five scientific articles. However, no clear definition of a climate-resilient airport had been identified in literature. Therefore, it was explored how a climate resilient system was defined according to authors in related research fields, such as urban areas, ecological systems, climate adaptation and infrastructure systems. Additional documents of global frontrunners regarding the topic, such as the Resilience Alliance, United Nations (UN), and Intergovernmental Panel on Climate Change (IPCC), are explored. By consulting a wide variety of sources, common denominators were identified which were used to define a climate-resilient airport.

In **activity A.2**, a detailly documented Climate Resilience study that NACO conducted for Singapore Changi Airport is used for the identification of NACO's experience with climate-resilient airports. This Climate Resilience Study is the only documented information in possession of NACO, describing their current knowledge.

In **activity A.3**, the first focus group session (FS1) was conducted to create an overview of NACO's ambitions concerning this research. Focus group sessions allow participants to respond to each other by adding to and criticizing each other's statements (Eliot 2005). By doing so, commonly agreed ambitions could be formulated which is considered essential for successful completion of this research. Both of NACO's supervisors for this research (NACO expert 3 and NACO expert 4) have been invited to participate in FS1, because this focus group session might guide the research in a certain direction which both supervisors should agree with. Besides, an additional expert from NACO who has been working on a climate resilience project before, has been invited in FS1 as well. It is expected that having a third climate resilience expert from NACO on board in FS1 will result in more discussions. Especially since one of the supervisors of this project (NACO expert 4) has no previous experience with climate resilience.

To further refine NACO's ambitions and to extract design requirements from these, three interviews (I1, I2 and I3) have been conducted. Interviews allow to ask open-ended questions and ask for individual experiences and opinions aiming to get in-depth information (Verschuren and Doorewaard 2010) which is needed to extract design requirement. Experts for I1, I2 and I3 have been selected based on the following inclusion criteria: they should have been working on a climate resilience-related project for NACO. In total there are four resilience experts within NACO, and two of RHDHV"s resilience experts closely works together with NACO. Since the number of experts who have been working on such a project for NACO before is limited, there is only one more selection criteria. This includes that one of the resilience experts of NACO that participated in FS1, should be invited for an interview as well. This allows us to build upon previously acquired information.

The interviews that have been conducted, were semi-structured (Silverman 2017). To efficiently prepare interviews, the defined questions have been distributed into different categories. Due to the semi-structured character of the study, the interviewees were allowed to answer the questions in an unconstrained way so that they could mention everything that will come up into their mind. When interviewees brought up themes that were part of questions in other categories, the related questions in that same category have been asked earlier. Basic structures have been used to ensure that important issues were covered in the conversation (Neuman 2014).

Activity A.4 was conducted in parallel with activity A.3. In this activity the five scientific articles about climate-resilient airports as found in Activity A.1 were consulted to identify what knowledge regarding assessing the climate resilience of airports was identified. Even though these five articles provided some useful information, no information regarding measuring climate resilience was identified. Therefore, literature concerning assessing resilience in related fields was consulted. In this respect literature regarding urban resilience assessment frameworks, assessment of water management and climate change, and disaster resilience assessment methods is consulted to explore what is known in the literature regarding assessing and operationalising resilience.

As resilience indicators can help to understand and diagnose performance, additional literature regarding disaster resilience indicators, environmental indicators, water poverty indicators, indicators for complex urban public spaces and indicators for measuring city performance, was consulted to further explore whether the development of indicators could play a role in response to NACO's ambitions for this research. In addition, literature regarding resilience (however not specifically related to the climate) in the aviation industry was explored to complete the overview of the current knowledge regarding the topic within the industry. Since resilience is a context-dependent concept, sector-specific indicators need to be developed for the application of indicators in the aviation industry.

In activity A.5, all previous information was synthesised in a design brief that forms the starting point of development of the AirCRAS, and includes design requirements that the AirCRAS should comply with. The correctness and completeness of the requirements was verified with NACO expert 1, 2 and 3.

Phase B – Designing

The prototype of the AirCRAS is designed based on the design brief. Also, additional literature has been reviewed and additional documents have been consulted. Next, we will explain what literature and documents were searched for, why it was needed and how it was acquired.

To assess the climate resilience status of airports, climate resilience categories, indicators and variables were identified. The climate resilience variables are converted into assessment questions. For the identification of these climate resilience categories, indicators and variables, the five scientific sources as identified in the previous literature study, are consulted again. In addition, documents were analysed. For the selection of relevant documents, we actively searched for documents related to climate resilience (measures), climate (change) adaptation and climate risks or impacts on aviation, published by the highest international organisations such as the International Civil Aviation Organisation (ICAO), the Airport Council International (ACI), and the Airport Cooperative Research Program (ACRP). By reading these documents, new documents were found due to snowballing. To ensure that no relevant articles are missed, the articles were presented to NACO expert 5 (NACO's Sustainable Aviation Lead). According to the expert, all essential documents were included. Appendix B presents the documents that have been analysed, describes them shortly and explains how they have been of use in this study. Table 14, Table 15 and Table 16 in Appendix C describe what quotes from the literature were used for the construction of the initial set of indicators and variables. The same literature and documents were used for the identification of the climate resilience vectors.

Phase C – Validation

Three validation sessions were conducted in the validation phase (phase C). These include two focus group sessions (FS2 and FS3) and one interview (I4). The sessions were conducted for two reasons, at first, to verify whether the design requirements are met **(activity C.1)** and secondly, to check whether the design complies with the user expectations **(activity C.2).**

In FS2, experts have been selected based on the following criteria: they should be experts in the field of airport resilience, and they should have experience in science. Besides, at least one expert from NACO being a potential user of the AirCRAS should be included. That is because NACO's experts will be the end-user of the AirCRAS, and therefore including their vision and expectations is of utmost importance. Also, one of the interview or focus group participants from the problem investigation phase (phase A), should participate again. This allows us to build upon previously acquired information and prevents the research from diverging into many different directions. The focus group consists of 3 experts, see Table 2.

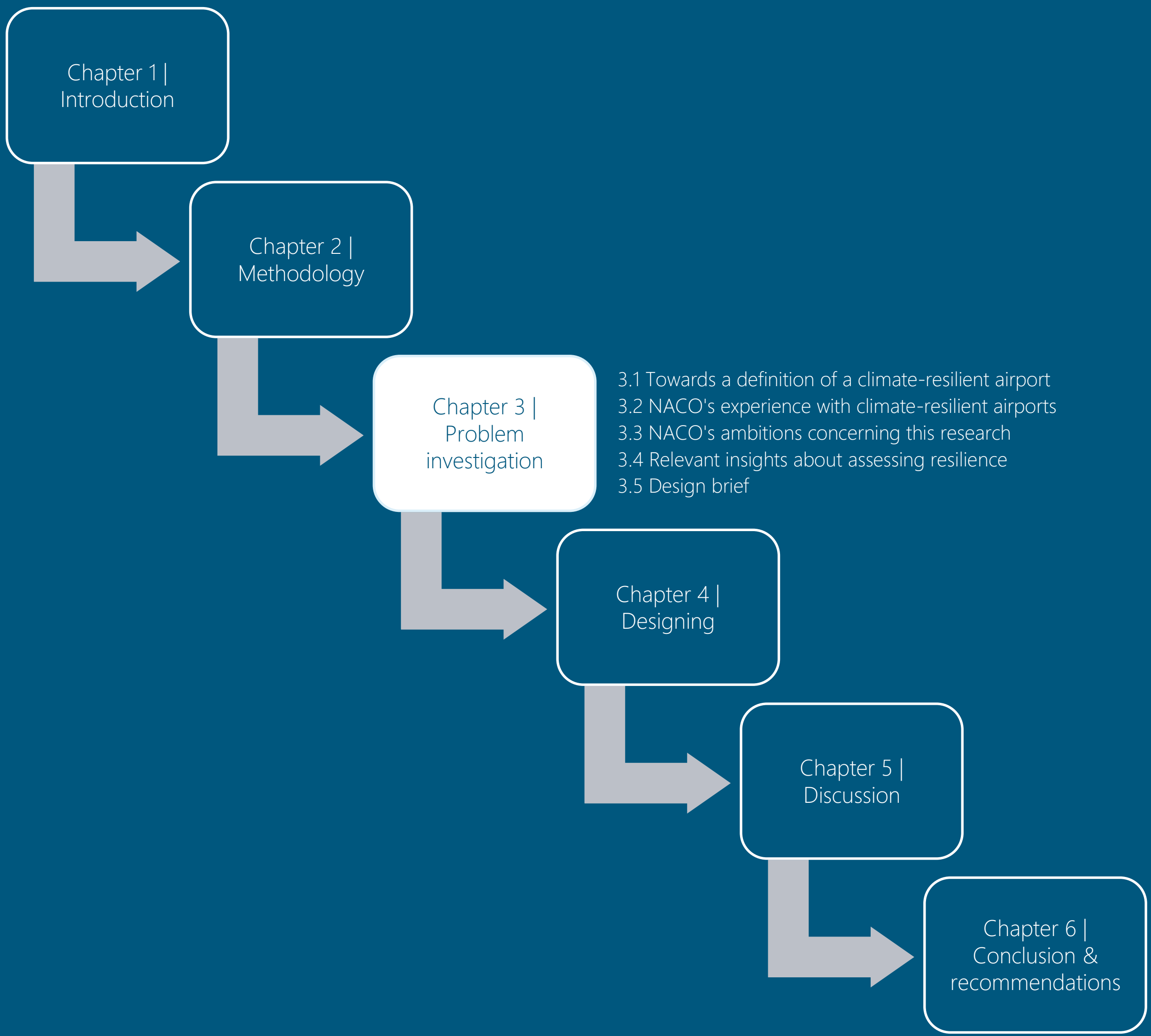
In FS3, the participant selection criteria differ from the selection criteria for FS2 to ensure various perspectives came into light. This time, only NACO and RHDHV experts (all being potential users of the AirCRAS) have been selected to ensure the user expectations are discussed extensively. Again, three experts who are familiar with the concept of resilience have been invited. All participating experts should have different backgrounds to ensure the representation of various groups of experts. Again, it was aimed to include a participant that also was involved in the problem investigation phase (phase A).

For the fourth interview (in which the final design is validated) the participating expert should have been working on a climate resilience study and should have been involved in either FS2 or FS3 to ensure building upon previously acquired information.

CHAPTER 3 | PROBLEM INVESTIGATION

This chapter elaborates on the problem investigation phase (phase A) of the design cycle. This chapter aims to identify the problem that is experienced in practice to improve the climate resilience status of airports, and creates an overview of the state-of-the-art literature that can be used to design a solution for this problem.

First of all, this chapter establishes the definition of a climate-resilient airport in Section 3.1. Next, the current stepwise approach that NACO runs through for improving the climate resilience of airports is be described in Section 3.2. Section 3.3. summarizes NACO's ambitions for improving the existing stepwise approach. In Section 3.4, a literature study was conducted to create an overview of the state-of-the-art literature that can be used to design a solution for these ambitions. All this information is translated into a design brief that forms the basis of development of the AirCRAS. The design brief is presented in Section 3.5.



3.1 Towards a definition of a climate-resilient airport

This section analyses the evolution of the definition of resilience over time and compares the definition of resilience to vulnerability and risk. This analysis leads to the definition of a climate-resilient airport that will be applied in this research.

The evolvement of the definition of resilience over time

Resilience comes from the Latin word 'resilio', meaning 'to jump back' (Kim and Lim 2016). The term was initially used in the field of mechanics as *"the ability of a material to absorb work without suffering permanent deformation"* (Hoffman 1948, p.147). Holling (1973) extended the resilience concept to ecological systems as the *"persistence of systems and of their ability to absorb change and disaster and still maintain the same relationships between populations or state variables"* (p.14). Since then, various other extensions of resilience have been introduced in other domains, such as economics, organisational science, and safety science (Cook and Rivas 2016).

Even though resilience has been the topic of a growing body of research, the global spread of resilience has not yet resulted in standardized definitions. Resilience means different things to different persons. That is because the definition of resilience differs per context.

According to the Department for International Development (2011), there are three widely used definitions of resilience, they are set out next (p.6):

I. *"The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner"* (United Nations 2016, p.22).
II. *"The ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organisation, and the capacity to adapt to stress and change"* (IPCC 2012, p.563).
III. *"The capacity of a system to absorb disturbance and reorganize while undergoing change"* (Resilience Alliance 2010, p.51).

The definitions of resilience introduce a new way of thinking about resilience. The crucial difference between the 'old' and 'new' understanding of resilience lies in the distinction between absorption and adaptation (Weyrich 2016; Ward et al. 2012). 'Absorption' focuses mainly on dealing with the current situation bouncing back to the state it was in before a disruption occurred. Whereas 'adaptation' stresses the need to adapt in a way that allows learning, utilizing opportunities and mitigating disaster impacts in the future (Sörensen et al. 2016).

With this transition from a traditional way of thinking about resilience towards the new way in mind, Francis and Bekera (2014) conducted a systematic review of the resilience developments across multiple domains and identified the following three resilience capacities: (i) absorptive capacity, (ii) restorative capacity, and (iii) adaptive capacity, together they form the resilience triangle (Ibid.).

- Francis and Bekera (2014) adopted the definition of 'absorptive capacity', as set by Vurgin, Warren, and Ehlen (2011): "**Absorptive capacity** is the degree to which a system can absorb the impacts of system disruptions and minimize consequences" (p.283).
- "**Restorative capacity** of a resilient system is often characterized by the rapidity of return to normal or improved operations and system reliability" (Francis and Bekera 2014, p.94).
- "**Adaptive capacity** is the ability of a system to adjust to situations by undergoing internal changes" (Francis and Bekera 2014, p.94). A system's adaptive capacity includes the reorganisation after the occurrence of a disaster event (Ibid.).

In Figure 3 each of these capacities is connected to a phase. The rising line in the last phase (adaptive capacity) of Figure 3 suggests that highly resilient systems possibly even benefit from disasters in such a way that the functionality of the system may improve with respect to the initial performance, enhancing the system's resilience to future adverse events.

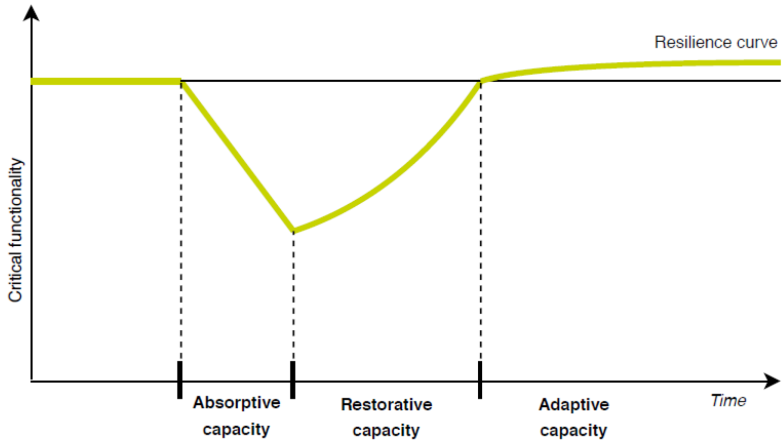


Figure 3: The three resilient capacities expressed in phases.

Resilience in relation to vulnerability and risk

The definition of resilience is highly related to vulnerability and risk. Next, we will clarify that their meaning, however, is dissimilar.

Since Francis and Bekera (2014), define resilience as a function of absorptive, restorative, and adaptive capacity, the definition of **resilience** can be converted to the following equation:

$$[1]\ Resilience = f(Absorptive\ capacity, Restorative\ Capacity, Adaptive\ Capacity)$$

In the Third Assessment Report of the IPCC, **vulnerability** is defined as: *"The degree to which a system is susceptible to, or unable to cope with the adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity"* (IPCC 2001, p. 995). With this definition in mind, Yusuf and Francisco (2009) define vulnerability as a function of exposure, sensitivity, and adaptive capacity, or (p. 2):

$$[2]\ Vulnerability = f(Exposure, Sensitivity, Adaptive\ Capacity)$$

- Yusuf and Francisco (2009) define exposure as "*the nature and degree to which a system is exposed to significant climatic variations*" (p. 2).
- Sensitivity is defined as *"the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli"* (Ibid.).
- Adaptive capacity is defined as *"the ability of a system to adjust to climate change (including climate variability and extremes), to moderate the potential damage from it, to take advantage of its opportunities, or to cope with its consequences"* (Ibid.).

The total amount of risk exposure is the probability of an unfortunate event occurring, multiplied by the potential impact or damage incurred by the event. With that, **risk** can be expressed in terms of impact and probability (Winch 2010):

$$[3]\ Risk\ = Probability * Impact$$

According to Proag (2014) vulnerability implies a measure of risk associated with aspects and implications resulting from the system's ability to cope with the resulting event. Resilience implies the ability of a system to perform properly even when placed under pressure or the ability of systems to absorb and recover from the impact of disruptive events without fundamental changes in function or structure. As resilience increases, the degree of damage (impact) for a given intensity hazard decreases (Proag 2014).

It has to be noted that various authors define resilience, vulnerability and their relation to risk differently. For example, according to Linkov et al. (2014) risk in a system can be interpreted as the total reduction in critical functionality, and the resilience of the system is related to the slope of the absorption curve and the shape of the recovery curve —

indicating the temporal effect of the disaster event on the system. The area under the curve is indicative of the overall system functionality, see Figure 4.

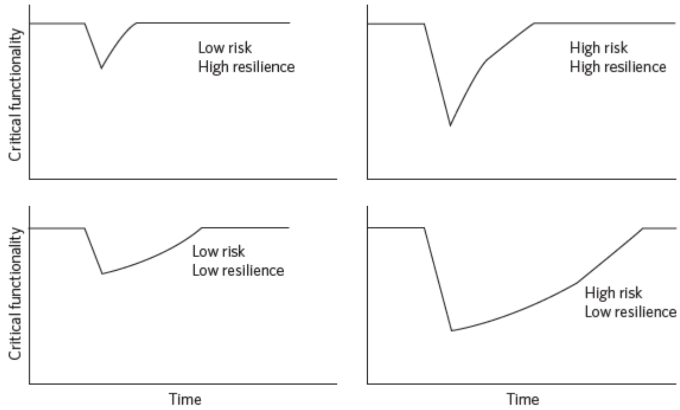


Figure 4: Four schematic representations of changes in critical functionality over time, showing the interplay of risk and resilience in a system's performance during an adverse event (Linkov et al. 2014, p.408).

However, according to the three capacities of a resilient system as defined by Francis and Bekera (2014), the diagram on the bottom left in Figure 4 not necessarily has 'low resilience' as stated by Linkov et al. (2014). That is because of the minimal reduction in critical functionality can also mean the system has a very high absorptive capacity. And because the absorptive capacity of the system is so high, the impact is minimal and hence, the risk is low.

The definition of a climate-resilient airport

In literature, no definition of a climate-resilient airport is given. Therefore, this research provides a tailor-made definition of a climate-resilient airport which is based on the three resilience capacities as identified by Francis and Bekera (2014):

> *A **climate-resilient airport** is an airport that can absorb impacts of extreme weather events, recover from disruptions caused by them and adapt to the changing conditions.*

In this research context, extreme weather events refer to both climate shocks (fast-moving variables, such as extreme rainfall and hurricanes), and climate stressors (slow-moving variables, such as the rising sea level, and temperature change).

It is to be noted that there is no maximum resilience level, or a fully resilient state exists, as resilience is not something that will ever be completely achieved. Since the environment has constantly changing needs and is vulnerable to external effects, its resilience can always be improved. Resilience thus must be something to strive for, instead of something to achieve (Kim and Lim 2016).

3.2 NACO's experience with climate-resilient airports

NACO was established in 1949 in the immediate aftermath of World War II by Albert Plesman, founder and the first director-president of Royal Dutch Airlines (KLM). In the years that followed, the company's experts worked on many projects (e.g. they started to play a direct role in the master plan development of Amsterdam Airport Schiphol (AAS)), which strengthened NACO's reputation as a world-class airport consultancy firm. In the later years, air traffic continuously kept on growing and NACO became an important player on a global scale (NACO 2020e).

As explained in the introduction (Chapter 1), NACO's current experience regarding improving the climate resilience of airports is limited. So far NACO has conducted one extensively documented Climate Resilience Study, for Singapore Civilian Airports. The Civil Aviation Authority of Singapore (CAAS) and NACO developed an innovative methodology to map and mitigate airport climate change risks (Dolman and Vorage 2019), see Figure 5. This methodology is referred to as the **'existing stepwise approach'** in this report. The scope of the Climate Resilience

Study for Singapore Civilian Airports covers the existing situation at Changi (SIN) and Seletar (XSP) Airport (NACO 2017).

The existing stepwise approach firstly conducts a benchmark study, which examined how the Singapore Changi Airport is performing compared with its international peers in terms of dealing with climate change risks (Dolman and Vorage 2019). It concluded that many airports face challenges related to climate change, such as an increased risk of flooding during extreme weather events. However, the number of airports making a concerted effort to mitigate these risks is still relatively limited. Following, based on climate projections the airport experiences, scenarios were determined. The vulnerability of critical airport assets and operations was identified, assessing the risks through scenario-based modelling and formulating climate change adaptation measures to address identified risks. Finally, a long-term, incremental and flexible whole-of-government adaptation pathway was defined for Changi Airport to enhance its resilience to climate change (Ibid.).

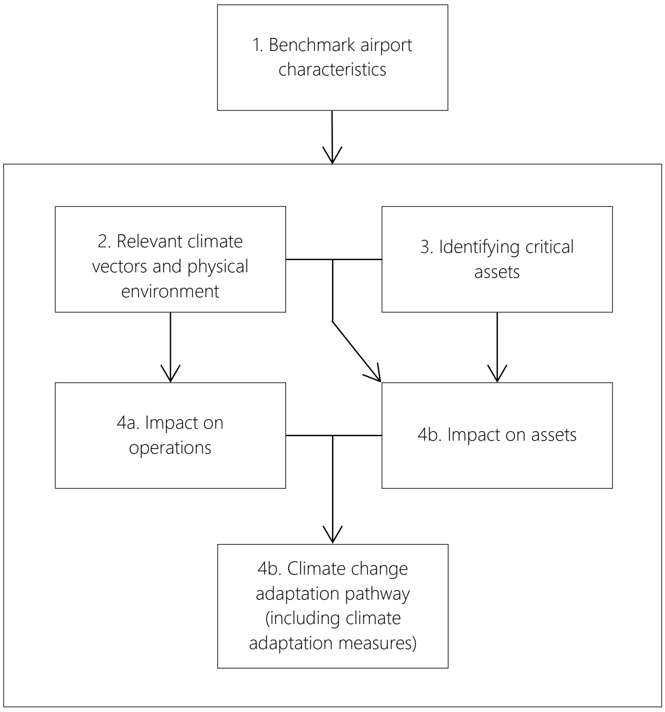


Figure 5: *The existing stepwise approach (NACO 2017).*

According to experts, this current stepwise approach can be further improved. The next section formulates ambitions regarding how this research can contribute towards improving the existing stepwise approach.

3.3 NACO's ambitions concerning this research

For the identification of NACO's ambitions regarding how this research can contribute to improving the existing stepwise approach, a focus group session and three interviews have been conducted. First, we will elaborate on the results per data collection method. After which the ambitions are presented in Table 5.

A focus group session and interviews
A focus group session (FS1) was organised to identify an initial set of ambitions that NACO's experts have concerning this research. The following ambitions were identified:

1. A flaw of the existing resilience approach is that engineers tend to go quickly into rather technical details. It would be useful to create an overview of the strengths and weaknesses of the overall system regarding the climate resilience of airports before going into more details.
2. It appears that it is extremely difficult for airports to establish the level of risk they are willing to accept. Hence, specific attention should be given to establishing the risk acceptance level. And with that, it should be clear how establishing the risk acceptance level falls into the current stepwise approach.

3. A ranking of the worlds' (most and less) vulnerable airports would be of use to NACO since it will allow them to approach the airports who are in need of help. Besides, due to the competitive nature between airports, such a ranking will be a reason for airports to increase their resilience status.
4. The stepwise approach should be based on trusted sources from preferably the highest international aviation organisations so that NACO can prove that their method is well-substantiated and up to date.
5. NACO should be able to reuse the stepwise approach for different projects. For that reason, the stepwise approach should be applicable to many airports around the world.

The researcher consulted literature for the identification of design ideas in response to the ambitions, see Section 3.4. It is found that climate resilience indicators are a useful mechanism to assess the climate resilience status of airports since they can provide insight into the strengths and weaknesses of the airport system regarding its resilience status. Based on the City Resilience Index, which is intended as a tool that enables cities to assess their resilience at a city scale in order to identify strengths, weakness and priorities for action, the idea arose to develop a climate resilience assessment scan for airports for similar purposes. Hence, the potential of this idea was discussed in three interviews (I1, I2 and I3). The comments that experts gave in response to the design idea are summarized as advantages and disadvantages of the AirCRAS in Table 3.

Table 3: *Advantages and disadvantages of developing the AirCRAS.*

	RHDHV expert 1 (I1)	NACO expert 1 (I2)	NACO expert 2 (I3)
Advantages of developing an airport climate resilience assessment scan			
1. Quick insight into the strengths and weaknesses of the airport regarding its current climate resilience performance, might help us to formulate a tailor-made roadmap for an in-depth climate resilience analysis.	✓	✓	
2. It can be supportive and supplementary to the in-depth analysis because it helps to communicate simple and understandable about the problems the airport might experience. This may raise the clients' awareness of the problem.	✓	✓	
3. It can provide a good starting point for a benchmark. Since the airport environment is a very competitive one, they will be eager to become more resilient than other airports.	✓		✓
4. Insight in relative performance regarding other airports, might help the airport authority to determine their risk acceptance level.			✓
5. A flaw of the existing resilience approach is that it is rather technical oriented. Experts recommended to include stakeholder engagement, resilience processes and organisational aspects in the AirCRAS.	✓	✓	✓
Disadvantages of developing an airport climate resilience assessment scan			
1. Often, in cases of indices, systems get assessed by an external company. It would be a disadvantage if the client is not taken on board in the process of doing so.	✓		✓
2. Its static nature forms a weakness because changes need to be made manually.	✓		
3. In order to create a benchmark, a 'base case' is needed. However, even experts cannot be sure whether an airport can be taken as a base case.			✓

NACO's ambitions concerning this research

The ambitions that originated from the focus group session were merged with the feedback that was provided in the interviews into a set of ambitions, see Table 4. For each ambition, the source from which it originated is presented.

The AirCRAS should measure performance rather than providing a comparison between airports. It will not deliver an overall single score for comparing performance between airports, neither will it provide a world ranking of the (most and less) vulnerable airports. For that reason, advantages 3 and 4, disadvantage 3 and ambition 3 are not translated into ambitions. Neither does this research aims to deliver a completely automated tool. Therefore, disadvantage 2 is not translated into an ambition.

Table 4: NACO's ambitions concerning this research.

#	NACO's ambitions	Source
1	The AirCRAS should provide an overview of the airports' strengths and weaknesses regarding their climate resilience status.	Based on FS1.
2	The AirCRAS should stimulate discussion about what level of risk the airport is willing to accept.	Based on FS1.
3	The climate resilience indicators and variables should be based on trusted sources.	Based on FS1.
4	The AirCRAS should be applicable to many airports around the world.	Based on FS1.
5	The results of the stepwise approach should allow simple communication of high amount of information.	Based on I1 and I2 – Table 2, advantage 2.
6	The experts of the airport should be actively engaged while running through the stepwise approach.	Based on I1 and I3 - Table 2, disadvantage 1.
7	The stepwise approach should focus more strongly on organisational aspects.	Based on I1 and I3 - Table 2, advantage 5.
8	The users should be able to conduct the AirCRAS quickly.	Based on I1 and I2 - Table 2, advantage 1.

3.4 Relevant insights about assessing resilience

This section explores literature to identify possible solutions in response to NACO's ambitions as presented in Table 4.

Resilience frameworks

Several frameworks have been used to assess various forms of resilience. Tyler and Moench (2012) attempt to develop an operational framework for local planning practitioners in urban areas. The framework they propose combines characteristics of urban systems, the agents that depend on and manage those systems, institutions that link systems and agents, and patterns of exposure to climate change. The characteristics they distinguish consist of flexibility and diversity, redundancy and modularity, and safe failure. Although these characteristics provide a guideline for future planning and thinking about complex urban systems, they are less suitable to provide prescriptions. Therefore, based on the work of Tyler and Moench (2012), Silva, Kernaghan, and Luque (2012) propose resilience characteristics that can be used to analyse urban systems, and describe the desired outcome of any intervention targeted at building urban resilience. For this, they rewrote the resilience characteristics of Tyler and Moench (2012) keeping flexibility, redundancy and safe failure, while adding resourcefulness, responsiveness, the capacity to learn, and dependency on local ecosystems. Many other resilience frameworks in the context of urban areas or disaster management exist (Cutter, Burton, and Emrich 2010; Alshehri, Rezgui, and Li 2015). Some of them elaborating on resilience characteristics (Tyler and Moench 2012; Silva, Kernaghan, and Luque 2012), while others focus on resilience factors (Suárez et al. 2016).

The resilience frameworks as proposed by Tyler and Moench (2012) and Silva, Kernaghan, and Luque (2012) focus on urban areas and are developed for planning practitioners. Hence, the frameworks should be strongly adapted to be applicable to the airport system. Besides, even though the frameworks aim to operationalise resilience, they are not particularly designed for the creation of an overall overview of the strengths and weaknesses of the climate resilience status. Hence, NACO's ambitions as presented in Table 4, cannot be met using the frameworks. Neither are these frameworks developed to be applied in contexts other than urban climate change. Therefore, this research will not use any of these frameworks as a basis for operationalising resilience in aviation.

Resilience principles

Other some studies describe general resilience principles. Resilience principles can have different applications, based on the situation in which they are utilized. They can serve as guidelines for policy development (Biggs et al. 2012), urban planning and design strategies (e.g. Ahern (2011)), or as a basis for a resilience framework for understanding urban resilience and resilient cities (Kim and Lim 2016; Tyler and Moench 2012; Silva, Kernaghan, and Luque 2012).

Appendix B compares the literature regarding resilience frameworks and principles. At first glance, literature seems to disagree on the ways to describe resilient systems, but at closer investigation, the greatest difference lies in the wording, as the explanation of principles, characteristics and factors is similar. The conclusion that can be drawn from a comparison of this literature is that even though the descriptions and applications differ, there are common denominators. These common denominators (summarized as resilience principles) are presented in Appendix B, Table 13. Even though common resilience principles (e.g. flexibility or redundancy) are found, these resilience principles are broad aspects that need to be more specifically formulated to be any use for practitioners in the aviation industry. In other words, findings from the scanned literature cannot be directly applied to the context of airports, since resilience is a context-dependent concept (Cariolet, Vuillet, and Diab 2019).

Resilience indicators

Apart from resilience frameworks and principles, resilience indicators can be used to transform resilience into a measurable concept (Sharifi and Yamagata 2016). An indicator is a quantitative or qualitative measure derived from observed factors that have the potential to simplify complex real-world phenomena into information that is easier to communicate (European Environment Agency 2003; Freudenberg 2003; Molle and Mollinga 2003). In the context of assessing resilience, it is found that resilience indicators can help to understand and diagnose performance since they are able to offer a quick scan of the situation of a resilient system, highlighting its strengths and weaknesses (Cutter, Burton, and Emrich 2010). Indicators appoint what seems to be the most critical issues and can identify areas of opportunity (Jensen and Wu 2018), thereby helping to set priorities, measure progress and allocate better practices (Van Leeuwen, Koop, and Sjerps 2016). Those participating in the decision-making are given the opportunity to distinguish a direct link between their actions, plans, and investments, and what the indicators measure (The Rockefeller Foundation and Arup 2014b). Indicators are often used as a mechanism to communicate performance with stakeholders (Cutter, Burton, and Emrich 2010). These functions signify the important role of resilience indicators as building blocks of any assessment system (Ilmola 2016).

It can be concluded that resilience indicators can be a useful mechanism in response to NACO's ambition regarding the creation of the overall overview of the strengths and weaknesses of the airport regarding the climate resilience status. At present, there is no single set of indicators that enables climate resilience to be measured at an airport scale.

The resilience of the air transportation system

Research on the resilience of air transport networks has generally been focused on analysing and modelling their dynamics (indirect connectivity and passenger dynamics, air traffic jams, and epidemic spreading) and vulnerability to disruptive events (Cardillo et al. 2013). Besides, the substantive research has dealt with modelling and estimating the costs of air transport affected by the various disruptive events (Chen et al. 2017; Dunn and Wilkinson 2016; Hosseini, Barker, and Ramirez-Marquez 2016; Ip and Wang 2011; Pien et al. 2015; Yoo and Yeo 2016). The costs of impacts of disruptive events affecting the airline hub airport(s) have also been the subject of intensive research (Janić 2015; Voltes-Dorta, Rodríguez-Déniz, and Suau-Sanchez 2017; Zhou and Chen 2020). Some studies, such as Ito and Lee (2005) and Gordon et al. (2007) have attempted to evaluate the economic impact and impact regarding the air traffic demand after the 9/11 terrorist attacks. However, little attention has been devoted to the qualitative analysis of airports under disruptive situations, such as extreme weather events.

To gather the relevant literature regarding assessing the climate resilience of airports, a systematic literature review was conducted. Appendix A describes how five relevant scientific articles are selected, and systematically explains per article how these articles are used in this research. Lopez (2016) aims at presenting the development of the vulnerability assessment method and highlighting the main steps to be conducted to perform a vulnerability assessment study to climate change. Even though Lopez (2016) elaborates on climate vectors that the airport experiences, and identifies the impacts of each of these vectors on the airport system, the vulnerability of the system was assessed rather than its resilience. Many scientific literature and documents elaborate on the impacts of climate change on aviation (Ferrulli 2016; NATS 2011; EUROCONTROL 2013; ACRP 2012; ICAO 2018b; 2018a; Pendakur 2017; ICAO 2016a; GTAA 2014; ACI 2018). Burbidge (2016) adds to this literature by identifying four priority areas for action.

Although there is a considerable amount of literature on the impacts of climate change, resilience, and adaptation, little information is available about how resilience can be qualitatively measured for airports. In particular, it remains unclear what factors affect airport resiliency performance (Zhou and Chen 2020). More importantly, no assessment scan providing insight into the overall overview of the strengths and weaknesses of the airport regarding the climate resilience status, exist. Therefore, it seems very useful to develop climate resilience indicators as a basis for an assessment scan.

Construction of climate resilience indicators for airports

Since it was found that climate resilience indicators seem a useful basis for an assessment scan, it was searched how these should be constructed.

The key to good indicators is credibility rather than the volume of data or precision in measurement (Lisa, Schipper, and Langston 2015). It is more helpful to have approximate answers to a few important questions than to have exact answers to many unimportant questions (Spearman and McGray 2011). Given that complete scrutiny of all related indicators is unapproachable, the identification of the most relevant ones describing the resilience is the main challenge. The larger the number of indicators included, the more difficult and time-consuming the methodology will be (Nogal and O'Connor 2016). Underlying this is the important question of how many indicators are necessary to accurately tell a story of resilience (Lisa, Schipper, and Langston 2015).

No fixed rules have been developed for the construction of indicators (Lu, Shen, and Yam 2008; Shen and Liu 2003). However, Xu and Xue (2017) present the steps they run through for the identification of the indicators to assess the resilience of complex urban public spaces. According to Xu and Xue (2017) indicators are defined by clustering or aggregating several variables (representing the performance of an indicator (Simpson 2006)) that relate to the same topic and are measured together (Cutter, Burton, and Emrich 2010). Indicators, in turn, can be aggregated up to categories, see Figure 6.

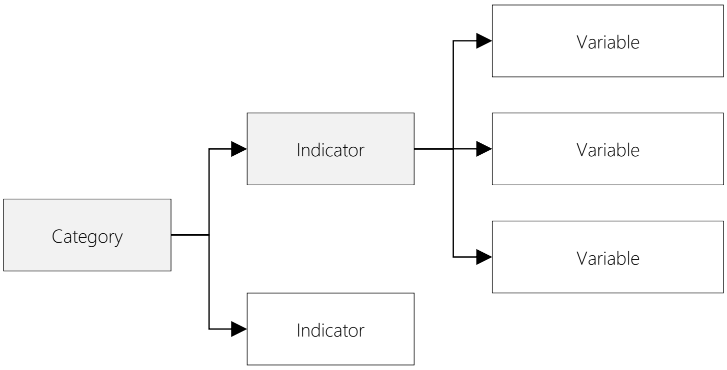


Figure 6: *An indicator three showing how several variables can be aggregated up to indicators, and how indicators can be aggregated up to categories.*

This research developed some tailor-made steps for the identification of climate resilience categories, indicators and variables. These steps will be presented in Section 4.1. These steps are inspired based on the steps as described by Xu and Xue (2017).

In the next section, the information of this chapter is synthesised in a design brief.

3.5 Design brief

Design motive

It was found that NACO's current stepwise approach to improve the climate resilience of airports is technically oriented and tends to go quickly into details. The current stepwise approach is generally focused on modelling the vulnerability to disruptive events to analyse the economic impact on infrastructure, rather than mapping their overall level of resilience on various aspects (e.g. organisational and operational). This approach potentially misses the identification of problems. To ensure that the most relevant problem is tackled, first the overall strengths and weaknesses of the climate resilience status need to be mapped.

It was found that, even though the literature regarding assessing resilience is significant, elaborating on e.g. operational frameworks, resilience principles and resilience indicators, air transportation is rarely mentioned in this respect. Similarly, assessing resilience is rarely mentioned in the literature regarding air transportation. As with the current stepwise approach it was found that these studies are generally focused on modelling the vulnerability to disruptive events to analyse the economic impact on infrastructure.

Considering these gaps, an Airport Climate Resilience Assessment Scan (AirCRAS) should be designed, connecting two research fields of assessing resilience, and the air transportation industry with each other and with practice. This design brief forms a starting point for developing the AirCRAS.

WHY | Project goal

This research aims to develop an AirCRAS, which intends to provide a holistic overview of the strengths and weaknesses of the airport system regarding its current climate resilience status (ambition 1). The premise is that this overview will stimulate discussion about the challenges that the airport experiences and the level of risk the airport is willing to accept (ambition 2). This provides priorities and constraints for the follow-up in-depth resilience study, and will finally result in important implications for future planning and investments to enhance the climate resilience of the airport in question.

WHO | The user

The AirCRAS should be a digital tool that can be used by an expert panel in a workshop at the beginning of the project. The expert panel consists of NACO's experts, who are the actual users of the tool, and experts of the airport in question. The experts from NACO's side need to be experts in the field of resilience and need to be familiar with the AirCRAS. Further conditions related to the expert panel composition have to be explored as part of the development of the AirCRAS.

WHAT | An initial set of design requirements

The AirCRAS should meet certain design requirements. These requirements originated either from NACO's ambitions as identified in Section 3.3, from literature research in Section 3.4. or they result from limitations in the research scope. The design requirements are summarized in Table 5.

This research does not aim to deliver a complete set of indicators and variables. Rather, the indicators and variables should cover the most relevant aspects to ensure the reliability of the results (see Section 3.4). Additionally, when new information arises after the development of the AirCRAS it should be possible to adjust the AirCRAS accordingly. Both are considered design requirements.

HOW | Methodology

To assess the climate resilience status of airports, sector-specific indicators need to be developed (see Section 3.4). These indicators are aggregated into categories and split into variables which represent the indicator in more detail. Qualitative variables will be quantified by assessment questions that can be answered on an ordinal scale (see Section 3.4). Hence, the users of the digital tool will have to answer a set of assessment questions after which insight into the strengths and weaknesses of the airport system is presented.

A prototype of the AirCRAS will be developed based on the design brief and additional literature review. This literature review is needed for the identification of climate resilience indicators and variables. Validation sessions will be conducted to verify whether design requirements will be achieved. During these validation sessions, new insights might arise which should also be discussed. The AirCRAS' prototype will be further improved according to the feedback that will be gathered in these sessions. Consequently, the process that will be run through for the development of the AirCRAS is going to be highly iterative.

Table 5 summarizes the design requirements. The correctness and completeness of the requirements was verified with NACO experts 1, 2 and 3.

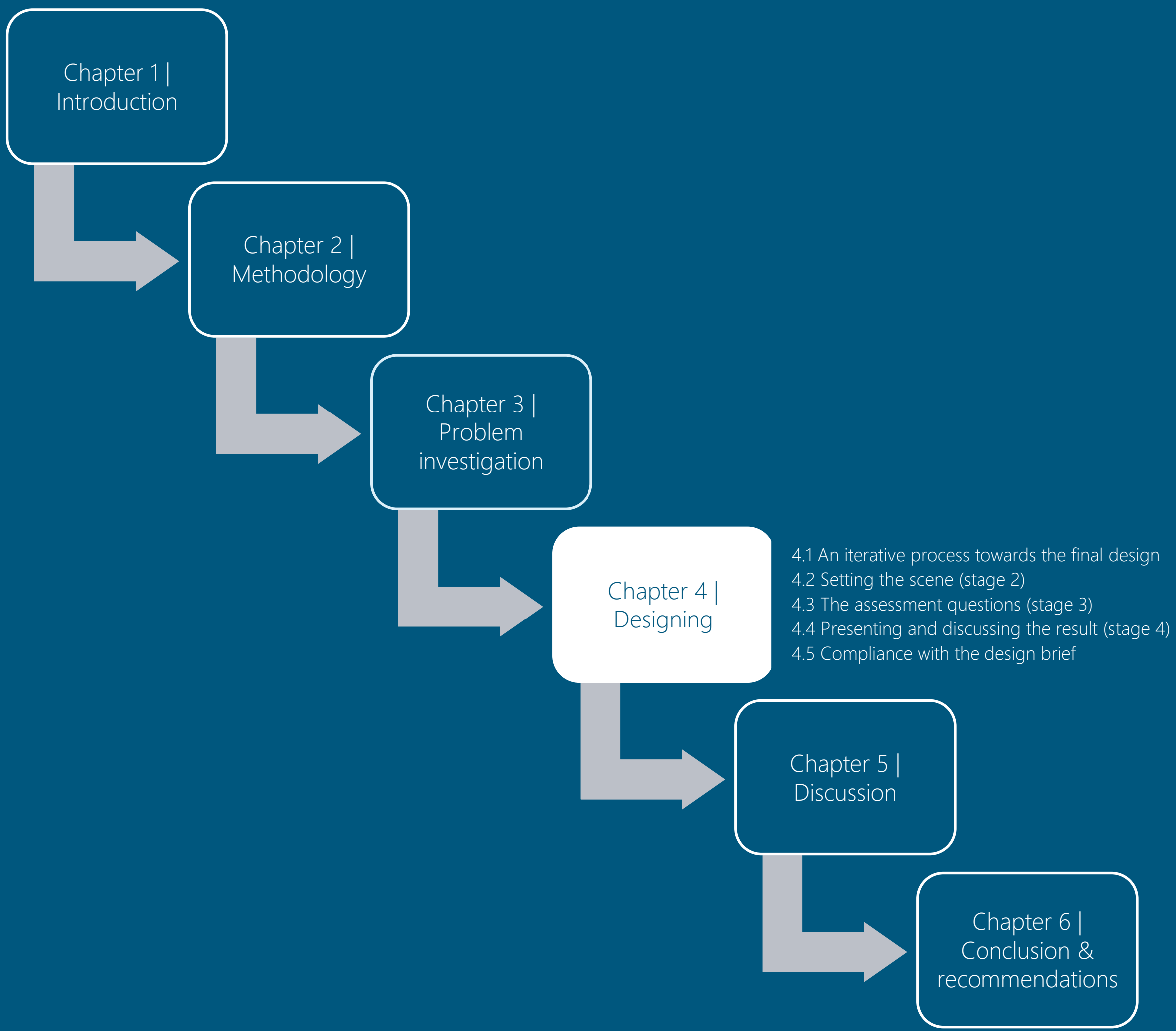
Table 5: *A set of initial design requirements.*

#	Design requirements	Source
1	The AirCRAS should provide an overview of the airports' strengths and weaknesses regarding their climate resilience status.	Based on FS1.
2	The climate resilience indicators and variables should be based on trusted sources.	Based on FS3.
3	The AirCRAS should be applicable to airports with different characteristics	Based on FS4.
4	The AirCRAS should allow simple communication of high amount of information.	Based on I1 and I2.
5	The experts of the airport should be actively engaged while conducting the AirCRAS.	Based on I1 and I3.
6	The climate resilience indicators and variables should not only focus on infrastructure and operational aspects such as in the existing stepwise approach, but also on organisational aspects.	Based on I1 and I3.
7	The users of the tool should be able to conduct the AirCRAS in approximately four hours.	Based on I1 and I2 and further specified. The requirement is verified with NACO expert 1, 2 and 3.
8	The climate resilience indicators and variables should be covering relevant topics.	This requirement has been additionally developed based on scope limitations and literature: Lisa, Schipper, and Langston (2015). The requirement is verified with NACO expert 1, 2 and 3.
9	It should be possible to adjust the AirCRAS based on new findings.	This requirement has been additionally developed based on scope limitations and is verified with NACO expert 1, 2 and 3.

CHAPTER 4 | DESIGNING

Chapter 4 presents the AirCRAS as developed in the design phase (phase B) of the design cycle. Section 4.1 provides insight into the process that has been run through towards a validated AirCRAS. The validated AirCRAS consists of four stages. The second to the fifth section of this chapter elaborates on each of these stages. Section 4.5 reflects on the design requirements as presented in Section 3.5, verifying whether these requirements are sufficiently processed in the design.

Appendix G visualises the AirCRAS using pictures and thereby shows the information as presented to its users. The AirCRAS as visualised in the appendix is filled in (and so, presents the answers) for the particular case of Singapore Changi Airport.



4.1 An iterative process towards the final design

Based on the design brief as formulated in Section 3.5, a prototype of the AirCRAS was developed. This prototype was discussed in the first validation session, where feedback was given in response and changes to the prototype were made accordingly. This process of presenting the AirCRAS, receiving feedback and refining the design accordingly is iterated three times. This section provides a high-level description of the prototype that is developed, and summarizes the most relevant changes that have been made to the design after each of the validation sessions.

4.1.1 The prototype of the AirCRAS

The AirCRAS is a digital tool. The users of the AirCRAS are experts from NACO who need to be experts in the field of resilience and need to be familiar with the AirCRAS. Together with the experts from the airport, they form an expert panel that jointly goes through the AirCRAS in a workshop at the start of a project. In the AirCRAS, the expert panel answers a set of assessment questions. These questions are divided into three categories: organisation, operations and infrastructure. It takes about half a day to complete the AirCRAS.

The exact composition of the team is to be established by project management at the start of the project. Regarding the participants from NACO, the team must include experts with different technical backgrounds to ensure a variety of perspectives. Consequently, it is recommended to include (depending on the scope of the project) 2 or 3 of NACO's experts. From the airports' side, it's important that an expert from the organisation, an expert in charge of the operations, and an expert related to the infrastructure, are included since knowledge regarding those aspects is needed for conducting the AirCRAS (this will be further explained in Section 4.4). In case the airport is having resilience experts in place, it is recommended to take them on board as well. Resulting in (depending on the scope of the project) up to 5 experts from the airport. In case the expert panel does not know the answer to a question, the question can be skipped.

Next, each of the three stages is described on high-level.

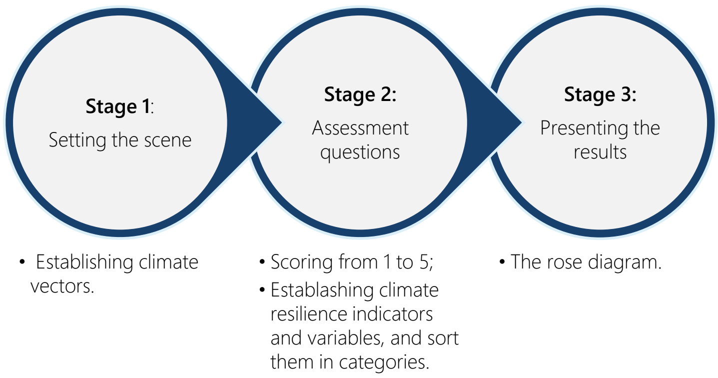


Figure 7: *The user journey as presented in the first validation session.*

Stage 1: Setting the scene

In the first stage, the users have to choose what climate vectors they consider relevant for their particular airport. Choosing what climate vectors are relevant for their airport is needed since only the assessment questions that relate to the relevant climate vectors have to be answered in the second stage. In the prototype seven climate vectors were established. These are not changed during the process towards the final design. The climate vectors are detailly explained in Section 4.2.

Stage 2: Assessment questions

In the second stage, assessment questions must be answered. These assessment questions quantify climate resilience indicators and variables by using a scale. Before assessment questions could be formulated, climate resilience indicators and variables had to be identified. In this design brief, it became clear that these climate resilience indicators are split into variables and sorted into categories. The following steps were run through for the identification of the climate resilience categories, indicators and variables:

1. Gather information regarding:
    a. The impacts of extreme weather events on the airport;
    b. Resilience measures that can be taken by airports to prepare for extreme weather events.
    Table 14, Table 15 and Table 16 in Appendix C describe what exact quotes from the literature were used for the development of the initial set of indicators and variables.
2. Merging double information that originated from different sources, while closely keeping track of the sources;
3. Grouping information based on topic, which results in a differentiation of climate resilience categories;
4. Sorting information based on the level of detail resulting in differentiation between climate resilience indicators and variables;
5. Validate the climate resilience categories, indicators and variables with experts and improve them accordingly.

From running through these steps three climate resilience categories resulted, namely the categories: **organisation, operations** and **infrastructure.** It was found that a lot of information regarding a) the impacts of extreme weather events on the airport, and b) resilience measures that can be taken by airports to prepare for extreme weather events, are related to airport operations and airport infrastructure (ACI 2018; Lopez 2016; Ferrulli 2016). Also, the existing stepwise approach explains the impacts of climate change on **infrastructure** and **operations** (NACO 2017), see Figure 5. Therefore, both are considered climate resilience categories in this research.

Moreover, in literature, we found that softer approaches such as improving effective sharing of information (GTAA 2014; ICAO 2018a), training staff to prepare them to deal with extreme weather events (ICAO 2018a; EUROCONTROL 2013), closely collaborating with stakeholders (EUROCONTROL 2013), and evaluating of disruptions (ISO 2017) is endorsed by several authors as a mean to improve the climate resilience of airports. These aspects cannot be aggregated into the infrastructural or operational categories, and thereby, a new category: **'organisation'** was created. The creation of this category is also in compliance with requirement 6 *(the climate resilience indicators and variables should also focus on organisational aspects)*.

Section 4.3 elaborates on the content of each of the climate resilience categories, indicators and variables. The climate resilience categories did not change in the process towards the final design, yet refinements to the climate resilience indicators and variables have been made after each of the validation sessions.

Stage 3: Presenting the results
The outcome that results from answering the assessment questions is presented in a rose diagram since this allows simple communication and easy comparison of a large amount of information. This visualisation of information is still used in the final design. However, additions to the presentation of the results are made in response to the feedback as acquired in the third validation session. This is all detailly explained in Section 4.4.

As described in the Methodology (Chapter 2) the validation sessions were conducted for two reasons, namely at first, to verify whether the design requirements are met. Therefore, the validation phase includes a verification element. And secondly, these validation sessions were conducted to check whether the design complies with user expectations. The user journey and the climate resilience categories, indicators and variables as presented and discussed in the three validation session, are visualised in Appendix E.

4.1.2 Design iteration 1: First validation session

In the first validation session, it was found that all requirements, except for requirement 5 *(the experts of the airport should be actively engaged while conducting the AirCRAS)* and 7 *(the users of the tool should be able to conduct the AirCRAS in approximately four hours)*, are either met or substantially met. Besides, even though it was found that relevant climate resilience indicators and variables were identified (requirement 8; *The climate resilience indicators and variables should be covering relevant topics*), comments were given for further refinement of these climate resilience indicators and variables. Apart from the requirements, many other user expectations arose and were topic of discussion.

The main feedback regarding both the design requirements and user expectations is listed next. More detailed feedback is presented in Appendix E.

- *Concerning requirement 5:* The context in which the AirCRAS is to be applied, was unclear to the users. They did not understand who should be using the AirCRAS and with what intention they should use it. In response to this feedback, a stage introducing the AirCRAS was added to the user journey. This stage clearly describes the goal and relevance of the AirCRAS and provides insight into its users;
- *Concerning requirement 7:* The experts unilaterally agreed that the three climate resilience categories: organisation, operations, and infrastructure, are well-defined. The consensus was that they are both relevant and complete. However, to ensure that the AirCRAS can be conducted in approximately four hours, and to ensure consistency in the results, the experts suggested ensuring a similar number of indicators per category. In response to this feedback, a discussion took place regarding the priority of indicators and variables resulting in the restructuring of some to pinpoint the most relevant indicators and variables.
- For each variable, a short assessment question was formulated. The users had to answer the question on a scale from 1 to 5. 1 meaning they did not agree with the statement and 5 meaning they fully agreed. However, the experts found that too little information was given to properly answer the assessment question. Therefore, they recommended describing the meaning of the minimum score (1) and maximum score (5). This suggestion was implemented.

4.1.3 Design iteration 2: Second validation session

In the second validation session, experts agreed that requirement 5 was now met (see Section 4.5). However, comments concerning requirement 7 were given, suggestions for refinement of the climate resilience indicators and variables have been received and additional feedback regarding the user expectations came above.

Again, detailed feedback is presented in Appendix E and the main comments are listed next:

- *Concerning requirement 7:* Experts found that defining the minimum and maximum score for each assessment question resulted in an overwhelming amount of information which would negatively contribute to the four hours in which the AirCRAS should be conducted. Since the feedback in the previous validation session suggested that providing only an assessment question did not give enough information, a balance had to be found. Therefore, a short description providing background information about the question was formulated followed by the assessment question. This new presentation of information was validated in the last validation session;
- Regarding the scale of the assessment questions, the experts found that a five-point scale was adequate. According to them, not enough differentiation between scores can be made on a three-point scale. Whereas a seven-point scale most probably results in confusion and long discussions which do not provide quick insight into the strengths and weaknesses. However, participants suggested using letters (A to E) instead of numbers (1 to 5). Using letters might prevent the users of the AirCRAS from trying to calculate detailed weighted scores. This idea was implemented;
- The experts suggest visualising and describing the process that the users should run through to manage their expectations regarding the AirCRAS. For the same reason, they suggested visualising the process in which the assessment questions have to be answered. This feedback was processed.
- One of the experts notified inconsequence of the formulation of the indicators and variables. That is where it was decided to construct all indicators and variables by combining a noun and a verb. The assessment questions provide more detailed insight into the actual meaning of the noun.

4.1.4 Design iteration 3: Third validation session

In the last validation session, it was found that also requirement 7 was now substantially met (see Section 4.5). During this validation session, the AirCRAS was applied to the specific case of Singapore Changi Airport. By doing so, final recommendations for refinement of the AirCRAS followed. This included recommendations regarding the reformulation of the assessment questions.

Once more, the detailed feedback is presented in Appendix E, and the main points of feedback are summarized next:

- The expert recommended to state the sources from which the information is collected since substantiation of information will help to convince experts of the correctness of the information. Not only the sources should be provided along with the AirCRAS, but also a summary should be provided at the beginning of the AirCRAS about the sources that were used to collect the information. This recommendation was implemented;
- The expert argued that more detailed insight into the results of the AirCRAS was needed to properly reflect on the results. Therefore, an open text box is attached to each of the assessment questions so that the users can explain the answer they provided. The given explanation is used to present the strengths and weaknesses of the AirCRAS per indicator. This allowed reflection on the results per indicator;
- In consultation with the expert, it was decided to add discussion points that stimulate open dialogues regarding the realised scores versus the ambition level of the airport authority.
- Since the result is presented on a five-point scale score (from A to E), scores are rounded. Which means that an average score of 2.6 and 3.4 are both rounded to a 3 and thus appointed label C. According to the expert, this was an over generalisation of the results. Therefore, to provide more detailed insight into the actual score, the scoring mechanism was slightly adapted, see Section 4.4, Figure 15.

The result as generated by the AirCRAS after applying it the particular case of Singapore Changi airport matched the experts' expectations about the results. The biggest problem that was found in the previous conducted Climate Resilience Study for Singapore Changi Airport, was that certain parts of the critical infrastructure of the airport are not well protected against sea level rise and increased intensity of the precipitation. Which leads to possible flooding of parts of the airport, including parts where critical infrastructure is located. Singapore Changi Airport scores worst on the indicator: robust infrastructure, which is in line with the previous findings.

4.1.5 The final design

After conducting the validation sessions and approving the AirCRAS accordingly, a validated AirCRAS results. This AirCRAS is a digital tool. As introduced previously, the users of the AirCRAS are experts from NACO. Together with the experts from the airport, they form an expert panel that jointly goes through the AirCRAS in a workshop at the start of a project. In the AirCRAS, the expert panel answers a set of assessment questions. It takes about half a day to complete the AirCRAS.

The AirCRAS consists of four stages which are visualised in Figure 8. Appendix G presents the exact information as presented to the expert panel in each stages. Next, each stage is shortly introduced:

1. The first stage of the AirCRAS is intended to align expectations with the experts regarding the relevance of performing the AirCRAS and the process which the expert panel will go through. Also, this stage elaborates on the sources that have been used for its development. This is necessary to convince the expert panel of the reliability of the information;
2. In the second stage, the users must choose what climate vectors they consider relevant for the airport in question. Choosing relevant climate vectors for their specific airport is necessary because the assessment questions to be answered in the third phase depend on those climate vectors. For example, for an airport located in Central Africa, it is irrelevant to answer questions related to sea level rise;
3. In this stage, the assessment questions have to be answered. These questions are divided into three categories: organisation, operations and infrastructure. The assessment questions must be answered on a scale from A (representing the best) to E (representing the worst);
4. Finally, the fourth stage presents the results in a rose diagram. Also, it provides discussion points that facilitate dialogues concerning, among others, the challenges the airport experiences in their transition towards becoming a climate-resilient airport. The outcome of the discussion results in priorities and/or constraints that might be used for a future in-depth resilience study.

Once the expert panel went through this information, they can start the AirCRAS by clicking 'Start AirCRAS', see Appendix G.

Section 4.5 reflects on the design requirements as presented in Section 3.5, verifying whether these requirements are sufficiently processed in the final AirCRAS.

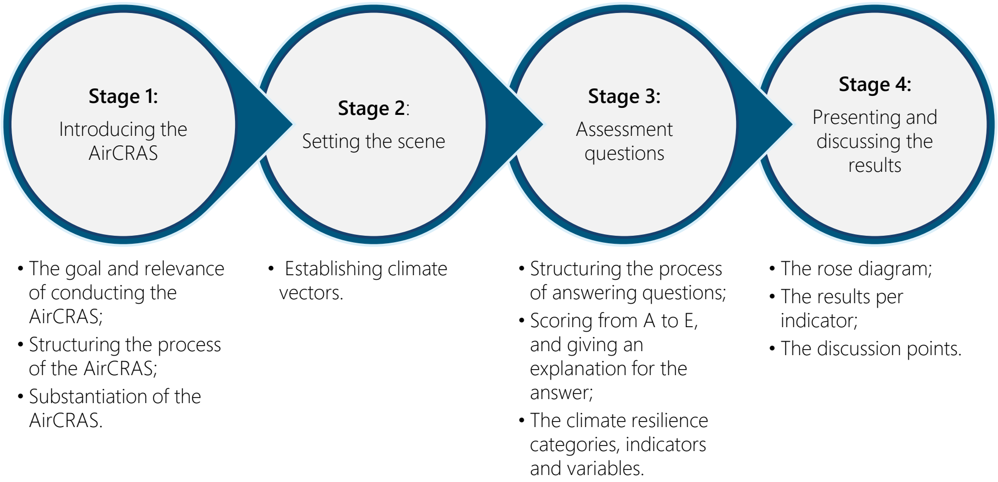


Figure 8: The user journey.

The following three sections of this chapter will each elaborate on the second, third and fourth stage of the AirCRAS.

4.2 Setting the scene (stage 2)

To increase the efficiency of the process of running through the AirCRAS, only the assessment questions which are related to the climate vectors experienced in a geographical location have to be answered. This section explains how seven climate vectors were identified, and elaborates on their meaning.

Table 6 presents the seven climate vectors that are differentiated based on reviewing literature and analysing documents. The research methodology (Chapter 2) describes why this literature and documents was selected. As can be seen in Table 6, similar climate vectors from literature are grouped together for this research.

Table 6: How the climate vectors that are used in this research came into being.

Climate vectors identified in literature	Lopez (2016)	Ferrulli (2016)	ICAO (2018a)	ICAO (2018b)	ACI (2018)	ICAO (2016a)	ACRP (2014)	Burbidge (2016)	NACO (2017)	The climate vectors as will be used in this study
Sea level rise	✓	✓	✓	✓	✓	✓	✓	✓	✓	1. Sea level rise
Hurricanes, tempests, snowfalls	✓									2. Increased intensity of storms
Increased intensity of storms			✓		✓		✓	✓		
Changes in lightning frequency and intensity									✓	
Storm surges				✓						
Temperature change	✓	✓	✓		✓	✓	✓	✓	✓	3. Temperature change
Changes in average and extreme temperatures				✓						
Changing precipitation		✓	✓	✓	✓	✓	✓	✓	✓	4. Changing precipitation
Changing icing conditions			✓	✓	✓					5. Changing icing conditions
Changes in the direction, patterns and speed of winds	✓							✓	✓	6. Changing wind
Changes to extreme wind phenomena									✓	
Changing wind		✓	✓	✓	✓	✓	✓			
Desertification			✓	✓	✓					7. Desertification

Climate vectors can be considered **climate shocks** (fast-moving variables) or **climate stressors** (slow-moving variables) (Ernstson et al. 2010; Maru 2010). Even though climate shocks require the most logistic effort (Van Wassenhove 2006), the shocks are reinforced (both in frequency and intensity) by climate stressors, see Figure 9. The case of Singapore Changi Airport shows the interdependency between shocks and stressors. In their case, storm drainage systems are connected to open water resulting in reduced drainage capacity due to sea level rise (climate shock). Additionally, since rainfall becomes more intense (climate chock) the pressure on the drainage system becomes more intense (NACO 2017).

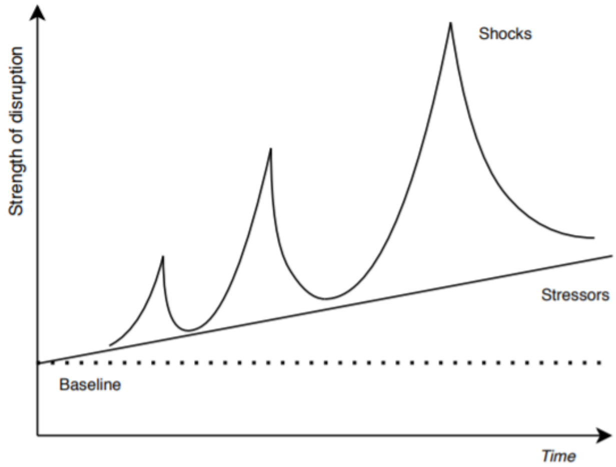


Figure 9: *The relation between shocks and stressors.*

In the AirCRAS, climate vectors are explained so the expert panel can decide what climate vectors will be considered for this research. The expert panel should check the bullets representing the relevant climate vectors and click 'Next' to continue to the assessment questions.

A description of each of the climate vectors that result is provided next.

1. **Sea level rise:** Sea level rise is caused by both increases in ocean warming and loss of mass from glaciers and ice sheets. Sea level rise can increase flooding (both in frequency and in the area flooded), contribute to greater coastal land erosion, and, in some areas, cause permanent seawater inundation (IPCC 2013).
2. **Increased intensity of storms:** Overall, storms are projected to become stronger as the climate changes. In some areas, storms also become more frequent. The types of storms that are reviewed in the AirCRAS include both winter storms and tropical cyclones (also classed as hurricanes or typhoons depending on the region in which they occur), extra-tropical cyclones, arctic cyclones, convective systems, and lightning (ICAO 2018a).
3. **Temperature change:** The global average annual temperature is rising (IPCC 2014). More frequent occurrence and longer-lasting high-heat days are also projected for some regions, particularly in the summer months (Heathrow Airport 2011; EUROCONTROL 2013; International Transport Forum 2015). Besides, higher temperatures cause significant decreases in air density (ACRP 2012).
4. **Changing precipitation:** Precipitation is any form of water - liquid or solid - falling from the sky. It includes rain, sleet, snow, hail and drizzle plus fewer common occurrences such as ice pellets, diamond dust and freezing rain (ICAO 2018a). This AirCRAS will consider changes in both types and intensities of precipitation.
5. **Changing icing conditions:** This climate vector covers ground icing, which is icing accumulated while an aircraft is on the ground (Heathrow Airport 2011; ICAO 2016b). This climate vector does not cover ice that may form as a result of precipitation, which is addressed in the changing precipitation vector. However, although freezing rain is a form of precipitation, there is some reference to it as it can contribute to the need for de-icing and it was often addressed alongside de-icing in the literature reviewed.
6. **Changing wind:** Changing wind includes changes or deviation in the prevailing wind direction (ICAO 2018a). Effects may include low-level wind shear which is a change in wind speed and/or direction in space, including updrafts and downdrafts (NACO 2017).

7. **Desertification:** Desertification is the process in which more land becomes desert. Climate change is contributing to desertification by leading to many dry regions becoming drying and hotter and having more dust or sand in the air. Unprecedented heat waves are already being recorded in many regions especially in the tropics. Desertification is also responsible for increased water scarcity and increased frequency of weather events such as high-intensity tropical cyclones and sandstorms in many regions (ICAO 2018b).

4.3 The assessment questions (stage 3)

In stage 3 the expert panel has to answer assessment questions. The assessment questions are based on climate resilience variables, which are aggregated into climate resilience indicators. These climate resilience indicators, on their turn, are aggregated into climate resilience categories.

Section 4.3.1. presents the three climate resilience categories and explains how the climate resilience categories are established. Section 4.3.2. elaborates on the content of all climate resilience indicators and variables. Each assessment question has to be answered on a scale. Section 4.3.3. elaborates on the possible scales that can be applied according to literature and explains what scale was used in the AirCRAS. In addition, Section 4.3.3. elaborates on how the assessment questions are systematically structured in the AirCRAS.

4.3.1 Climate resilience categories

This section roughly explains what each of the climate resilience categories, as introduced in Section 4.1., entails.

Organisation
The modern air transportation system is a complex and dynamic system with many diverse actors actively interacting. With ever-growing numbers of passengers, airports are now operating at their maximum capacity levels. This even further increases the complexity of air transport operations and thus it becomes more and more of a challenge to manage the air transportation system in an effective, safe, and resilient manner. This is especially evident when disruptions occur. Unexpected disruptions of air transport operations are often handled inefficiently, their effects persist for days, if not weeks (Kurtz 2016). Stranded passengers frequently complain about the lack of information and overall coordination of recovery processes (Blok, Sharpanskykh, and Vert 2018).

Early detection is an important element to prevent disruptions in airport operations, or to mitigate their impacts. The earlier the warning, the more a company can do in preparation. Detection also means perceiving the scope and magnitude of the disruption. Even though disruptions might seem innocent in their early stages, gauging the magnitude of a large disruption early, requires a culture that allows "maverick" information to be heard, understood and acted upon (Sheffi and Rice 2005). Hence, empowerment of employees is essential. This is an organisational aspect that increases the level of resilience of an airport.

Not only early detection is essential to mitigate the impacts of disruptions, but also the fast response is essential in doing so. Accelerating a company's information flow (effective sharing of information) is an important organisational factor in fast response (Sheffi 2015b; EUROCONTROL 2013; ICAO 2018a). Other organisational factors that support fast response include training staff to deal with extreme weather events (ICAO 2018a; EUROCONTROL 2013).

Third, a climate-resilient airport should prevent itself from repeatedly making the same mistakes but instead, learn from its past and with increasing its resilience status after an extreme weather event. To do so, it is important to encourage the evaluation of disruptions and the sharing of lessons learned about success and failure (ISO 2017).

These and many more organisational factors help to absorb the impacts of extreme weather events, recover from disruptions caused by them and adapt to changing conditions.

Operations
Weather is a leading cause of disruption to flight operations (Lan, Clarke, and Barnhart 2006; Koetse and Rietveld 2009), either through direct impacts on airport capacity and flight routes or through cascading delays across the aviation system (Coffel, Thompson, and Horton 2017; Fleurquin, Ramasco, and Eguiluz 2013). The impacts of such can range from a few delays, cancellations and missed connections to significant economic losses (Voltes-Dorta, Rodríguez-Déniz, and Suau-Sanchez 2017).

For example, changes in wind direction and speed may lead to an increase in crosswind operations and ultimately reduce runway usability (NACO 2017). Due to changing precipitation, takeoff and landing conditions may become hazardous which may also result in closure or reduction of runway capacity. Also, changing precipitation causes reduced visibility which leads to increased application of low visibility procedures (ICAO 2018a; Pendakur 2017). Moreover, changes in lightning frequency and intensity would result in more frequent cessation of airport operations to safeguard the safety of service personnel (Ibid.). To ensure service continuity for airport operations during extreme weather events, it is necessary to create climate-resilient airport operations (NACO 2017), so that when disturbances happen the airport is able to recover quickly to normal operations.

Infrastructure
This category includes airport infrastructures (e.g. runways, taxiways and terminals) and systems (e.g. commercial power systems and warning systems). First of all, to prevent extreme weather events from damaging infrastructure and disrupting operations, early detection is essential. Therefore effective systems need to be in place that can warn for, among others, fires, heatwaves, tsunamis and earthquakes (IPCC 2014; Heathrow Airport 2011; Sheffi 2015a).

Once the airport is subject to the disruption, it is essential to have climate resilience infrastructures in place so that when extreme weather events occur, infrastructure is able to mitigate its effects (NACO 2017). For example, often the current drainage systems cannot handle the futures' expected amount of rain which can lead to inundation of vital infrastructures such as runways and taxiways. Additionally, the intensity of storms put strains on commercial power, landlines, and cell phones (ACRP 2012).

4.3.2 Climate resilience indicators and variables

This section describes the climate resilience indicators and variables as identified in this research. All climate resilience categories, indicators and variables are presented in Figure 10.

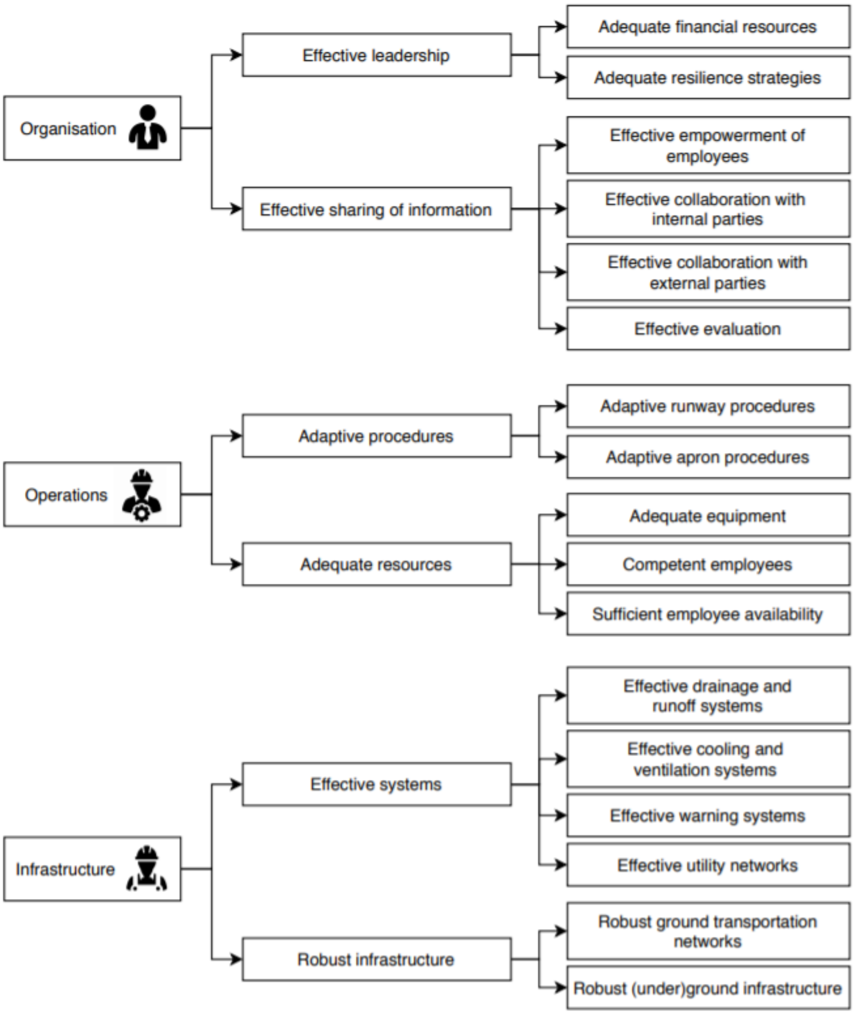


Figure 10: An initial set of climate resilience categories, indicators and variables applicable to the aviation industry.

Organisation

The category 'organisation' is divided into two indicators: (1) 'effective leadership', and (2) 'effective sharing of information', both being split up into variables.

Effective leadership

Organisational resilience is enhanced by leadership that develops and encourages managers to lead under a range of conditions and circumstances, including during periods of uncertainty and disruption (ISO 2017). Hence, this indicator maps two variables: *'adequate financial resources'*, and '*adequate resilience strategies'*.

First of all, the variable *'adequate financial resources'* plots whether adequate financial resources are made available for improving the climate resilience of the airport. The organisation should allocate such resources to address vulnerabilities and to be able to adapt to changing circumstances. Hereby it's important to routinely review the suitability of financial resources, taking account of the impact of any changes in the organisation and its context (ISO 2017). The proper level of investment in resilience varies from company to company and industry to industry. Proper investment levels are relative to the risks, which depends on many aspects e.g. geography and the airport's general reputation. Unlike insurance, which pays off only in a crisis, resilience drives everyday improvements in costs, operations, revenues, reputation and agility (Sheffi 2015b).

The second organisational variable is *'adequate resilience strategies.'* "Companies can reduce the impact of disasters by preparing a timely and effective response to disruptions" (Sheffi 2015, p. 49). Therefore, climate-resilient airports should have predefined response strategies in place to cope with relatively high-likelihood, identifiable risks. For example, airports experiencing changing icing conditions should include snow and ice removal targets e.g. keeping a specific number of runways open (ACRP 2012; GTAA 2014). Yet, airports also have to prepare for unforeseen or unknown types of disruptions by defining a clear vision regarding climate resilience, that provides strategic direction and clarity to decision making. For example, climate resilience language should be included in the business continuity plans, business continuity policy, business continuity objectives, design guidelines and maintenance plans (San Diego International Airport 2019; ISO 2017). Example 1 shows how Hong Kong International Airport (HKIA) prepares itself for typhoons by applying its safety contingency plan.

> *Hong Kong's typhoon season generally runs from May to October. This year (2020), the Hong Kong Observatory (HKO) has predicted that four to seven tropical cyclones will come within 500 kilometres of the city. Generally, whenever a typhoon approaches the city, many aircraft need to park at Hong Kong International Airport (HKIA) to ride out the storm. Airlines and the airport community have to follow forecast information from the HKO and implement safety measures well in advance. For this year, however, a massive number of aircraft have already been grounded at the airport due to the COVID-19 pandemic which has brought the global aviation industry to a semi-standstill. The challenge ahead is to prepare for possible inclement weather with a large number of aircraft currently parked at HKIA for a long time (Hong Kong International Airport 2020).*
>
> *The airport authority has drawn up a safety contingency plan with relevant airlines, referring to past wind speed and wind direction data, aircraft equipment manufacturers' recommendations on aircraft wind resistance, and previous typhoon experience. For active aircraft, the airport authority and airlines enact preventative measures by weighing them down through methods such as fuelling, tying weights to the nose gear, and adding bulk to the cargo hold. Additionally, all aircraft hangars are filled, hangar doors are closed during the passage of the typhoon, aircraft parked on taxiways are spaced out, excess aircraft are moved to remote bays, and extra chocks are placed against aircraft wheels. As a tropical cyclone approaches, airlines are required to be on standby and are responsible for contacting crew members to assist in relocation, if necessary. If the crew members are unable to be reached within two hours, a service provider will be commissioned to do the job. Another measure taken involves idle aircraft. Currently, there are about 150 such aircraft parked at HKIA, most of which have already undertaken typhoon safety measures based on airport authority safety contingency plan in collaboration with relevant airlines. Excess aircraft may also be rerouted to other airports (Ibid.).*

Example 1: *How a safety contingency plan should get Hong Kong International Airport through the typhoon season, even during the COVID-19 pandemics.*

Effective sharing of information

Organisational resilience is enhanced when information is widely shared where appropriate. The indicator: 'effective sharing of information' includes four variables: *'effective empowerment of employees'*, *'effective collaboration with internal parties'*, *'effective collaboration with external parties'*, and *'effective evaluation'*.

First, employees should be empowered to identify and communicate threats and opportunities and to take individual action that will improve climate resilience (ISO 2017). Hence, the first variable is: *'effective empowerment of employees*.' In their early stages, disruptions may seem innocent. But gauging the magnitude of a large disruption early, requires a mindset that continuously asks questions prevailing wisdom and requires a culture that allows "maverick" information to be heard, understood and acted upon (Sheffi and Rice 2005). Anything but the opposite happened recently as a consequence of which COVID-19 distributed worldwide, see Example 2. A culture of empowerment – granting authority to people to do what is needed – should extend to all levels of the organisation to respond quickly and effectively to extreme weather events.

Li Wenliang is credited with being the first medical professional to sound the alarm on the Wuhan coronavirus weeks before he contracted the illness himself and died. In late December, he messaged his medical school alumni group on WeChat, informing them that seven people from a local seafood market who showed signs of a SARS-like illness were quarantined in his hospital in Wuhan. When screenshots of his post went viral with his name in plain view, Li said, "I realized it was out of my control and I would probably be punished." Li was later called to a police station, reprimanded for spreading rumours online, and forced to sign a statement acknowledging his "misdemeanour" before he was allowed to leave (Bociurkiw 2020). Li was one of eight people who were detained for "spreading rumours" about the deadly disease's outbreak – the fates of the other seven, also believed to be medical professionals, are not known (Yu 2020). Due to COVID-19, Li died on February 7th. At the 25th of August, 7 months later, COVID-19 has caused 815K deaths worldwide (Worldometer 2020).

Example 2: *How the corona outbreak is linked to the empowerment of employees.*

Second, the variable: *'effective collaboration with internal parties'* maps whether the organisation ensures that knowledge and information are effectively shared with all relevant internal parties to enable sound decision making (EUROCONTROL 2013). To do so, the information should be accessible and understandable, and the organisation should promote communication and cooperation between departments (ISO 2017). Accelerating a company's information flow and its decision-making processes is an important factor in the detection and fast response, see Example 3. Also, GTAA (2014) found that they would have benefitted from more effective collaboration, information-sharing and face-to-face meetings, rather than primarily relying on operational conference calls during the disruptions of 2014 caused by long periods of unusual weather conditions.

On June 2013, Delta Airlines was jolted to discover an unfavourable YouTube video of soldiers returning from Afghanistan who was complaining about being charged extra for a fourth checked bag. The video went viral. Delta immediately understood the looming public relations disaster. Later the same day, it issued a corporate apology and by the next morning, it changed its policy to allow soldiers travelling on order to check four bags for free. The policy change meant that software systems had to be updated, airport kiosk modified, and employees around the world notified. By noon of that next day, Delta updated its blog posts and Facebook page alerting the public to the changed policy. The fast action prevented the video from gaining the notoriety of the video "United Breaks Guitars" (Schaal 2011).

Example 3: *How close communication can mitigate the impact of an unknown extreme event.*

Airports are operating in a multi-stakeholder environment where many are dependent on the effective functioning of the airport system and vice versa. Therefore, climate resilience depends on successful collaboration and engagement with external parties (being, for example, airlines, ground handlers and surrounding) (ISO 2017). Therefore, the fourth variable is '*collaboration with external parties*.' This variable maps whether the airport understands and strengthens its relationships with relevant external parties, and monitors the organisation's context (ISO 2017). The importance of collaboration with external parties is something which is becoming more acknowledged within the industry, as shows the example of Airport Collaborative Decision Making (A-CDM). A-CDM is a joint venture between ACI EUROPE, EUROCONTROL, the International Air Transport Association (IATA), and the Civil Air Navigation Services Organisation. The A-CDM aims to improve the operational efficiency of all airport operations by reducing delays, increasing the predictability of events during the progress of a flight and optimising the utilisation of resources. This aim is to be achieved via improved real-time information sharing between airport operators, aircraft operators, ground handlers and air traffic control. The A-CDM concept has been globally recognised. A-CDM is fully implemented in 29 airports across Europe (EUROCONTROL 2017).

Finally, a climate-resilient airport should prevent itself from repeatedly making the same mistakes but instead, learn from its past and increase their resilience status after an extreme weather event. To do so, the airport authority should encourage the evaluation of disruptions and the sharing of lessons learned about success and failure (ISO 2017). This is captured in the variable '*effective evaluation*'. Example 4 shows how evaluating one of the biggest disasters in aviation history caused a turning point regarding communication requirements in the complete industry. Not only evaluating actual disasters can be useful, but also the detection of minor events that did not cause disruption, but could have, turned out extremely useful. The Aviation Safety Reporting System (ASRS) collects and analyses voluntarily submitted, confidential aviation incidents reports to identify systemic or latent errors and hazards and to alert the industry about them. The ASRS receives more than 20.000 reports annually and issues directives on a regular and as-needed basis. Most aviation experts agree that these efforts have resulted in an ever-increasing level of civilian airline safety as system operators increase their vigilance by recognizing more conditions that can lead to disasters (Sheffi 2015b).

On the 27th of March in 1977, two Boeing 747 passenger jets, operating KLM Flight 4805 and Pan Am Flight 1736, collided on the runway at Los Rodeos Airport (now Tenerife North Airport) on the Spanish island of Tenerife resulting in 583 fatalities (Tedeschi 2019). The collision occurred when the KLM airliner initiated its takeoff run while the Pan Am airliner, shrouded in fog, was still on the runway and about to turn off onto the taxiway. The impact and resulting fire killed everyone on board KLM 4805 and most of the occupants of Pan Am 1736, with only 61 survivors in the front section of the aircraft (Eugene Register-Guard 1977).

Facts showed that false assumptions and misinterpretations had made before the accident. Transcript analysis of the cockpit voice recorder showed that the KLM pilot thought that he had been cleared for takeoff, while the Tenerife control tower believed that the KLM 747 was stationary at the end of the runway, awaiting takeoff clearance. It appears that KLM's co-pilot was not as certain about take-off clearance as the captain (Tenerife Information Centre, n.d.).

As a consequence of the accident, sweeping changes were made to international airline regulations and to aircraft. Aviation authorities around the world introduced requirements for standard phrases and a greater emphasis on English as a common working language. For example, air traffic instruction must not be acknowledged solely with a colloquial phrase such as "OK" or even "Roger" (which simply means the last transmission was received), but with a readback of the key parts of the instruction, to show mutual understanding (Ibid.).

Cockpit procedures were also changed after the accident. Hierarchical relations among crew members were played down, and greater emphasis was placed on team decision-making by mutual agreement. Less experienced flight crew members were encouraged to challenge their captains when they believed something to be incorrect, and captains were instructed to listen to their crew and evaluate all decisions in light of crew concerns. This course of action was later expanded into what is known today as crew resource management (CRM), training which is now mandatory for all airline pilots (Jedick 2014; Helmreich, Merritt, and Wilhelm 1999).

In 1978, a second airport was opened on the island of Tenerife – the new Tenerife South Airport (TFS) – which now serves the majority of international tourist flights. Los Rodeos, renamed Tenerife North Airport (TFN), was then used only for domestic and inter-island flights until 2002, when a new terminal was opened, and Tenerife North began to carry international traffic again (Tenerife Information Centre, n.d.). The Spanish government installed a ground radar system at Tenerife North Airport following the accident (Ibid.).

Example 4: *How disaster evaluation contributed to improving communication in the aviation industry.*

Operations

This category maps the impacts of extreme weather events on airport operations and considers how these impacts are reinforced by climate change. The category*: 'operations'*, consists of two indicators: (1) 'adaptive procedures', and (2) 'adequate resources', both being split into variables.

Adaptive procedures

Whereas the word might suggest the opposite, standardised procedures contribute to creating flexibility and agility in operations. That is because having the same procedures in place at different locations, allows employees to easily jump in at other places. However, structure and standards can only create flexibility and agility when well-trained teams have the authority to adopt their training to new situations, see Example 5. The indicator 'adaptive procedures', maps two variables: *'adaptive runway procedures'*, and *'adaptive apron procedures.'* The procedures that are in place at the airport, might need to be changed due to climate change. Hence, the impacts of climate change on these procedures are mapped to indicate whether the airport is considering these impacts.

When the hurricane Katrina veered toward New Orleans in August 2005, the United States Coast Guard (USCG) was ready to respond. In fact, the USCG leapt into action days before the hurricane struck. When the commanding officer for Coast Guard Sector New Orleans saw that Katrina "was making a beeline for New Orleans … from that point it was ready, set, go" (Sanial 2007).

After investigating the United States Coast Guard (USCG) response to Katrina, the Government Accountability Office (GAO) concluded that "a key factor was the agency's reliance on standardized operations and maintenance practices that provided greater flexibility for using personal and assets from any operational unit for the response." As Captain Bruce Jones, commanding officer of Air Station New Orleans, said: "The fact that you can take a rescue swimmer from Savannah and stick him on a helicopter from Houston with a pilot from Detroit and a flight mechanic from San Francisco, and these guys have never met before and they can go out and fly for six hours and rescue 80 people and come back without a scratch on the helicopter – there is no other agency that can do that" (Sanial 2007). Paradoxically, structure and standards can create flexibility and agility, not rigidness and sluggishness, but only when well-trained teams have the authority to adapt their training to new situations.

The use of standards to create flexibility for response is not unique to the USCG. For example, Southwest Airlines uses only Boeing 737 aircraft. This means that any mechanic can service any plan and any pilot can fly any aeroplane in the fleet, allowing for quick recovery from weather, congestion, and other disruptions that bedevil an airline. Coupled with empowerment, standards are the key to flexible operations – they allow for risk pooling of assets and surge capacity while empowering frontline responders to improvise when the conditions change. The flexibility of the Coast Guard stems from trusting people to do the right things, giving them the authority to take action, and not putting too many bureaucratic hurdles in their way (Sheffi 2015b).

***Example 5:** How standard procedures do not always lead to rigidness, but can also result in flexibility.*

The variable *'adaptive runway procedures'*, maps whether the airport has carefully considered the effects of temperature change, changing precipitation and changing wind on approach, landing, and takeoff procedures.

As air temperature increases at constant pressure, air expands and becomes less dense (Coffel, Thompson, and Horton 2017). However, at lower air densities, a higher airspeed is required to produce a given lifting force. For a given runway and aircraft, there is a temperature threshold above which takeoff at the aircraft's maximum takeoff weight (MTOW) is impossible due to runway length or performance limits on tire speed or braking energy. Above this threshold temperature, a weight restriction (entailing the removal of passengers, cargo, and fuel) must be imposed to permit takeoff (Ibid.).

Due to changing precipitation, takeoff and landing conditions may become hazardous which may result in closure or reduction of runway capacity. Furthermore, changing precipitation causes reduced visibility which leads to increased application of low visibility procedures (ICAO 2018a; Pendakur 2017).

Changes to, or deviation from, the prevailing wind direction at airports and wind shear could affect runway utilisation and schedules. Flights might be cancelled, delayed or redirected when crosswinds are too strong for aircraft to safely take off or land (Heathrow Airport 2011). In turn, this could reduce airport and aircraft operating efficiency, capacity and safety. Changing wind may also reduce flight arrival and departure punctuality (ACI 2018; EUROCONTROL 2013). Low-level wind shear warning and detection systems would mitigate the risk to low levels (NACO 2017).

Second, the variable *'adaptive apron procedures'*, maps whether the airport has carefully reconsidered ground procedures since they might need to change due to temperature change and changing precipitation.

As global temperatures increase, lightning is projected to also increase. Hence, lightning-induced ramp closures are a necessity to ensure the safety of outdoor personnel servicing gate-side parked aircraft. However, ramp closures cause notable air traffic impacts on both departures and arrivals. The inability to ready aircraft for departure during ramp closures will result in a delayed gate pushback time. Prolonged or multiple successive ramp closures can create a backlog of departing aircraft that will have to queue up for taxiing out after operations resume again, which yields additional delays. Besides, delays can also be found for arriving flights in form of increased taxi-in times, which is a consequence of unavailable gates that remain occupied by aircraft unable to get ready for departure (FAA 2013).

Additionally, temperature changes may influence the types of precipitation experienced in a geographical area. For example, in cold regions, there may be combinations of snow, freezing rain, rain or melt events. These changes in precipitation cause a variety in runway conditions (e.g. wet, dry, frost, dry snow, wet snow, wet ice) (ICAO, n.d.). That brings along challenges for aircraft operations since the braking deceleration of aircraft depends on the runway condition. In response, apron procedures might need to change according to the recently developed guidelines. ICAO developed the Global Reporting Format for Runway Surface conditions, providing an overarching conceptual understanding of the surface friction characteristics that contribute to controlling an aircraft via the critical tire-to-ground contact area. The intent is to provide broad and fundamental guidance related to support maintenance of surface friction characteristics and the global reporting system and format for assessing and reporting runway surface conditions applicable since 5th of November 2020 (ICAO, n.d.).

Adequate resources
Both spare capacity and high quality of resources are needed to minimize impacts and accelerate recovery times of a disaster. The indicator 'adequate resources', maps three variables: *'adequate equipment'*, *'competent employees'*, and *'sufficient employee availability.'*

The variable *'adequate equipment'* maps whether enough equipment and the right quality of equipment is available (ACRP 2012). The variable is dependent on the climate vectors: changing precipitation, temperature change and changing icing conditions. In certain areas more de-icing products need to be available since "*rain and freezing rain can have an impact on operations by decreasing traction on runways and taxiways, necessitating the use of de-icing products before takeoff*" (Pendakur 2017, p.51). As a knock-on effect, an increase in the use of de-icing fluids may increase concentrations in run-off, potentially triggering increases to the surcharge agreements (ACRP 2012). However, whereas in some areas more de-icing products are needed, temperature change may lead to a reduction in de-icing in other areas (EUROCONTROL 2013). Example 6 shows how a deficiency of supplies can result in huge loss of revenue.

> *In February 2011, the Dallas, Texas region received about 7 cm of snow just two days before a major sporting event. Although this may not be considered as heavy snowfall in some regions, "at Dallas/Fort Worth International Airport (DFW), runways and taxiways could not be cleared quickly enough because the existing snow and ice removal equipment had significant limitations; the existing equipment could only clear one of DFW's seven runways in one hour after a de-icer had been applied". As a result, more than 300 arriving flights were cancelled at DFW, a hub for American Airlines (ACRP 2012).*

Example 6: *How a deficiency of supplies can result in extreme loss of revenue.*

Second, the variable *'competent employees'*, maps whether sufficient training is given to prepare staff for dealing with extreme weather events and practice procedures that are related to weather events (e.g. using simulations). As implied, this variable is not related to a specific climate vector. Training may have an ignition financial outlay but by improving resilience they may eventually reduce financial costs (ICAO 2018a, p.59; EUROCONTROL 2013).

Third, the indicators map whether adequate measures are taken to ensure that enough employees available during extreme weather events (NATS 2011). Hence, the variable: *'sufficient employee availability'*, is not related to a specific climate vector. For example, there could be staffing issues during heavy snow events if personal cannot reach airports or control centres. By using Land Rovers to shuttle staff to work and providing hotel accommodation close to work for key personnel (Ibid.).

Infrastructure
The category: 'infrastructure', is divided into two indicators: (1) 'effective systems', and (2) 'robust infrastructure'.

Effective systems
The indicator 'effective systems', is divided into four variables: *'effective drainage and runoff systems'*, *'effective cooling, heating and ventilation systems'*, *'effective warning systems'*, and *'effective utility networks.'*

A climate-resilient airport should have effective drainage and runoff systems in place that are suitably sized to deal with future runoff peaks (ICAO 2018b). Failure of drainage systems could cause the failure of pollution control systems with risks of contaminating groundwater (Heathrow Airport 2011). The first variable is: *'effective drainage and runoff systems.'* The variable is related to two climate vectors, being: sea level rise, and changing precipitation. Due to both sea level rise and changing precipitation the drainage and runoff systems might be less effective or not be able to handle the increased volumes of water (ICAO 2018b, p. 9-5).

The second variable is: *'effective cooling and ventilation systems.'* This variable is related to the climate vector: temperature change. Due to more high-heat days in areas in which temperature increases, employees may be affected creating more demand for cooling (Heathrow Airport 2011). Hence, high-heat days may stress existing cooling systems (IPCC 2014, p.109). Besides, back-up and additional measures for cooling and ventilating terminal areas should also be considered (ICAO 2018a).

Third, an important part of reducing the impacts of disruption is quick detection. The earlier the warning, the more a company can do in preparation. Detection also means perceiving the scope and magnitude of the disruption (Sheffi 2015b). Temperature and smoke sensors can warn of a fire, and many industrial sites connect these sensors automatic fire suppression, fire evacuation alarms, and emergency responders. Similarly, tsunami sensors and earthquake early warning systems automatically activate sirens and evacuation alert. Example 7 shows the relevance of such systems. Additionally, warning systems for heatwaves have been planned and implemented broadly, for example in Europe, the United States, Asia, and Australia (IPCC 2014, p.52). That is because due to temperature change heatwaves are more likely to occur and can contribute to increased risk of fire at airport facilities (Heathrow Airport 2011). Such warning systems should be placed on effective locations and should be tested regularly. The effectivity of such systems is captured in the variable: *'effective warning systems.'*

In 2003, OKI's (Japanese company manufacturing and selling info-telecom and printer products) semiconductor factory suffered $15 million in damage and 30 days of lost production from two earthquakes near Sendai, Japan. The company then installed a system that used Japan's new Earthquakes Early Warning system (J. J. Lee 2013). Earthquake warning systems can't predict when or where a quake might start, but they can predict when and where the shockwave will go once a quake does start. An earthquake's shockwave radiates through rock at about 3.000 to 6.000 miles per hour, but radio signals from a seismograph and government warning systems travel at the speed of light or 186.000 miles per second. In places like Japan, Mixon, and California, seismologist has deployed real-time warning systems using networks of detectors. For facilities located more than a few miles from the epicentre, the detection signal can arrive seconds or a few tens of seconds before the shaking. Although a few seconds of warning seems useless in the event of a devastating quake, it can avert some of the consequential disasters. Organisations can use an early warning signal to bring elevators to halt, close pipe valves carrying hazardous materials, park the heads of hard disk drives to reduce the change of lost data, shut of heat sources, halt trains, and alert people to seek shelter. After OKI installed an early warning system, two subsequent earthquakes caused only $200.000 in damage and a total of only eight days of downtime. The same applies to tsunami warning systems, which can provide minutes or even hours of warning based on fast analysis of seismic activity and deep-water sensing of the passing tsunami wave (Ibid).

Example 7: *The advantages of Earthquake and tsunami warning systems.*

The fourth variable is: *'effective utility networks.'* The airport authority should ensure that utility networks including water pumps and communication, navigation and surveillance (CNS) systems, are always in working order. Therefore, among others, these systems need to be maintained well and there should be enough buffer and spare capacity available. Two climate vectors might impact the effectiveness of utility networks: sea level rise, and increased intensity of storms. First, often utility networks are low-lying infrastructure and are vulnerable to the effects of sea level rise (ICAO 2018a). Besides, increased intensity of storms put strains on commercial power, landlines, and cell phones. Increased intensity of storms may damage electrical systems, so lights and navigational aids should be ready to work when needed (ACRP 2012).

Robust infrastructure

The indicator 'robust infrastructure' is divided into two variables: *'robust ground transportation networks'* and *'robust (under)ground infrastructure.'*

Firstly, the variable: *'robust ground transportation networks'* maps whether the airport is accessible for employees, passengers and freight at all times. This variable is impacted by three climate vectors: sea level rise, increased intensity of storms, and changing precipitation. A climate-resilient airport should ensure that the airport is available at all times for employees, passengers and freight. The existing ground transportation networks should be able to withstand the impacts of extreme weather events without damage or loss of function. In case the network is affected, alternative route opportunities should exist. Example 8 shows what can happen if no alternative route opportunities exist. Ground transportation networks (for example, the metro or train, roads) are vulnerable to the effects of sea level rise because ground transportation is often low-lying infrastructure (ICAO 2018a). Besides, increased precipitation and increased intensity of storms can lead to blockage of ground transportation links (International Transport Forum 2015).

On September 4th, 2018, Kansai International Airport was forced to close as waves reaching 5 m in height overtopped coastal defences. Kansai International Airport was hit by Jebi, an extremely damaging tropical cyclone that became the strongest and costliest typhoon to strike of Japan since 1993 (Zhang 2018; "Typhoon Jebi Forces Closure of Kansai Airport, near Osaka in Japan" 2018). The storm surge caused serious floods, however, Kansai International Airport had crucial infrastructure like a disaster response centre and an electric substation located on the basement floor of the terminal building, an area susceptible to flooding, resulting in a large-scale power blackout (Kamohara 2018). Additionally, a bridge providing the only road and rail access to the airport from the mainland was severely damaged after a 2591-ton tanker slammed into the bridge after being swept away by strong winds and waves. Up to about 7800 passengers and employees were believed to have stayed overnight, some for more than 18 hours in terminals without power, before ferries and speedboats were deployed to evacuate them (Ibid.).

Example 8: *How limited accessibility of ground transportation and having crucial infrastructure on the basement floor, was fatal in the case of a typhoon.*

The variable: *'robust (under)ground infrastructure'* is captured within this indicator. Four climate vectors can have an impact on this variable, being: sea level rise, temperature change, changing precipitation and desertification.

To protect infrastructure and vulnerable areas from the effects of sea level rise, various measures can be taken (ACRP 2014; ICAO 2016a; San Francisco Bay Conservation and Development Commission 2017; IPCC 2013):

1. Increase platform level;
2. Relocating vulnerable infrastructure – Which could have prevented a large-scale power blackout in the case of Kansai International airport, see Example 8.
3. Building or reinforcing flood defences;
4. Retaining or introducing natural barriers.

Since the effects of sea level rise will vary by locality, there is no single strategy that will be appropriate for the entire aviation sector. Based on the documents reviewed for this research there seems to be a broad recognition that sea level rise projections and vulnerabilities must be assessed at the local level (ICAO 2018b). Airports can choose to either prevent inundation from happening by taking the above-described measures, or the airport can allow a certain degree of inundation as long as safety is not compromised (Ibid.).

Warmer temperatures may cause permafrost to thaw, which can destabilize and damage ground infrastructure and contribute to erosion (ACRP 2012; EUROCONTROL 2013; ICAO 2016a; Pendakur 2017). In areas affected by permafrost thaw, adaptation and resilience measures are being taken, including, reinforcement or elevation of runways and access roads, and relocation of facilities. For example, in Alaska (USA), a few coastal communities are relocating and moving their airports due to permafrost thaw and the subsequent erosion of land (ACRP 2012).

Extreme heat causes asphalt pavements to rut and bleed (Transportation Research Board 2008). Besides, changes to air density caused by rising temperature affect aircraft lift and the ratio of lift to weight, which may affect the required runway length to maintain normal operations (Boston-Logan International Airport 2016; Heathrow Airport 2011; ICAO 2016a; NATS 2011; Pendakur 2017).

More frequent or more intense precipitation leads to increased risk of flooding and flood damage to both runways and infrastructure. Besides, increased snowfall may cause flooding in the thaw seasons (ICAO 2018a).

Finally, due to desertification, there is an increased risk of soil erosion around the apron and runways (ICAO 2018a). Therefore, the airport authority should take measures to control erosion (for example, planting vegetation that requires little water and does not attract wildlife). Besides, airports planners and designers may need to design windbreaks to reduce dust and sand (ICAO 2018b).

4.3.3 Scoring and structuring the assessment questions

Qualitative indicators may be difficult to quantify. To overcome this challenge qualitative indicators will be quantified using a scale (Lisa, Schipper, and Langston 2015). That is why the current climate resilience status of an airport is mapped by answering assessment questions. Several different approaches were considered for converting qualitative (or subjective responses) questions into numerical scores (Rezaei 2015; Sincero 2012):

1. **Yes – No:** The variables are worded as a question. A 'Yes' generates a score 1, a 'No' a score of 0.
2. **Perceptions:** The variables are worded as a statement. Scores are assigned on an ordinal scale with 1 equates to 'strongly disagree', and 5 'strongly agree'.
3. **Bounded range:** The variables are translated into the worst-case and best-case scenarios. Scores are assigned on a scale of 1 (worst case) and 5 (best case).
4. **Thresholds:** The variable is presented as question beginning 'to what extent'. Scores are assigned based on predefined scenarios that describe the interim performance thresholds associated with scores 2-4, as well as extremes.

The option that is implemented in this research is the perception approach. It provides more granularity than a yes-no approach and more flexibility than the bounded range and threshold approach which are considered to be too prescriptive for global application. Since it is desired that the AirCRAS is globally applicable, the definition of the best and worst case will differ for different airports. Besides, the development of a bounded range and threshold requires more detailed research and is therefore not feasible within the research boundaries. Therefore, the perception approach is implemented. In consultation with experts in the validation session, the questions are answered on a scale from A (representing the 5, which is the highest score) to E (representing the 1, which is the lowest score) offering the possibility of attaching labels (from A to E) to the result.

The answer that is given by the expert panel should be argued in the open text box, see Figure 11. This information will be presented when discussing the results in stage 4, because it creates an understanding of the origin of a particular score, and it functions as a reminder to previously given information. Moreover, when the AirCRAS is conducted for several airports, the information can be used for the formulation of a bounded range or threshold.

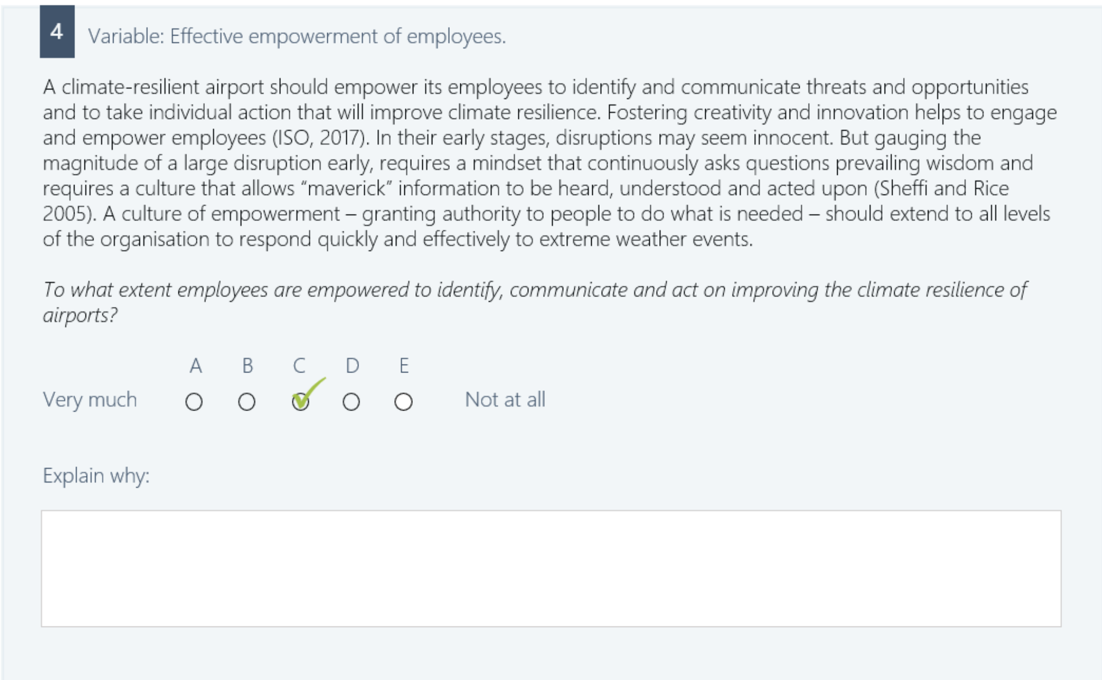


Figure 11: *An example showing how questions are visualised in the AirCRAS. This particular question is related to the variable.*

Before the questions are stated, a visual (such as Figure 12) proves insight into the status of the process.

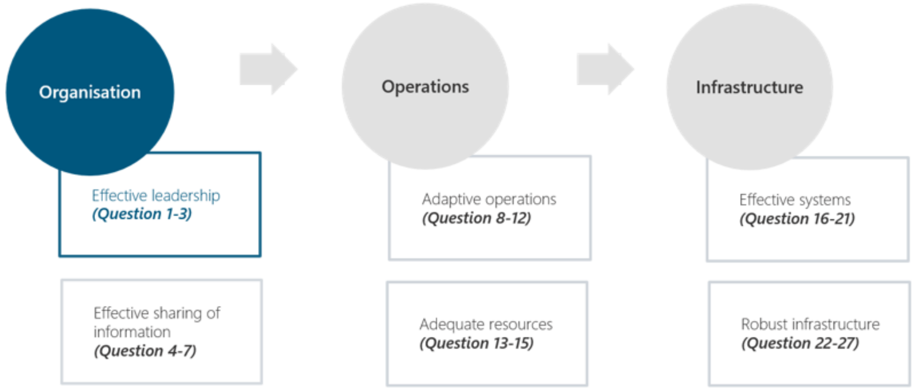


Figure 12: The process in which assessment questions are to be answered, indicating that questions related to the category 'organisation' and indicator 'effective leadership' are to be answered next.

4.4 Presenting and discussing the result (stage 4)

The purpose of the AirCRAS visualization is to provide a quick understanding of the airports' overall resilience strengths and weaknesses.

While considering options for the visual encoding, the rose diagram, sunburst diagram and TreeMaps have been considered as immediate options. TreeMaps display hierarchical (tree-structured) data as a set of nested rectangles (Shapira et al. 2019). TreeMaps are known by their ability to display and to query big datasets (hundreds of indicators) (Jadeja and Shah 2015). It is due to both the nature (hierarchical displaying) and the size (hundreds of indicators) that the use of TreeMaps is not considered relevant for this research. Also, Sunburst visualization is a radial space-filling visualisation for displaying hierarchical data (Shapira et al. 2019). Again, it's due to the hierarchical displaying of information that it is not considered relevant for this research.

The rose diagram, however, is primarily used for ordinal measurements, where all variables are measured on the same scale (Basu 2009). One application of the rose diagram is the control of quality improvement to display the performance metrics (Ibid.). Therefore, the results of the assessment questions are summarized in a rose diagram, see Figure 13. Such a diagram allows simple communication of the results summarizing the overall strengths and weaknesses of the airport system. Besides, the diagram allows easy comparison of the results per indicator.

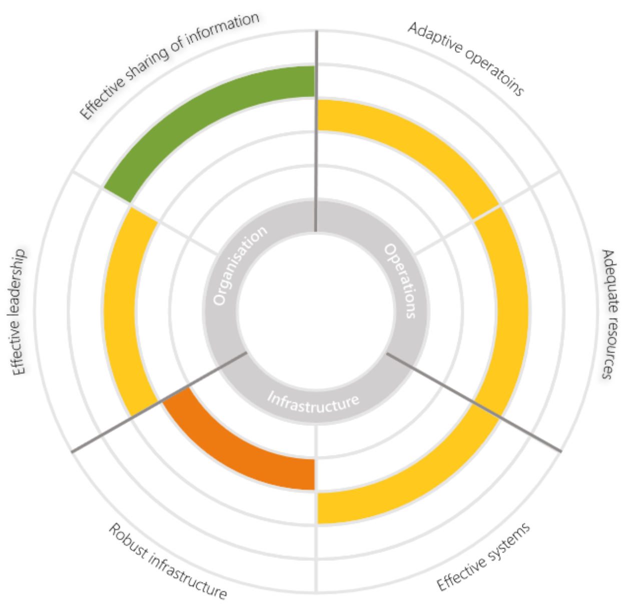


Figure 13: The rose diagram that results from conducting the AirCRAS for the case of Singapore Changi Airport.

Once the overall result is presented in a rose diagram, the results will be discussed in more details per indicator, see Figure 14. For each indicator the key issues that the airport experiences are discussed, as well as the airports' level of ambition regarding that indicator. Insight into the current status helps to formulate both.

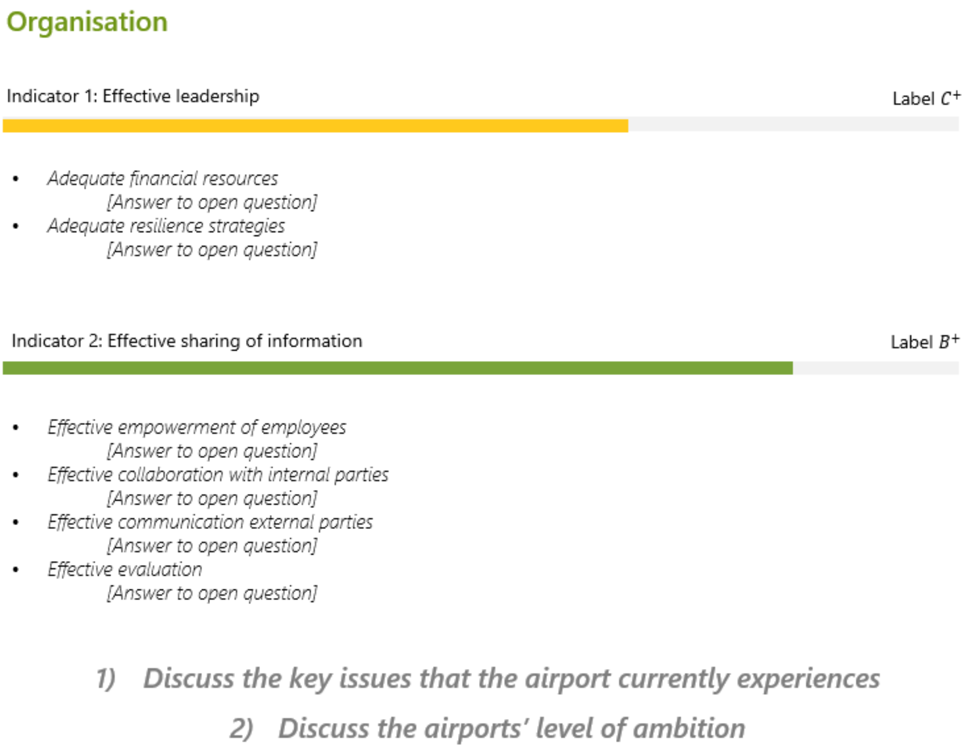


Figure 14: An example showing how, after the presentation of the rose diagram, the results are presented per indicator in more detail.

As can be seen in Figure 14 all indicators are provided with a label varying between A and E. These labels are established by adding up the assessment scores (A representing the 5 and E representing the 1) and divided through the number of questions that are related to the indicator. Figure 15 presents the scores represented by each of the labels. It is chosen to distinguish between e.g. C^+, C and C^-, to provide more detailed insight into the results.

Label A	Label B^+	Label B	Label B^-	Label C^+	Label C	Label C^-	Label D^+	Label D	Label D^-	Label E
• 1 - 1,4	• 1,5 - 1,9	• 2	• 2,1 - 2,4	• 2,5 - 2,9	• 3	• 3,1 - 3,4	• 3,5 - 3,9	• 4	• 4,1 - 4,4	• 4,5 - 5

Figure 15: The scores that are represented by each of the climate resilience labels.

Now for each indicator the key issues that the airport experiences are discussed, as well as the airports level of ambition, the following step is to discuss the overall level of risk the airport is willing to accept. No specific answer is needed in response to these discussion points. The main goal is to end with priorities and constraints for the follow up in-depth resilience study, which allows NACO's experts to design a valuable and tailor-made solution to the problems.

4.5 Compliance with the design requirements

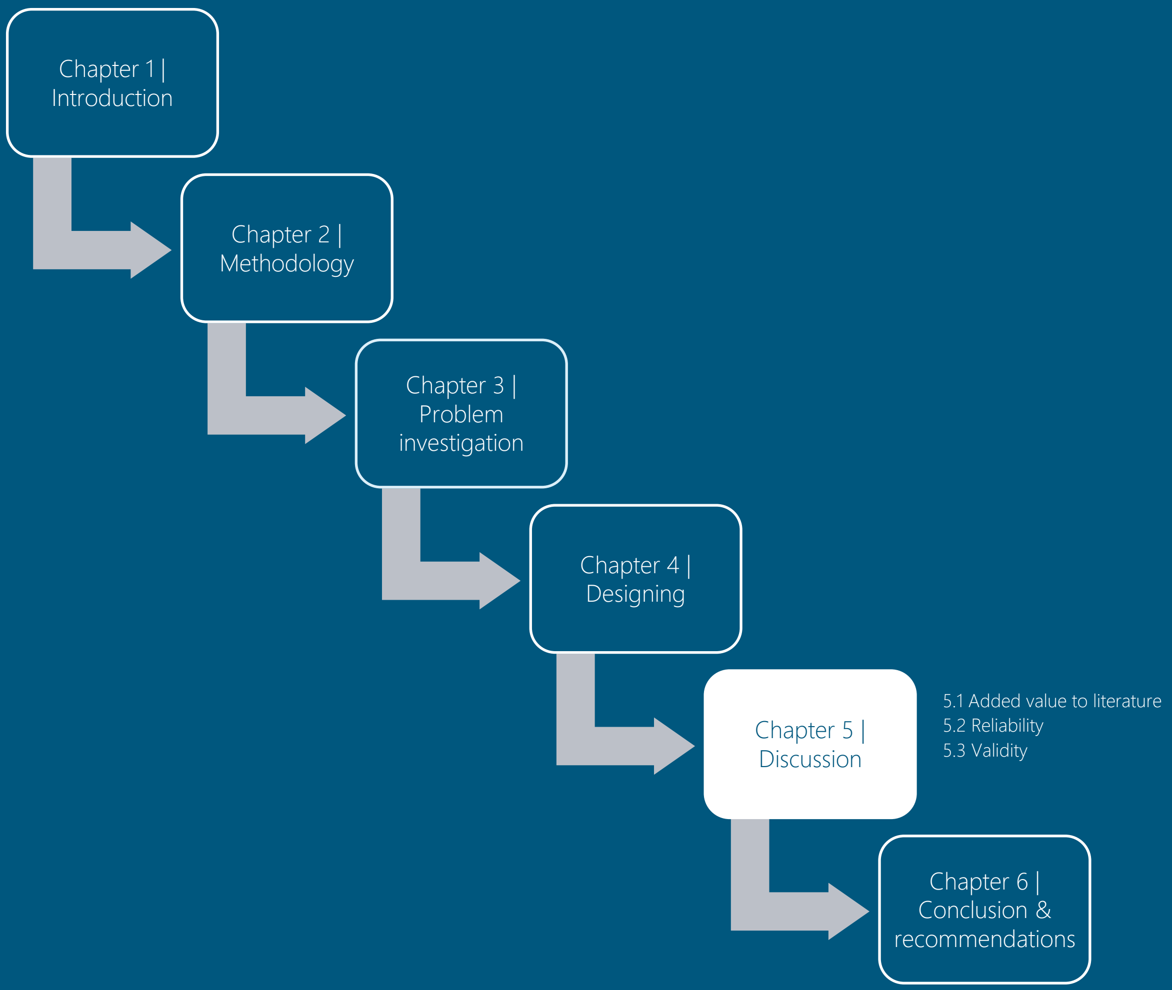
This section verifies whether the AirCRAS meets the design requirements as summarized in the design brief. As described in the Methodology (Chapter 2), the design requirements are verified in the three validation sessions. In response, comments were given (summarized in Section 4.1 and elaborately described in Appendix D) and used to further improve the AirCRAS. Table 7 reasons if and why requirements are 'met', 'substantially met', or 'not met'. In some cases, experts expected that the AirCRAS would meet the requirement, however, it could not be stated with certainty since the AirCRAS has not been implemented yet on an ongoing project. Therefore, these requirements are referred to as 'substantially met'.

Table 7: Verification of the design requirements.

#	Requirements	Reasoning	Compliance
1	The AirCRAS should provide an overview of the airports' strengths and weaknesses regarding their climate resilience status.	After all assessment questions are answered, the strengths and weaknesses of the airport regarding its climate resilience status are presented in a rose diagram. Experts in FS2 and FS3 agreed that this form of presentation gives a clear insight into the strengths and weaknesses of the airport regarding its climate resilience status. In I4 the expert recommended presenting the results in more details. Hence, changes were made so that the results will be presented and discussed in more details per indicator. The changes were verified with the expert in I4. The expert positively reflected upon the new way of presenting the strengths and weaknesses regarding the climate resilience status.	Met
2	The climate resilience indicators and variables should be based on trusted sources.	For the selection of relevant documents, we actively searched for documents related to climate resilience (measures), climate (change) adaptation and climate risks or impacts on aviation, published by the highest international organisations such as ICAO and ACI. By reading these documents, new documents were found due to snowballing. In addition, NACO expert 5 (NACO's Sustainable Aviation Lead), was asked for essential documents that had to be considered in the creation of climate resilience indicators and variables for airports. This process resulted in a selection of the documents as summarized in Appendix B.	Met
3	The AirCRAS should be applicable to the airport with different characteristics.	The climate resilience indicators and variables are developed from the starting point that they should be able to assess the current climate resilience status of airports all over the world. In FS2 and FS3 experts indicated they believed in their application for various airports having different characteristics. Additionally, when discussing the assessment questions in I4, the expert stated that all questions could be relevant to all airports. However, since the AirCRAS has not been implemented for various types of airports, we cannot argue with any certainty that this requirement is fully met. Therefore, this requirement is referred to as 'substantially met'.	Substantially met
4	The AirCRAS should allow simple communication of high amounts of information.	The overall result is presented in a rose diagram. Experts in all validation sessions agreed that this way of presenting the information allows clear and rapid insight into the strengths and weaknesses of the airport system.	Met
		To manage the expectations regarding the process that is to be run through, in FS3 the experts suggest visualising and describing such in the AirCRAS itself. That is why the AirCRAS now has figures in place that are illustrating the process. Besides, the AirCRAS opens with a description of the process that is to be run through. The expert in I4 agreed that these changes foster simple communication of high amounts of information.	Met
5	The experts of the airport should be actively engaged while conducting the AirCRAS.	The AirCRAS is to be conducted by an expert panel consisting of NACO's experts and experts from the airport (see Section 4.1). In FS2 this was rather unclear to the experts. However, when clarifying this is the second design of the AirCRAS, the experts in FS3 and I4 agreed that this requirement is met.	Met
6	The climate resilience indicators and variables should also focus on organisational aspects	The climate resilience indicators and variables are sorted into three categories: operations, infrastructure and organisation (see Section 4.3). Two climate resilience indicators and six climate resilience variables regarding organisational aspects are developed. Hence, experts in all validation sessions unilaterally agreed that the requirement is met.	Met
7	The users of the tool should be able to conduct the AirCRAS in approximately four hours.	In the first two validation sessions, experts did not agree that this requirement could be met. Hence, the design has to be improved according to the comments. In the third design, a maximum of 27 assessment questions is to be answered. Therefore, and due to the nature of these assessment questions, the expert of the third validation session considered one daypart as a reliable estimation for the total duration of conducting the AirCRAS. However, since the AirCRAS has not been conducted with an actual expert panel for an ongoing project, we cannot state for sure that the requirement is met. Therefore, the requirement is considered substantially met.	Substantially met
8	The climate resilience categories, indicators and variables should be covering relevant topics	Even though in all validation sessions many feedback was given regarding restructuring, reprioritizing or deleting climate resilience indicators and variables, no feedback was given in response to missing information. Hence, we conclude that all relevant topics are covered.	Met
9	It should be possible to adjust the AirCRAS based on new findings.	Experts in all validation sessions agreed that it would be possible to adjust the AirCRAS based on new findings. Experts emphasized the relevance of having one person responsible for further development of the AirCRAS.	Met

CHAPTER 5 | DISCUSSION

This chapter provides a discusses on the reliability and validity of the research, and elaborates on the added value to literature.



5.1 Added value to literature

This section elaborates on how this study contributes to the literature.

The AirCRAS as an operational method for assessing the resilience of airports
This research aims to design an Airport Climate Resilience Assessment Scan (AirCRAS), which is based on climate resilience indicators and variables. Previous studies are related to this research; a number of which focus on operationalising urban climate resilience (Tyler and Moench 2012; Silva, Kernaghan, and Luque 2012; Suárez et al. 2016) or assessing disaster resilience (Cutter, Burton, and Emrich 2010; Alshehri, Rezgui, and Li 2015). And while some are focussed on the identification of resilience indicators (Freudenberg 2003; Sharifi and Yamagata 2016), others aim to develop resilience principles (Biggs et al. 2012; Cariolet, Vuillet, and Diab 2019), or attend to build assessment frameworks (Li et al. 2019; Vurgin, Warren, and Ehlen 2011). In the context of airports, research however is generally focused on modelling resilience and vulnerability to disruptive events (Cardillo et al. 2013). In these studies, the economic impact of disruptions is analysed (Chen et al. 2017; Dunn and Wilkinson 2016; Hosseini, Barker, and Ramirez-Marquez 2016; Ip and Wang 2011; Pien et al. 2015; Yoo and Yeo 2016), rather than their level of resilience. This research contributes to the current body of literature by presenting the AirCRAS which transforms the theoretical concept of resilience into an operational method for assessing the overall level of resilience of airports. The premise is that such an overview stimulates discussion about the challenges that the airport experiences and the level of risk the airport is willing to accept.

An initial set of sector-specific climate resilience indicators
Sector-specific indicators seem to be the most effective way to assess resilience (Lisa, Schipper, and Langston 2015) since they provide enough context by asking detailed questions. Even though resilience indicators are identified in the context of e.g. urban areas (Sharifi and Yamagata 2016), currently there are not any climate resilience indicators to measure the resilience of airports have been identified. Therefore, this research contributes to the current body of literature by developing an initial set of sector-specific climate resilience indicators that form the basis of the AirCRAS. This research, however, does not aim to deliver a complete set of indicators (see research scope, Section 0), as the aim of the scan does not necessitate this. Instead, the indicators should cover the most relevant issues.

5.2 Reliability

According to van Burg (2011) both the stability and consistency are important for the reliability of design-oriented research. Next, it is explained how both are considered for this research.

Stability
To ensure stability of the research, **traceability** is of importance (van Burg 2011). Traceability means that it should be possible for another researcher to conduct the study similarly (Ibid). For that purpose, all activities that have been conducted in this research, are numbered. Both the content and purpose of each of these activities is described in the Methodology (Chapter 2). It is explained what data collection method was used to gather the information per activity. For the focus group sessions and interviews, all selection criteria for participants are given. For the literature review and document analysis, the specific search operations are presented. This should encourage the traceability of the research. In addition, the traceability of the research is encouraged by presenting the roadmap (5 steps), that were run through for the identification of the climate resilience categories, indicators and variables from literature and documents

In addition, to determine the stability of the results **'member checks'** can be done (van Burg 2011). In such a check, the people who provided data are asked whether they want to verify the research results (Ibid.). In this research the data which is acquired in the first focus group session and in the first three interviews is translated into design requirements. To ensure stability of the results, it had to be checked whether the information was correctly interpreted and translated into requirements. Therefore, the correctness and completeness of the requirements was verified with three experts. In addition, in the second and third focus group session it was discussed whether the requirements are incorporated in the design correctly. To ensure stability of the results, it was verified whether the design requirements are met, and it was validated whether the experts agree with the result.

Consistency
To ensure the consistency of the research results, research results should yield mutually comparable results (van Burg 2011). This has been showed by the focus group session and three interviews as conducted in the problem investigation phase as they acquired similar outcomes. However, when more interviews would have been conducted, consistency of the results could have been more strongly demonstrated.

In the validation phase, two focus group sessions and an interview were conducted to acquire feedback and improve the AirCRAS accordingly. The feedback from the two focus group sessions was highly comparable, even though the participants had different backgrounds. However, since only two focus group sessions were conducted, it is hard to demonstrate consistency of the results.

5.3 Validity

The validity of a study tells something to what extent the measuring instruments measures what it should measure (van Burg 2011). This section reflects on three types of validity: convergent validity, external validity, and pragmatic validity.

Convergent validity
The best strategy for achieving convergent validity is to use multiple disparate data collection methods for the same purpose (van Burg 2011). This is called **triangulation** (Ibid.). Triangulation is applied in in each design phase. In the problem investigation phase, both a focus group session and interviews were used to identify NACO's ambitions regarding this research. In the design phase, a broad range of sources varying from documents as published by the highest international organisations and scientific literature were consulted for the identification of climate resilience categories, indicators and variables. In the validation phase, two focus group sessions and an interview were conducted to verify and validate the design. In all validation sessions experts having different backgrounds participated. Consistency in the outcomes, resulted in consistency of the research results. In addition, to encourage the convergent validity of this research, all quotes that resulted in the first set of indicators and variables are documented in Appendix D.

External validity
The external validity of a design-oriented research is important to determine whether the design is valid not only in the researched context, but also in other contexts (van Burg 2011). Therefore, the sensitivity of the AirCRAS' for other contexts is examined.

Change of the user: The AirCRAS is developed for airport engineering and consultancy firms. Hence, not only NACO but other companies should be able to use the AirCRAS as well. However, we strongly advise airports against conducting the AirCRAS without the help of experts from outside. An outside perspective is needed to reflect critically on behaviour. Without an outsiders' help, the answers to the assessment questions will most probably be biased. Moreover, the engineering and consultancy firm should be able to offer expert knowledge of a resilience expert which is needed to be able to ask relevant questions and stimulate critical discussions. Hence, it is the outside perspective of resilience experts that will result in critical reflections.

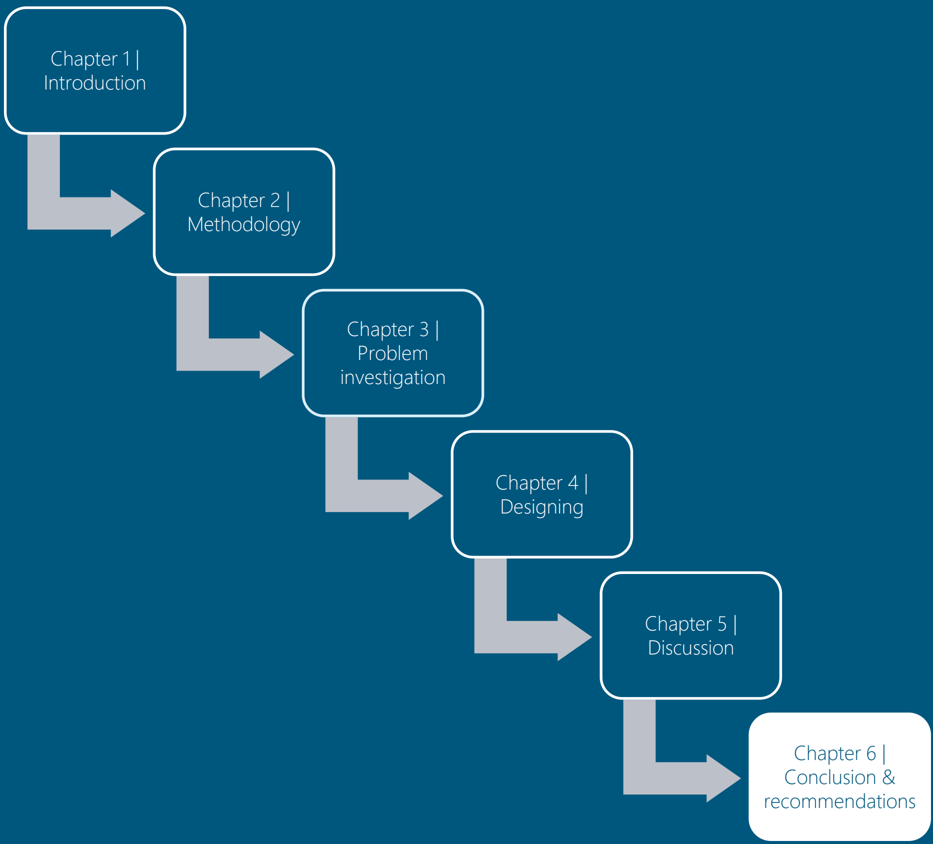
Sensitivity to a change of topic or object: The AirCRAS is designed so that its framework can be interpreted separately from its content. This means that the process of running through the four stages can stay the same, even when the topic or object changes. A different topic or object, however, asks for a different content for the four stages, meaning e.g. different indicators. Despite these changes, the AirCRAS will still result in an overview of the overall strengths and weaknesses of the system. Similarly, even though the content of the discussion points may change, the discussion points still stimulate dialogues regarding the challenges the airport experiences. Given that the framework can be taken apart from the content, the framework on itself can also be applied in other contexts.

Pragmatic validity
The ultimate test for the pragmatic validity of the result in a design science project, is to test whether the design leads to the desired improvements (van Burg 2011). Therefore, the AirCRAS has been filled in for Singapore Changi Airport. The result as generated by the AirCRAS after applying it the particular case of Singapore Changi airport matched the experts' expectations about the results. The biggest problem that was found in the previous conducted Climate Resilience Study for Singapore Changi Airport, was that certain parts of the critical infrastructure of the airport are not well protected against sea level rise and increased intensity of the precipitation. Which leads to

possible flooding of parts of the airport, including parts where critical infrastructure is located. Singapore Changi Airport scores worst on the indicator: robust infrastructure, which is in line with the previous findings. However, the AirCRAS was only run through by one expert, instead of an expert panel as required. Therefore, the results might be biased. To be able to state that the results of the AirCRAS point out the correct strengths and weaknesses and finally lead to the desired improvements, the AirCRAS should be applied to more airports. In these projects, it is important to evaluation the results in the end-stage of the project. During these evaluation sessions it should be determined whether the changes have increased the airports' climate resilience level.

CHAPTER 6 | CONCLUSION & RECOMMENDATIONS

This chapter concludes on the main findings of this research and provides recommendations for future research and practical purposes.



6.1 Conclusion

The goal of this study was to design an Airport Climate Resilience Assessment Scan (AirCRAS) that can be used by airport engineering and/or consultancy companies to create a holistic overview of the climate resilience status of an airport.

In the problem investigation phase, a gap was found between the literature regarding assessing resilience and the air transportation system. The literature regarding assessing resilience is significant, elaborating on e.g. operational frameworks, resilience principles and resilience indicators. However, air transportation is rarely mentioned in this respect. Similarly, assessing resilience is rarely mentioned in the literature regarding air transportation. These studies are generally focused on modelling the vulnerability to disruptive events to analyse the economic impact on infrastructure, rather than mapping their overall level of resilience. These findings are in line with NACO's current methodology to improve the climate resilience of airports. Their current stepwise approach is rather technically orientated which tends to go quickly into modelling the impacts of climate change and calculating the financial impacts. It may therefore miss the identification of relevant problems in the creation of climate-resilient airports on, for example, organizational aspects. Before going into details, it is therefore important that the strengths and weaknesses of a climate resilience airport are first assessed on various aspects. This is to avoid overlooking relevant problems.

It can be concluded that in literature there is a lack of knowledge on how climate resilience can be measured and operationalised on the airport level. This knowledge gap is what causes that lack of strategical guidance for airports in the transition to become more climate resilient. Considering these gaps, the AirCRAS aims to connect the two research fields of assessing resilience and the air transportation industry with each other, and with practice. The findings from the problem investigation phase are summarized in a design brief that forms the basis for the development of the AirCRAS.

In the design phase, a prototype of the AirCRAS is developed based on the design brief. In the validation phase, three validation sessions were conducted. Feedback was received in each of these validation sessions and improvements to the design were made accordingly. The process of presenting the scan, receiving feedback and refining the design was repeated three times.

The AirCRAS that results from applying this iterative process, is a digital tool. The users of the AirCRAS are experts from NACO. Together with the experts from the airport, they form an expert panel that jointly goes through the AirCRAS in a workshop at the start of a project. In the AirCRAS, the expert panel answers a set of assessment questions. It takes about half a day to complete the AirCRAS. The AirCRAS consists of four phases:

1. The first stage of the AirCRAS is intended to align expectations regarding the relevance of performing the AirCRAS and the process which the expert panel will go through. Also, this stage elaborates on the sources that have been used for its development;
2. In the second stage, the users must choose what climate vectors they consider relevant for the airport in question. Choosing relevant climate vectors for their specific airport is necessary because the assessment questions to be answered in the third phase depend on those climate vectors. For example, for an airport located in Central Africa, it is irrelevant to answer questions related to sea level rise;
3. In this stage, the assessment questions have to be answered. These questions are divided into three categories: organisation, operations and infrastructure. The assessment questions must be answered on a scale from A (representing the best) to E (representing the worst);
4. Finally, the fourth stage presents the results in a rose diagram. Also, it provides discussion points that facilitate dialogues concerning, among others, the challenges the airport experiences in their transition towards becoming a climate-resilient airport. The outcome of the discussion results in priorities and/or constraints that might be used for a future in-depth resilience study.

To conclude, this research presents the first Airport Climate Resilience Assessment Scan. By transforming the theoretical concept of resilience into an operational assessment method, the AirCRAS is able to provide a holistic overview of the climate resilience status of an airport. The premise is that this overview will stimulate discussion about the challenges that the airport faces in the transition towards becoming a more climate-resilient airport, and facilitates dialogues about the level of risk the airport is willing to accept. This provides priorities and constraints for the follow-up in-depth resilience study, and will finally result in important implications for future planning and investments to enhance the climate resilience of the airport in question.

6.2 Recommendations for future research

This section provides two recommendations for future research.

Acquire insight into why airports' do or don't prepare for extreme weather events
Even though evidence exists that extreme weather events can cause huge disruptions for airports, today there is only limited insight into what actions airports currently take to prepare for extreme weather events. The information regarding *if* airports take any measures is also limited. Therefore, it is recommended to conduct further research regarding if airports prepare for extreme weather events, and if they do, what measures are they taking? And if they do not, what is holding them back? This information can be used by international aviation organisations to guide and support the future planning of airports' resilience.

Towards a climate resilience assessment scan for benchmarking airports
The AirCRAS is developed for the individual assessment of airports. Even though all questions are currently answered on the same scale: A to E, the meaning of these labels is subjective. For the sharing of lessons-learned between airports, it is recommended to further develop the AirCRAS into a benchmark method. To ensure comparability, all labels should have the same meaning. Therefore, future research can be conducted to define the scores associated with each answer.

Towards an evaluation tool
It is recommended to explore the possibilities of developing the AirCRAS into an evaluation tool. It may be interesting to use the AirCRAS in the end-stage of the project to validate whether (the correct) changes are made.

Collaboration between transportation modes to increase the resilience of the overall transportation system
In this study, the resilience of airports is considered at the airport-level. It is recommended to consider airports as a part of the complete transportation system. In that context, the possibilities of collaboration between air transport and HSR to increase the resilience of the overall transportation system can be explored. It is recommended to exam whether or not the development of HSR can have any influence on the resilience performance of airports. A clarification of this question would provide important implications for future planning and investments of transportation infrastructure, to enhance the resilience of the overall transportation system.

6.3 Practical recommendations

This section summarizes recommendations for practical purposes.

Resilience as a well-founded concept to create a competitive advantage for NACO
In October 2020 organisational changes have been made within NACO. The biggest shift for NACO's business is that is now focussed on three thematic areas – Smart Assets & Operations; Sustainability; and Passenger Experience. The development of these three thematic areas puts sustainability in a central place, which response to the changing stakeholder needs. It is recommended to pay significant attention to resilience within the sustainability theme. The application of the AirCRAS can result in a competitive advantage for NACO, but understanding the relevance of the concept is needed for successful implementation of the AirCRAS. NACO's upper management should support further development of this area of expertise within NACO.

Appointing someone in charge of implementation and further development of the AirCRAS
It is recommended to appoint someone in charge of the implementation and evaluation of the AirCRAS. This responsibility includes ensuring that the AirCRAS will be improved accordingly. It is advised to keep track of the information based on which changes in the AirCRAS are made so that the reasons can be traced back when desired.

Quick insight into the most vulnerable airports for the acquisition of new projects
It is recommended to develop a model that provides insight into NACO's clients that are at the highest risk to extreme weather events. This insight emphasizes the need to prepare for extreme weather events, and therefore this information can be used to actively approach the most vulnerable airports for the acquisition of new projects aiming to improve the climate resilience of airports.

6.4 Food for thought

Today's COVID-19 crisis is a reminder of long-standing, interrelated and unresolved problems characterizing the global air transportation system. For example, aviation's growing contribution to climate change (IPCC 1999) and the sector's small and often negative profit margins (IATA 2019). Furthermore, global air transport increases risks, such as the spread of diseases on global scale within very short timeframes (Gössling et al. 2017). The aviation industry has been and still is highly dependent on State aid, especially in times of crisis (Gössling 2020). This is a characteristic of a non-resilient system. Even though this is considered outside the research scope, this section aims to point out some aspects which cannot be ignored in the transition towards a complete climate-resilient air transportation system.

Start taxing kerosene to stimulate collaboration and fair competition with HSR
Based on the hypothesis that the resilience of the overall transportation system can be improved when air transportation and HSR start collaborating closely, a practical recommendation for politics is formulated to stimulate collaboration and fair competition amongst both.

Today there are taxes on diesel, petrol, oil and gas. However, kerosene, the fuel that powers aircraft, is duty-free since 1944 (Hansens 2020). That kerosene is the only fuel that is not taxed today, creating unfair competition with HSR (or other modes of transport). Krenek and Schraztenstaller (2016) show that, if kerosene was taxes at the European level, this could bring billions of extra revenue to the European Union's budget. It is recommended to start taxing kerosene which stimulates fair competition with HSR (or other forms of mobility). Since it is very costly to plan, construct and maintain a European wide HSR network (Sun, Zhang, and Wandelt 2017), the money could be used for that purpose.

Use COVID-19 to reorganise the current air transportation system and increase its resilience
When push comes to shove, it is politics that has the power to guide change with policies, regulations and by issuing grants. Air transportation brings many opportunities, but only when the right business models are in place. It is recommended to examine business models that are focused on profitability rather than revenue. This could eliminate much air travel and yet increase the sector's profit margins. COVID-19 has forced many airlines to reduce their fleets, retire old aircraft, or stop serving long-haul destinations (Wood 2020). Moreover, many airlines have gone bankrupt (Ibid.). It is recommended, that instead of returning to business-as-usual, critically reflect on the current global air transportation system and use COVID-19 as a period to start reorganising the air transportation system to increase its level of resilience.

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APPENDIX A | Data about the interviews and focus group sessions

This appendix provides details about the participants of the interviews and focus group sessions. Additionally, it presents the protocol that was followed during these sessions.

Interview and focus group participants

Table 8 describes the background of each participant of the interviews and focus group sessions insight into the participants per data collection method

Table 8: Participants per data collection method.

Data collection method	Reference to participants	Background description of participants
	PHASE A – Problem investigation	
First focus group session (FS1)	NACO expert 1	NACO expert 1 is a Region Manager in India. He has about 14 years of experience at NACO. While working on various projects in India, NACO expert 1 also worked as airport master planner on other projects. Among others, he was closely involved in the resilience study for Kansai Airport.
	NACO expert 3	NACO expert 3 is a Senior Airport Engineer. He has over 10 years of professional experience as an engineering consultant in the aviation sector. He has worked on a broad range of projects for civil aviation authorities, airport authorities and contractors including airside design development, runway rehabilitation supervision, construction phase technical assistance and climate change resilience. NACO expert 3 is the supervisor from NACO for this research.
	NACO expert 4	NACO expert 4 works as a Business Analyst. He has been working for over 2 years as a business analyst implementing and leading software teams to deliver applications. NACO expert 4 is the daily supervisor from NACO for this research.
First interview (I1)	RHDHV expert 1	RHDHV expert 1 is a leading professional in Water Resilient Airports. He has been working for over 20 years as the Strategic Adviser of Amsterdam Airport Schiphol for coping with climate change, and he is involved in resilient airport studies internationally.
Second interview (I2)	NACO expert 1	Introduced previously
Third interview (I3)	NACO expert 2	NACO expert 2 is a Project Manager with over two years of working experience at NACO. She is working on the airport master planning and was closely related to the resilience study of Kansai Airport.
	PHASE C - Validation	
Second focus group session (FS2)	RHDHV expert 1	Introduced previously
	NACO expert 5	NACO expert 5 is working as Sustainable Aviation Lead. He has over 7 years of experience at NACO in which he focusses on preparing airports for a sustainable future. This includes many different topics such as aircraft noise, aircraft emissions, climate change adaptation, circular economy, air traffic forecasting, and airport terminal simulations. He is the main responsible person regarding sustainability and resilience within NACO.
	EUROCONTROL expert 1	EUROCONTROL expert 1 is working as Environment and Climate Change Policy Officer at EUROCONTROL. She is one of the key authors publishing about resilience airports, being the first one who identified the impacts of climate change as a risk for the aviation sector.
Third focus group session (FS3)	NACO expert 3	Introduced previously
	RHDHV expert 2	RHDHV expert 2 has about 28 years of experience at RHDHV. He is an expert in Urban Water Management. Among others, he has been working at the Resilience Study of Singapore Changi Airport. All projects he is working on are related to climate adaptation.
	NACO expert 6	NACO expert 6 is an Architect. She has experience for about 5 years at NACO. As an architect, she has been working mainly on master planning for airports. Recently Singapore Changi Airport has invited NACO for a second resilience study. NACO expert 6 is involved in this project.
Fourth interview (I4)	NACO expert 3	Introduced previously

Interview and focus group protocol

All interviews and focus group sessions are built up in three parts. Part I and part III is similar for all. However, the main part, part II, differs for each session. Table 9 describes what happened or what questions have been asked in each part.

Table 9: Protocol of the interviews and focus group sessions.

Part I - Introduction
• Introduce myself
• Explain the research objective
• Explain the purpose of the interview/focus group session
• Ask whether the participant(s) wants to stay anonymous
• Ask whether the participant(s) agrees with me recording the meeting
• Ask whether the participant(s) has any questions on beforehand
Part II – The main part of the interview or focus group session
First focus group session (FS1)
• Ask participants to introduce themselves
• How would you define resilience?
• Why do you aspire to conduct research to creating climate-resilient airports?
• Can you tell me something about the current stepwise approach as developed and implemented by NACO for Singapore Changi Airport?
• What are the advantages and disadvantages of the current stepwise approach for Singapore Changi airport?
• Are there any requirements that, according to you, the design has to meet?
First, second and third interview (I1, I2 and I3)
• Ask participants to introduce themselves (background, work experience, expertise, area of interest)
• How would you define resilience?
• What are the advantages of the current stepwise approach for Singapore Changi airport?
• What are the disadvantages of the current stepwise approach for Singapore Changi airport?
• Are you familiar with the City Resilience Index?
• Do you think a similar concept regarding airports can be of added value to NACO? Why or why not?
• How would an Airport Resilience Index differ from the City Resilience Index?
• Are there any requirements that, according to you, the design I am developing has to meet?
Second and third focus group session (FS2 and FS3)
• Ask participants to introduce themselves
Present the AirCRAS as developed and explain how it is intended to be used.
• Are there any aspects which are unclear or that are missing in the user journey?
• Does the design meet your expectations? Why or why not?
• In your opinion, are the airport experts actively engaged while conducting the AirCRAS?
• What do you think about the representation of information in a rose diagram? In your opinion, does it give a clear overview of the strengths and weaknesses regarding the climate resilience status of the airport?
• Would it be feasible to say that the AirCRAS can be conducted in approximately four hours? Why, or why not?
Discuss the climate resilience categories, indicators and variables in more details
• Do you agree with the three climate resilience categories? Why, or why not?
• Are the climate resilience indicators relevant? Are they missing any aspects?
• Would the indicators need to change, according to you, when being applied to different airports?
Fourth interview (I4)
Run through the AirCRAS and all assessment questions, and answer them for the case of Singapore Changi Airport;
• Discuss the clarity and relevance of the assessment questions;
When the complete AirCRAS is run through;
• Does the result meet your expectations?
• Are there any expectations you had about the AirCRAS which do not come above?
• After running through the AirCRAS and all assessment questions, do you believe that the AirCRAS can be conducted in approximately four hours?
Part III – Closing
• Provide contact information
• Offer to send a transcript of the interview

APPENDIX B | Data about the literature review and document analysis

This appendix provides information about the literature review and document analysis. It describes how articles and documents have been selected, what they contain and how they are used in this research.

To gain an overview of the current literature regarding climate resilience of airports, specific search operators were used to select the relevant articles in Scopus library, see Table 10.

Table 10: Scopus search operators.

Constraint	Search operators	Result
Terminology	Climate AND resilience OR resilient AND airport OR aviation OR "air traffic network" OR "air transportation industry"	29 articles results
Language	English	16 articles remain
Subject areas	Social Sciences and Environmental Sciences	16 articles remain
Document type	Excluding complete books	14 articles remain

After obtaining a list of potentially relevant research studies, the next step was to remove irrelevant articles. Irrelevant articles have been removed based on title and abstract for two reasons:

1. The airport is not taken as a central component, but used as a small part or example;
2. The article focusses on sustainability issues of airports, in which negligible attention is given to 'resilience'.

By applying the process as described, five relevant articles remained. Table 11 short describes each of these articles, and explains how the article is used in this study.

Table 11: An overview of the scientific literature regarding the climate resilience of airports.

Source	Description	What knowledge can be applied to this research
(Lopez 2016)	The French technical centre for civil aviation (STAC) conducted a three-step study in order to provide airport operators with a consistent assessment methodology for the evaluation of airports vulnerability to climate change. This paper aims at presenting the development of the vulnerability assessment method and highlighting the main steps to be conducted to perform a vulnerability assessment study to climate change.	This paper is used for the identification of climate vectors, and climate resilience categories and indicators. The following information can be applied: • The paper elaborates on climate vectors the airport experiences and identifies the impacts of each of these vectors on the airport system; • Following, the paper splits the airport system into three elements (infrastructure, buildings and operations) since the impacts of climate change differ for each of these elements.
(Ferrulli 2016)	This book chapter aims at developing a framework of considerations in the design of airports to withstand climate change effects. It develops method and tools to check and evaluate the sustainability design performances during the whole project development.	This book chapter is used for the identification of climate resilience categories and indicators. The following information can be applied: • The chapter provides an overview of the impacts of climate vectors on the airport infrastructure and operations; • For each impact, technological and design solutions are suggested.
(Burbidge 2016)	This paper expands on previous analysis from the European Organisation for the Safety of Air Navigation (EUROCONTROL), to further clarify what the expected impacts for airports might be. In particular, it highlights the need for action in areas which are expected to experience both high growth in demand and significant climate change impacts. It also presents an analysis of the outcomes of a stakeholder consultation which identifies a lack of awareness, information and guidance as key barriers preventing aviation organisations from taking climate adaptation.	This paper is used for the identification of climate vectors, and climate resilience categories, indicators and variables. The following information can be applied: • The paper elaborates on the climate vectors that European airports experience; • The paper identifies key questions to ask when conducting a climate risk assessment; • The paper identifies barriers to adaptation action; • The paper presents four key priorities for action to adapt global aviation to a changing climate.
(Burbidge 2018)	This paper is very similar to Burbidge (2016a), as many information is repeated in this paper. It adds to the paper by further clarifying the impacts which the aviation sector is likely to face from climate change. Besides, it describes how to begin assessing and addressing those risks.	This paper is used for the identification of climate vectors, and climate resilience categories and indicators. The following information can be applied: • It further clarifies the impacts which the aviation sector is likely to face from climate change; • It describes how to begin assessing and addressing those risks.
(Dolman and Vorage 2019)	This paper summarizes the results of the Climate Change Resilience Study for Singapore Civilian Airports, as conducted by NACO and explained in Section 3.2, in the form of a paper.	This research builds upon the 'existing stepwise approach', as designed by NACO and presented in this paper.

Table 12 provides an overview of the documents that are used in this research. For the selection of relevant articles, we actively searched for documents related to climate resilience (measures), climate (change) adaptation and climate risks or impacts on aviation, published by the highest international organisations such as ICAO and ACI. By reading these documents, new documents were found due to snowballing. To ensure that no relevant articles are missed, the articles were presented to NACO expert 5 (NACO's Sustainable Aviation Lead). According to the expert, all essential documents were included.

All documents are shortly described, and for each it is explained how the information was of use for this study.

Table 12: An overview of documents regarding climate resilience of airports that is applied in this research.

Source	Description	How information is applied
ICAO (2018a)	The Climate Adaptation Synthesis (2018), synthesizes existing information on the range of projected climate impacts on the aviation sector to better understand risks to airports, air navigation service providers (ANSPs), airlines and other aviation infrastructure. The science content of the report is based on the findings of IPCC AR5, and supplemented with other peer-reviewed scientific information, as required. The scientific content was also reviewed by the ICAO Committee on Aviation Environmental Protection (CAEP).	• ICAO (2018a) describes seven climate vectors, these are used as a foundation for the creation of climate vectors in this research; • The description of the effects of the climate vectors on aviation is used to extract climate resilience indicators and variables; • The description of resilience measures is used to extract climate resilience indicators and variables; • ICAO (2018a) provides new sources elaborating on the effects of climate change on aviation. These sources are consulted as well.
ICAO (2018b)	The purpose of Chapter 9 from ICAO's climate change resilience and adaptation report is to identify possible impacts, risks and vulnerabilities produced by climate changes that are likely to affect airport infrastructure and operations. It will also present examples of effective adaptation and resilience practices to reduce projected climate change impacts on airports.	• Provides nine climate vectors; • The description of the potential impacts of climate vectors on airport infrastructure and operations are used to extract climate resilience indicators and variables; • Since the impacts on aviation are described for infrastructure and operations, this is considered in the identification of climate resilience categories.
ACI (2018)	The Airports' Resilience and Adaptation to a Changing Climate policy brief have been produced to support airport operators and help them better understand the risks related to more adverse weather events, and consider conducting risk assessments to define their adaption plans for both existing and new infrastructure and operations. It helps airport management teams in several different departments to learn from their peers as it includes case studies of best practice adopted at other airports.	• Provides seven climate stressors; • The policy brief provides questions to ask airport for the identification of the risks experienced by that airport. These questions are used as input for the formulation of climate resilience assessment questions; • Since the impacts on aviation are described for infrastructure and operations, this is considered in the identification of climate resilience categories; • The description of the potential impacts of climate vectors on airport infrastructure and operations are used to extract climate resilience indicators and variables.
Pendakur (2017)	This report is a snapshot in time, presenting the state of knowledge about climate risks to the Canadian transportation sector, and identifying existing or potential adaptation practices that may be applied to reduce them.. This report provides transportation decision-makers and practitioners with information intended to support enhanced resilience to climate risks, while also serving as a knowledge foundation for future research.	• Since this report zooms in on the effects experienced in a particular geographical area, it provides detailed information about the effects of climate vectors on aviation, which can be used for the identification of climate resilience indicators and variables.
ISO (2017)	This document establishes the principles for organizational resilience. It identifies the attributes and activities that support an organization in enhancing its resilience. This document includes: principles providing the foundation for enhancing an organization's resilience; attributes describing the characteristics of an organization that allow the principles to be adopted; and activities guiding the utilization, evaluation and enhancement of attributes.	The principles that provide the foundation for enhancing an organization's resilience are used to extract climate resilience indicators and variables for the category: organisation. The attributes and characteristics are used to explain and provide more detailed information about the principles.
ICAO (2016a)	This chapter provides an overview of the climate change impacts on the aviation industry while highlighting the need for further research on the local effects of climate change on aircraft and airport operations. Many overlaps between the scientific articles regarding climate resilience of airports have been found since the author of the scientific articles also delivered most of the content of this report.	• Identified five climate vectors; • Identified questions to ask for conducting a risk assessment. These are used as input for the formulation of climate resilience assessment questions; • The key priorities for building aviation climate resilience are used as a basis for the AIRCRAS; • The chapter emphasizes the identification of operational and infrastructural measures to build resilience. Additionally, it names the relevance of communicating and collaborating. This information has been used for the identification of climate resilience categories.

ACRP (2014)	This report provides a guidebook to help airport practitioners understand the specific impacts climate change may have on their airport, to develop adaptation actions, and to incorporate those actions into the airport's planning processes.	• Provides climate vectors; • The description of the effects of the climate vectors on aviation is used to extract climate resilience indicators and variables.
GTAA (2014)	From January 5 to 9, 2014, much of Canada and the United States experienced and an unusual combination of winter weather conditions. Over the period, Toronto Pearson experienced a combination of rain, snow and unexpected snow squalls. Following from these events the Greater Toronto Airports Authority (GTAA) Board of Directors established an ad hoc committee to study the impact of, and operational response to, the unusual combination of winter weather conditions. This report summarizes the recommendations that have been developed.	This document provides recommendations for improving climate resilience related to operations, communications and passenger well-being. This information adds to the existing knowledge regarding infrastructural and operational resilience and is used for the creation of climate resilience categories, indicators and variables.
IPCC (2014)	The Working Group II contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC WGII AR5) considers climate change impacts, adaptation, and vulnerability. It provides a comprehensive, up-to-date picture of the current state of knowledge and level of certainty, based on the available scientific, technical, and socioeconomic literature.	This document is used consulted to formulate a clear description of the climate vectors.
EUROCONTROL (2013)	This report consults stakeholder consultation to determine whether the industry now considers that measures to increase climate resilience are required, and what actions they are taking. The research was carried out in two parts; an online survey and a follow-up workshop.	This report elaborates on various impacts of climate change on aviation. These are used to extract climate resilience indicators and variables.
ACRP (2012)	This synthesis study is intended to provide airport heads and their technical managers with a document that reviews the range of risks to airports from projected climate change and the emerging approaches for handling them.	This report summarizes climate effects and potential adaptation measures to define and plan for climate risks. These are used for the identification of climate resilience indicators and variables.
NATS (2011)	This report details how NATS is assessing the risks posed by a changing climate, and how they have adapted their business to ensure resilience to climate change effects.	Identifies current and future risks due to climate events on operations, ATC systems, buildings, remote sites, business and people. This information is used for the identification of climate resilience categories, indicators and variables.
Heathrow Airport (2011)	This study considers assets owned by Heathrow Airport Limited and has involved a comprehensive risk assessment of climate-related risks to the direct and indirect operations of Heathrow.	This report summarizes risks that airports face due to climate change. It also elaborates on the adaption responses needed to cope with these changes. Both are used for the identification of climate resilience indicators and variables.

APPENDIX C | Assessing resilience

This appendix compares the literature regarding various possibilities of measuring resilience. By no means it aims to provide a complete overview of all resilience principles, characteristics, and qualities that can be found in the literature. Instead, it gains general insight into existing knowledge.

Tyler and Moench (2012) attempt to develop an operational framework for local planning practitioners in urban areas. The framework they propose combines characteristics of urban systems, the agents that depend on and manage those systems, institutions that link systems and agents, and patterns of exposure to climate change. The characteristics they distinguish as consist of flexibility and diversity, redundancy and modularity, and safe failure.

- Flexibility and diversity: when a system that has key assets and functions that are physically distributed, so that they are not all affected by a hazard at the same time.
- Redundancy: refers to spare capacity purposely created within systems so that they can accommodate disruption, extreme pressures or surges in demand,
- Modularity here refers to interacting components, composed of similar parts that can replace each other if one or more fail. The idea behind this is that of a 'back-up', to maintain functionality at all times.
- The safe failure characteristic describes the relationship between different elements of the system, where the failure of one element doesn't transfer throughout the entire system.

Although these characteristics provide a guideline for future planning and thinking about complex urban systems, they are less suitable as technical prescriptions. Therefore, based on the work Tyler and Moench (2012), Silva, Kernaghan, and Luque (2012) propose resilience characteristics that can be used to analyse urban systems, as well as describe the desired outcome of any intervention targeted at building urban resilience. For this, they rewrote the resilience characteristics of Tyler and Moench (2012) keeping flexibility, redundancy and safe failure, while adding resourcefulness, responsiveness, the capacity to learn, and dependency on local ecosystems.

- Resourcefulness describes the capacity to visualize and act, to identify problems, to establish priorities and mobilize resources.
- Responsiveness refers to the ability to rapidly reorganize/re-establish functionality following a disturbance.
- The capacity to learn includes the learning processes of individuals and institutions that will help avoid repeating mistakes.
- Dependency on local ecosystems describes the degree of control over assets that are essential elements of supporting well-being.

The Rockefeller Foundation and Arup conducted extensive research of 4 years, distributed over 7 reports aiming to develop a City Resilience Index. In 2014 they provide an evidence-based definition of urban resilience which culminated in the publication of the City Resilience Framework (CRF). The framework is further developed towards a City Resilience Index (CRI). For the CRI they developed a comprehensive set of indicators, variables and metrics that allow cities to understand, baseline and subsequently measure local resilience over time.

The CRF research identified seven qualities of resilience associated with systems, assets, behaviours and practices that contribute to resilience. They state that universally these goals and qualities are what matters most when a city faces a wide range of chronic problems or a sudden catastrophe. These qualities add to the previously mentioned characteristics: flexibility, redundancy, and resourcefulness, by adding robust, reflective, inclusive and integrated. However, the Rockefeller Foundation and Arup give a slightly different meaning to flexibility and redundant. In their case redundancy includes diversity: the presence of multiple ways to achieve a given need or fulfil a particular function. Besides, according to their definition flexibility implies that systems can change, evolve and adapt in response to changing circumstances.

- Robust systems include well-conceived, constructed and managed physical assets so that they can withstand the impacts of hazard events without significant damage or loss of function.
- Reflective systems refer to people and institutions examine and systematically learn from their past experiences and leverage this learning to inform future decision-making.

- **Inclusion** emphasis the need for broad consultation and engagement of communities. An inclusive approach contributes to a sense of shared ownership or a joint vision to build city resilience.
- **Integrated** and alignment between city systems promotes consistency in decision-making and ensures that all investments are mutually supportive to a common outcome.

Studies that focus more on specific indicators of resilience are those of Cutter, Burton and Emrich (2010) and Suárez, et al. (2016). In their paper, Cutter, Burton and Emrich (2010) aimed to devise a set of indicators for measuring baseline characteristic of communities that foster resilience, potentially allowing monitoring of changes in resilience over time, and comparison of places. To reach their goal, subcomponents were determined to select variables, consisting of social resilience, economic resilience, institutional resilience, infrastructure resilience and community capital. Compared to the characteristics, as mentioned by Tyler & Moench (2012) and Silva, et al. (2012), these show similarities, as they also stress the importance of diversity and redundancy. The other subcomponents mainly focus on the social aspects, such as the adaptive and social capacity of the community, as well as the overall level of citizen participation. The study of Suárez, et al. (2016) identified factors that can be used to increase resilience. Those are: diversity, modularity, social cohesion, tightness of feedbacks, and *innovation*. Diversity, modularity and social cohesion have already been discussed in the previously mentioned literature.

- The **tightness of feedbacks** is closely related to the factor of responsiveness as mentioned by Silva, Kernaghan, and Luque (2012), as tightness is necessary to respond quickly and appropriately to signals and shocks.
- **Innovation** is described by Suárez et al. (2016) as collective learning and experimentation. Indicators for assessing innovation within the city environment are the diversity of organized citizen groups, spaces for citizen participation and the degree of citizen participation.

Besides studies on resilience frameworks and indicators, some studies describe general resilience principles. Resilience principles can provide a solution to the conceptual vagueness around resilience, by making the concept of 'urban resilience' more specific and translating it to practice (Wardekker et al. 2010).

Resilience principles can have different applications, based on the situation in which they are utilized. They can serve as guidelines for policy development (Biggs et al. 2012), urban planning and design strategies (e.g. Resilience Alliance 2010; Ahern 2011), or for creating a framework for understanding urban resilience and resilient cities (Kim and Lim 2016). The conclusion that can be drawn from a comparison of these works is that, even though the descriptions and applications differ, there are common denominators. At first glance, literature seems to disagree on the ways to describe resilient systems, but at closer investigation, the greatest difference lies in the wording, as the explanation of the factors/indicators/characteristics is similar. Most works mention, in one form or another, the importance of *diversity*, *redundancy*, *modularity*, *flexibility* and *responsiveness*. Additional components of resilient urban systems that some studies mention *openness* (Resilience Alliance 2010), *multi-scale networks and connectivity* (Ahern 2011), and *adaptive planning and design* (Ahern 2011; Kim and Lim 2016).

- **Openness** is considered a difficult component to use for an assessment, as there exists no optimal degree of openness. Both a high- and low degree of openness of an urban system can reduce resilience (Resilience Alliance, 2010).
- **The multi-scale networks and connectivity** are related in a way to redundancy, as it builds resilience through redundant connections, that maintain functional connectivity after disturbances (Ahern, 2011).
- **Adaptive planning and design** refer to a way of thinking and preparing for the future, which is crucial.

We found that most of the research regarding resilience assessment focuses on urban areas or disaster risk management (Cutter, Burton, and Emrich 2010; Alshehri, Rezgui, and Li 2015; Silva, Kernaghan, and Luque 2012; Tyler and Moench 2012). Within these contexts, researchers describe resilience principles (Kim and Lim 2016), while others use resilience characteristics or qualities (Tyler and Moench 2012; The Rockefeller Foundation and Arup 2016) as a mechanism to measure resilience.

Table 13 summarizes several resilience principles, characteristics and qualities found in the literature review. By no means this table aims to provide a complete overview of all resilience principles, characteristics and qualities, instead it gains general insight into existing knowledge.

Table 13: *The resilience principles.*

Resilience principles	Description
Flexibility	Flexibility implies that systems can change, evolve and adapt in response to changing circumstances. Flexibility can be achieved through the introduction of new knowledge and technologies. It also means considering and incorporating traditional knowledge and practices in new ways.
Reflectiveness	Reflective systems learn from past experiences and leverage this learning to inform future decision-making and modify standards and behaviours accordingly.
Resourcefulness	Resourcefulness implies that people and institutions are able to rapidly recognise alternative ways to use resources at times of crisis to meet their needs or achieve goals.
Integration	Integration and alignment between various systems and departments promote consistency in decision-making and ensures that all investments are mutually supportive to a common outcome. Exchange of information between systems enables them to function collectively and respond rapidly through shorter feedback loops.
Inclusiveness	Inclusion emphasis the need for broad consultation and engagement of stakeholders. An inclusive approach contributes to a joint vision to build resilience.
Robustness	Robust systems include well-conceived, constructed and managed physical assets so that they can withstand the impacts of extreme events without significant damage or loss of function.
Diversity and redundancy	Refers to spare capacity purposely created within systems so that they can accommodate disruption, extreme pressures on surges in demand. It includes diversity: the presence of multiple ways to achieve a given need or fulfil a particular function.

The conclusions that can be drawn from a comparison of this literature, is that even though at first glance literature seems to disagree on the ways to describe resilient systems, at closer investigation the greatest difference lies in the wording as the explanation of principles, characteristics and factors is similar. Hence, common denominators (summarized as resilience principles) are identified and presented in Table 13. Even though common resilience principles are found, these resilience principles are broad aspects that need to be more specifically formulated to be any use for practitioners in the aviation industry. In other words, findings from the scanned literature cannot be directly applied to the context of airports, since resilience is a context-dependent concept (Cariolet, Vuillet, and Diab 2019).

APPENDIX D | Quotes from the literature that resulted in the initial set of climate resilience indicators and variables

This appendix describes what original literature has led to the formulation of the initial set of climate resilience indicators and variables. The quotes are sorted per category in Table 14, Table 15 and Table 16.

Table 14: Quotes from the literature that resulted in an initial set of climate resilience indicators and variables as a part of the category: organisation.

<table>
<tr><th rowspan="2">Category</th><th rowspan="2">Indicators</th><th rowspan="2">Variables</th><th colspan="7">Climate vectors</th></tr>
<tr><th>1. Sea level rise</th><th>2. Increased intensity of storms</th><th>3. Temperature change</th><th>4. Changing precipitation</th><th>5. Changing icing conditions</th><th>6. Changing wind</th><th>7. Desertification</th></tr>
<tr><td rowspan="13">Organisation</td><td rowspan="3">Understanding and influencing the context</td><td>Relationships with external parties</td><td colspan="7">The organisation should understand, collaborate and strengthen the relationships with relevant interested parties to support the delivery of the organisations' purpose and vision performance (ISO 2017).</td></tr>
<tr><td>Information exchange and transparency among internal stakeholders</td><td colspan="7">The organisation should identify and design management disciplines that contribute towards the organisation's resilience, and regularly assess hoe each management discipline contributes to the overall resilience of the organization (ISO 2017; EUROCONTROL 2013; ICAO 2018a). Also, the organisation should build flexibility into the management disciplines so that the organization can absorb and adapt to change. The organisation should enhance communication, coordination, and cooperation between management disciplines of the organisation to build a coherent approach (ISO 2017).

The organisation should ensure that knowledge and information are effectively shared with all relevant internal parties to enable sound decision making (EUROCONTROL 2013). To do so, the information should be accessible and understandable, and the organisation should promote communication and cooperation between departments (ISO 2017). The GTAA (2014) found that they would have benefitted from more effective collaboration, information-sharing and face-to-face meetings, rather than primarily relying on operational conference calls during the disruptions of 2014 caused by long periods of unusual weather conditions. Besides, during regular day-to-day operations, often airlines are passengers' primary point of contact. Each airline has its media relations and employee communication protocols. During irregular operations that affect the entire airport and its visitors, there should be clear communications protocols to deliver proactive, pertinent information to passengers and frontline employees (the primary point of face-to-face interaction with passengers during irregular operations) (GTAA 2014).</td></tr>
<tr><td>Monitoring and evaluating the organisation's context</td><td colspan="7">The organisation should monitor and evaluate the organisations' context, including interdependencies, political, regulatory, environmental and competitor activities under changing circumstances (ISO 2017). Additionally, the organisation should encourage the creation and sharing of lessons learned about success and failure and promote the adoption of better practices (Ibid.).</td></tr>
<tr><td rowspan="7">Effective leadership and management</td><td>Engagement of senior management</td><td colspan="7">The airports' senior management should be committed to a sustained focus on climate resilience. This commitment can be shown by a formulated purpose, vision and values regarding resilience, that provides strategic direction and clarity to decision making at all levels of the organisation (ISO 2017). This is demonstrated in various ways. For example, senior management ensures that resilience is included in the business continuity policy and business continuity objectives. Besides adequate financial resources are made available for improving the climate resilience of the airport (Ibid.)</td></tr>
<tr><td>Adequate resources</td><td colspan="7">The organisation should develop and allocate resources, such as people, premises, technology, finance and information, to address vulnerabilities, providing the ability to adapt to changing circumstances. Hereby it's important to routinely review the suitability, availability and allocation of resources, taking account of the impact of any changes in the organisation and its context (ISO 2017).</td></tr>
<tr><td rowspan="2">Adequate strategies*</td><td colspan="7">Strategies should include a clear description of roles and responsibilities in disaster situations, and for enhancing climate resilience (ISO 2017). Resilient airports should have response strategies in place to cope with relatively high-likelihood, identifiable risks. For example, airports experiencing changing icing conditions should include snow and ice removal targets e.g. keeping a specific number of runways open (ACRP 2012; GTAA 2014). Yet, airports also have to prepare for unforeseen or unknown types of disruptions by formulating values, a clear purpose, and a vision regarding climate resilience, that provides strategic direction and clarity to decision making. For example, climate resilience language should be included in the business continuity plans, business continuity policy, business continuity objectives, design guidelines and maintenance plans (San Diego International Airport 2019; ISO 2017).</td></tr>
<tr><td></td><td>When forecasted storms are severe, some airports or airlines may pre-emptively cancel flights to ensure the safety of their operations and to reduce business impacts (ICAO 2016a).</td><td>As temperature changes, demand for air travel to certain locations may also change, which may stress capacity in some areas (ACI 2018).

Schedule changes to allow fog to dissipate could mitigate the effects of more frequent fog events. This could mean moving early morning departures to late morning for some locations (Pendakur 2017).</td><td>Too little precipitation leading to drought conditions may lead to reduced water availability with restrictions imposed on water sensitive activities (Heathrow Airport 2011).

For drought conditions, the use of reclaimed water provides a secondary benefit of drought resistance (ACRP 2012).

It is important to take precipitation projections into account when planning and developing new infrastructure and ensuring appropriate design standards are applied to new buildings to address risks from water ingress/flooding (Heathrow Airport 2011, p. 89)</td><td>The use of de-icing fluids may increase concentrations in the run-off of chemical pollutants in the water supply as it runs off the airfield, which can cause various water issues. For many airports, this may be a regulated aspect of the airport; the airport must maintain a permit or agreement regarding discharges, and water quality is tested regularly to ensure water quality standards are being met (ACRP 2012).

Specific measures that can be included in a strategy, are now and ice removal targets. Such targets include keeping a specific number of runways open (ACRP 2012; GTAA 2014).</td><td></td><td></td></tr>
<tr><td>Adaptive leadership</td><td colspan="7">The organisation should demonstrate and enhance leadership that can adapt to changing circumstances (ISO 2017).</td></tr>
<tr><td>Utilizing diversity</td><td colspan="7">According to ISO (2017) organisational resilience should demonstrate and enhance leadership that utilizes a diverse set of skills, knowledge and behaviour within the organisation to achieve organisational objectives.</td></tr>
<tr><td>Engagement with stakeholders</td><td colspan="7">The organisation should understand, collaborate and strengthen the relationship with relevant interested parties to support the delivery of the organisation's purpose and vision performance (ISO 2017). This includes monitoring and evaluating the organisation's context (interdependencies, regulatory environment and competitor activities) under changing circumstances (Ibid.).</td></tr>
<tr><td rowspan="3">A supportive culture</td><td>Empower employees</td><td colspan="7">The organisation should empower employees to identify and communicate threats and opportunities to take individual action that will benefit the organisation (ISO 2017). In their early stages, disruptions may seem innocent. But gauging the magnitude of a large disruption early, requires a mindset that continuously asks questions prevailing wisdom and requires a culture that allows "maverick" information to be heard, understood and acted upon (Sheffi and Rice 2005). A culture of empowerment – granting authority to people to do what is needed – should extend to all levels of the organisation to respond quickly and effectively to extreme weather events (Ibid.).</td></tr>
<tr><td>Foster creativity and innovation</td><td colspan="7">A culture that is supportive of organisational resilience should foster creativity and innovation that enhances organizational resilience (ISO 2017).</td></tr>
<tr><td>Employee engagement</td><td colspan="7">A culture that is supportive or organisational resilience should engage people at all levels to promote the organisation's values (ISO 2017).</td></tr>
</table>

Table 15: *Quotes from the literature that resulted in an initial set of climate resilience indicators and variables as a part of the category: operations.*

Category	Indicators	Variables	Climate vectors						
			1. Sea level rise	2. Increased intensity of storms	3. Temperature change	4. Changing precipitation	5. Changing icing conditions	6. Changing wind	7. Desertification
Operations	Adequate airport accessibility	Alternative routes	Ground transportation networks are vulnerable to the effects of sea level rise because this is often low-lying infrastructure (ICAO 2018a).	Access to ground transportation to and from airports may be affected due to increased intensity of storms (ICAO 2016a).		Increased precipitation can lead to blockage of ground transportation links (International Transport Forum 2015).			
	Available and skilled employees	Well-trained employees	This variable maps whether training is given to prepare staff for dealing with extreme weather events and practice procedures that are related to weather events. Training may have an ignition financial outlay but by improving resilience they may eventually reduce financial costs (ICAO 2018a, p.59; EUROCONTROL 2013).						
		Staff availability	Third, the indicators map whether adequate measures are taken to ensure that enough employees available during extreme weather events (NATS 2011). However, the variable: 'employee availability', is not related to a specific climate vector. For example, there could be staffing issues during heavy snow events if personal cannot reach airports or control centres. By using Land Rovers to shuttle staff to work and providing hotel accommodation close to work for key personnel (Ibid.).						
		Adequate equipment*			Unusual extreme cold spells, especially for an extended period, can cause equipment underperformance and equipment freezing (GTAA 2014). The temperature change may lead to a reduction in de-icing equipment in some areas (EUROCONTROL 2013).	In certain areas more de-icing products need to be available since "rain and freezing rain can have an impact on operations by decreasing traction on runways and taxiways, necessitating the use of de-icing products before takeoff" (Pendakur 2017, p.51). As a knock-on effect, an increase in the use of de-icing fluids may increase concentrations in run-off, potentially triggering increases to the surcharge agreements (ACRP 2012).	Changes in snow conditions may lead to increased or reduce requirements for snow clearing and de-icing equipment (EUROCONTROL 2013).		
	Procedures	Diligent maintenance checks		Increased intensity of storms has a potential effect on the performance and maintenance requirements of jet engines (ICAO 2016a, p. 207). Aircraft may require maintenance checks and repair after a lightning strike (ICAO 2018a, p. 20)					Puempel and Williams (2016) identified that desertification may lead to increased dust storms, which may affect aircraft engine design for fuel efficiency; in order to burn fuel more efficiently, engines become hotter and as a result, "silicates contained in typical sand and dust storms will melt [during the combustion process] and thus affect the performance and maintenance requirements of jet engines" (ICAO 2016a, p.116).
		Approach and departure procedures		Increased intensity of storms put strains on the process of fuelling a jet (ACRP 2012).	Due to temperature rise, air will become less dense. However, it takes an aircraft more thrust to take off in less dense air, which may create greater noise impact and CO_2 emissions. Therefore, the maximum takeoff weight may be restricted due to the temperature rise (ACI 2018). As global temperatures increase, lightning is projected to also increase. Consequently, lightning-induced ramp closures are a necessity to ensure the safety of outdoor personnel servicing gate-side parked aircraft. However, ramp closures cause notable air traffic impacts on both departures and arrivals. The inability to ready aircraft for departure during ramp closures will result in a delayed gate pushback time. Prolonged or multiple successive ramp closures can create a backlog of departing aircraft that will have to queue up for taxiing out after operations resume again, which yields additional delays. Besides, delays can also be found for arriving flights in form of increased taxi-in times, which is a consequence of unavailable gates that remain occupied by aircraft unable to get ready for departure (FAA 2013).	Due to changing precipitation, takeoff and landing conditions may become hazardous which may result in closure or reduction of runway capacity. Furthermore, changing precipitation causes reduced visibility which leads to increased application of low visibility procedures (ICAO 2018a; Pendakur 2017). Temperature changes may influence the types of precipitation experienced in a geographical area. For example, in cold regions, there may be combinations of snow, freezing rain, rain or melt events. These changes in precipitation cause a variety in runway conditions (e.g. wet, dry, frost, dry snow, wet snow, wet ice) (ICAO, n.d.). That brings along challenges for aircraft operations since the braking deceleration of aircraft depends on the runway condition. In response, apron procedures might need to change according to the recently developed guidelines. ICAO developed the Global Reporting Format for Runway Surface conditions, providing an overarching conceptual understanding of the surface friction characteristics that contribute to controlling an aircraft via the critical tire-to-ground contact area. The intent is to provide broad and fundamental guidance related to support the maintenance of surface friction characteristics and the global reporting system and format for assessing and reporting runway surface conditions applicable since the 5^{th} of November 2020 (ICAO, n.d.).		Changes to, or deviation from, the prevailing wind direction at airports and wind shear could affect runway utilisation and schedules. Flights might be cancelled, delayed or redirected when crosswinds are too strong for aircraft to safely take off or land (Heathrow Airport 2011). In turn, this could reduce airport and aircraft operating efficiency, capacity and safety. Changing wind may also reduce flight arrival and departure punctuality (ACI 2018; EUROCONTROL 2013). Low-level wind shear warning and detection systems would mitigate the risk to low levels (NACO 2017).	
		Snow removal procedures			Snow removal procedure: As temperature increases in cold -weather areas, the requirements for aircraft and tarmac de-icing and snow removal may change (ACI 2018).				

Table 16: Quotes from the literature that resulted in an initial set of climate resilience indicators and variables as a part of the category: infrastructure.

Category	Indicators	Variables	Climate vectors						
			1. Sea level rise	2. Increased intensity of storms	3. Temperature change	4. Changing precipitation	5. Changing icing conditions	6. Changing wind	7. Desertification
Infrastructure	Effective systems	Drainage and runoff systems	Such systems will be less effective or not be able to handle the increased volumes of water (ICAO 2018b, p. 9-5)			Such systems will be less effective or not be able to handle the increased volumes of water (ICAO 2018b, p. 9-5)			
		Ventilation, heating and cooling systems			Due to more high-heat days in areas in which temperature increases, employees may be affected creating more demand for cooling (Heathrow Airport 2011). High-heat days may stress existing cooling systems (IPCC 2014, p.109). And high-heat days may contribute to increased risk of fire at airport facilities (Heathrow Airport 2011). Besides, back-up and additional measures for heating terminal areas should also be considered (GTAA, 2014)				
		Reliable technology networks	Often aviation navigation, satellite coverage and communication systems are low-lying infrastructure and are vulnerable to the effects of sea level rise (ICAO 2018a, p.13).	Increased intensity of storms put strains on commercial power, landlines, and cell phones. Increased intensity of storms may damage electrical systems, so lights and navigational aids should be ready to work when needed (Airport Cooperative Research Program 2012, p. 16).					
	Robust infrastructure	Reinforcing or relocating existing infrastructure	The effects of sea level rise may damage (under)ground infrastructure. To protect infrastructure and vulnerable areas, measures like installing sea defences are taken (ACRP 2014; ICAO 2016a; San Francisco Bay Conservation and Development Commission 2017; IPCC 2013). This includes, as the ICAO Airport Planning Manual (2018) explains, "…building infrastructure higher or reinforcing existing infrastructure (e.g., using salt water-resistant materials and/or sealants). The building or reinforcing sea-defences, retaining or introducing natural barriers, allowing a certain degree of inundation as long as safety is not compromised" (p. 9-5). Relocating vulnerable infrastructure and even developing new secondary airports that will not face the same sea level impacts are also potential options (ACRP 2014; San Francisco Bay Conservation and Development Commission 2017; Pendakur 2017).		Warmer temperatures may cause permafrost to thaw, which can destabilize and damage ground infrastructure, and contribute to erosion (ACRP 2012; EUROCONTROL 2013; ICAO 2016a; Pendakur 2017). Besides warmer temperatures can damage the airfield surface if temperatures exceed design standards (Heathrow Airport 2011). Also, in some regions of Canada, as described by Pendakur (2017), there may be an increase in the "frequencies of freeze-thaw cycles over the short-term, damaging runways and underground infrastructure" (p.117). Besides, changes to air density caused by rising temperature affect aircraft lift and the ratio of lift to weight, which may affect the required runway length to maintain normal operations (Boston-Logan International Airport 2016; Heathrow Airport 2011; ICAO 2016a; NATS 2011; Pendakur 2017). Unusually cold spells, especially for an extended period, can also cause burst water pipes (GTAA 2014). Extreme heat causes asphalt pavements to rut and bleed (Transportation Research Board 2008).	Concerning changing precipitation, more frequent or more intense precipitation leads to increased risk of flooding and flood damage to both runways and infrastructure (ICAO 2018a). In some regions of Canada, as described by Pendakur (2017), "Increased snowfall may cause flooding in the thaw seasons, damaging permafrost under runways/taxiways" (p.51).	Concerning changing icing conditions, rain and freezing rain can have an impact on operations by decreasing traction on runways and taxiways (Pendakur 2017).		Concerning desertification, ICAO (2018b) stated, "Airports planners and designers may need to design windbreaks to reduce dust and sand, plant trees that require little water and that do not attract wildlife, and use recycled water for irrigation" (p.9-8). Besides, there is an increased risk of soil erosion around the apron and runways (ICAO 2018a).
		Runway length recalculation s			Changes do air density caused by rising temperatures affects aircraft lift and the ratio of lift to weight, which may affect the required runway length to maintain normal operations or may limit climb performance (Heathrow Airport 2011; NATS 2011; ICAO 2016a; Pendakur 2017; Boston-Logan International Airport 2016; ICAO 2016b).				
		Gravel runways			Gravel runways can correct for ground settlement resulting from permafrost thaw by adding material to the runway/taxiway (Pendakur 2017)				

APPENDIX E | Detailed description of the findings from the validation sessions

This appendix provides the user journey and the climate resilience indicators and variables that are presented in each of the validation session. Besides the feedback as presented in Chapter 4, this appendix provides additional detailed feedback that is given regarding the improvement of the user journey and the climate resilience indicators and variables per validation session. As described in the research methodology (Chapter 2), three validation sessions have been conducted.

Findings of the first validation session

In the validation session, the user journey has been presented by showing the mock-up of the AirCRAS as visualised in Figure 16. As a part of the AirCRAS, the climate resilience categories, indicators and variables are discussed. The experts unilaterally agreed that the three climate resilience categories: organisation, operations, and infrastructure, are well-defined. The consensus was that they are both relevant and complete.

Table 17 in Appendix F presents the climate resilience indicators and variables as discussed in the first validation session. Besides, the appendix detailly describes all feedback as provided by the experts.

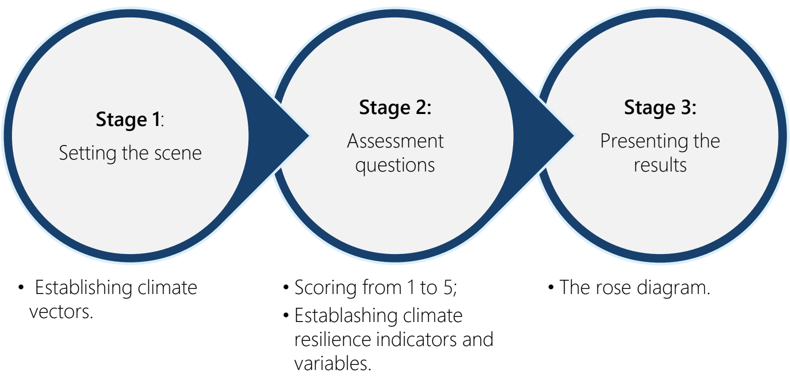

Figure 16: The user journey as presented in the first validation session.

- Experts emphasised that the variables: 'engagement of senior management', 'employee engagement', and 'adequate resources', are important and can all be captured under the indicator: 'effective leadership and management'. This suggested change has been implemented.
- Experts were wondering who should be using the AirCRAS and with what intension they should use it. In response to this feedback a stage introducing the AirCRAS is added in the user journey;
- Experts suggest ensuring an equal number of indicators per category. In response to this feedback, the researcher changed the indicator 'adequate airport accessibility' to a variable being part of the indicator 'robust infrastructure'. Additionally, the indicator: 'available and skilled employees', has been changed into the variable: 'well-trained and available employees', being part of the indicator: 'adaptive procedures';
- To deal with the subjectivity of answering the questions on a scale of 1 to 5, the experts suggested to explicitly define the meaning of the minimum and maximum score. We will refer back to this point of feedback in the second validation session.

Table 17 presents the climate resilience indicators and variables as presented in the first validation session. Below, detailed feedback in response to the climate resilience indicators and variables is summarized.

Table 17: Climate resilience indicators and variables as presented in the first validation session.

Categories	Indicators	Variables
Organisation	Understanding and influencing context	Relationships with external parties
		Information exchange and transparency among internal stakeholders
		Monitoring and evaluating the organisation's context
	Effective leadership and management	Engagement of senior management
		Adequate resources
		Adaptive leadership
		Utilizing diversity
	A supportive culture	Empower employees
		Foster creativity and innovation
		Employee engagement
	Adequate risk and resilience strategies	The clarity in roles and responsibilities
		Disaster planning
		Disaster evaluation
	Early detection	Weather forecasting
		Monitoring
		Warning systems
Operations	Adequate airport accessibility	Alternative routes
	Available and skilled employees	Well-trained employees
		Staff availability
		Adequate equipment
	Procedures	Diligent maintenance checks
		Approach and departure procedures
		Snow removal procedures
Infrastructure	Effective systems	Drainage and runoff systems
		Ventilation, heating, and cooling systems
		Reliability technology networks
		Spare capacity
	Robust infrastructure	Reinforcing or relocating existing infrastructure
		Runway length recalculations
		Gravel runways

- The experts suggested moving the indicator: 'early detection', from the category: 'organisation', to the category: 'operations'. Because, in case an extreme weather event can be detected early, operations will be adapted accordingly. This suggested change has been implemented;
- The experts suggested moving the indicator: 'airport accessibility', from the category: 'operations', to the category: 'infrastructure', because the ground transportation network that facilitates airport accessibility can be considered infrastructure. This suggested change has been implemented;
- The experts recommended transforming the indicator: 'a supportive culture', as a variable in the indicator: 'early detection'. This recommendation has been implemented;
- Experts emphasised that the variables: 'engagement of senior management', 'employee engagement', and 'adequate resources', are important and can all be captured under the indicator: 'effective leadership and management'. This suggested change has been implemented;
- Experts suggest ensuring an equal number of indicators per category. In response to this feedback, the researcher changed the indicator 'adequate airport accessibility' to a variable being part of the indicator 'robust infrastructure'. Additionally, the indicator: 'available and skilled employees', has been changed into the variable: 'well-trained and available employees', being part of the indicator: 'adaptive procedures';

Findings of the second validation session

Figure 17 presents the user journey resulting from the improvements as given previously. This user journey is discussed in the second validation session. Again, the experts, rapidly agreed that the three climate resilience categories: organisation, operations, and infrastructure, are well-defined.

Table 18 in Appendix F presents the climate resilience indicators and variables which result from the improvements as given previously, and as discussed in the second validation session.

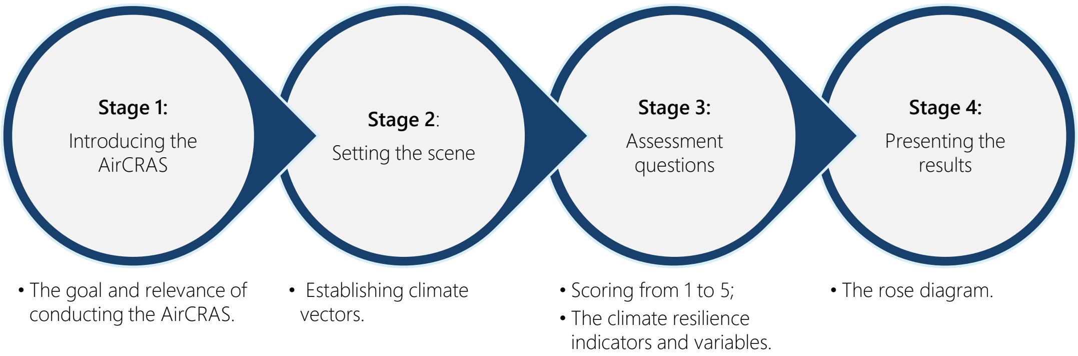

Figure 17: The user journey as presented in the second validation session.

- The experts suggest visualising and describing the process that is being run through in the AirCRAS. Besides, they suggested visualising the process in which the assessment questions have to be answered. Both suggestions are implemented.
- Two additional changes were implemented from indirect feedback in the focus group sessions. First, the indicator 'adaptive procedures', was renamed to 'adequate resources', because the naming was not representing the actual content of the indicator. Since 'adaptive procedures', is an important indicator, it should be considered an indicator, after all, however new variables (being 'adaptive approach, landing and take-off procedures', and 'adaptive ground procedures') are connected to it. Second, the indicator: 'adequate resilience strategies', was changed to a variable as part of the indicator: 'effective leadership.'
- The indicator: 'early detection', includes several different variables, such as 'warning systems' and 'open culture'. The experts discussed that some of these variables (e.g. 'warning systems') should be included in the category: infrastructure, whereas others (e.g. 'open culture') should be captured in the category: organisation. In response to this feedback, the indicator 'early detection' was removed since it describes a characteristic of a resilient system, instead of a climate resilience indicator. The variables that were part of the indicator were replaced to other indicators, such as: 'effective systems.'
- According to experts, employees should not be referred to as 'internal stakeholders.' They recommended to rename and replace the variable: 'information exchange and transparency among internal stakeholders.' This recommendation was implemented;
- In response to previous feedback, a description was added to the minimum and the maximum score of answers. However, the experts found that this was quite overwhelming and unclear. Therefore, instead of defining the scores, a short description providing background information about the question was added. This new presentation was validated once more in the last validation session;
- Regarding the scale of the assessment questions, the experts found that the scale from one to five was adequate (three was not considered enough, and seven was too much). Besides, they suggested using letters (A to E) instead of numbers (1 to 5). Using letters might prevent the users of the AIRCRAS from calculating and manipulating the outcome. This idea was implemented.

Table 18 presents the climate resilience indicators and variables as presented in the second validation session. Below, detailed feedback in response to the climate resilience indicators and variables is summarized.

Table 18: Climate resilience indicators and variables as presented in the second validation session.

Category	Indicators	Variables
Organisation	Effective leadership and management	Engagement of senior management
		Adequate resources
		Adaptive leadership
		Utilizing diversity
	Adequate resilience and risk strategies	Resilience strategies
		Risk strategies
		Extreme event evaluation
	Engagement with stakeholders	Relationships with external parties
		Information exchange and transparency among internal stakeholders
		Monitoring and evaluating the organisation's context (incl. political regulatory, environment, competitor activities)
Operations	Early detection	Weather forecasting
		Monitoring
		Warning systems
		Open culture
	Adaptive procedures	Procedures in place
		Adequate equipment
		Well-trained staff
		Available staff
Infrastructure	Effective systems	Effective drainage and runoff systems
		Effective ventilation, heating, and cooling systems, and warming stations
		Reliability technology networks (e.g. spare capacity of commercial, power, navigational aids, landline cells)
	Robust infrastructure	Airport accessibility
		Reinforcing or relocating existing infrastructure
		Appropriate runway length

- The indicator: 'early detection', includes several different variables, such as 'warning systems' and 'open culture'. The experts discussed that some of these variables (e.g. 'warning systems') should be included in the category: infrastructure, whereas others (e.g. 'open culture') should be captured in the category: organisation. In response to this feedback, the indicator 'early detection' was removed since it describes a characteristic of a resilient system, instead of a climate resilience indicator. The variables that were part of the indicator were replaced to other indicators, such as: 'effective systems.'
- According to experts, employees should not be referred to as 'internal stakeholders.' They recommended to rename and replace the variable: 'information exchange and transparency among internal stakeholders.' This recommendation was implemented;
- Two additional changes were implemented from indirect feedback in the focus group sessions. First, the indicator 'adaptive procedures', was renamed to 'adequate resources', because the naming was not representing the actual content of the indicator. Since 'adaptive procedures', is an important indicator, it should be considered an indicator, after all, however new variables (being 'adaptive approach, landing and takeoff procedures', and 'adaptive ground procedures') are connected to it. Second, the indicator: 'adequate resilience strategies', was changed to a variable as part of the indicator: 'effective leadership.'

Findings of the third validation session

In the last validation session, again the improved user journey and the climate resilience indicators and variables as a part of it, have been discussed. Additionally, this session validated the correctness of the results of the AirCRAS by filling in the assessment questions for the particular case of Singapore Changi Airport. By doing this, some recommendations for improvement followed. Since all assessment questions are discussed, many additional smaller recommendations (which are not summarized next) regarding the formulation and question design were suggested and implemented.

Table 19 presents the improved climate resilience indicators and variables as discussed in the third validation session.

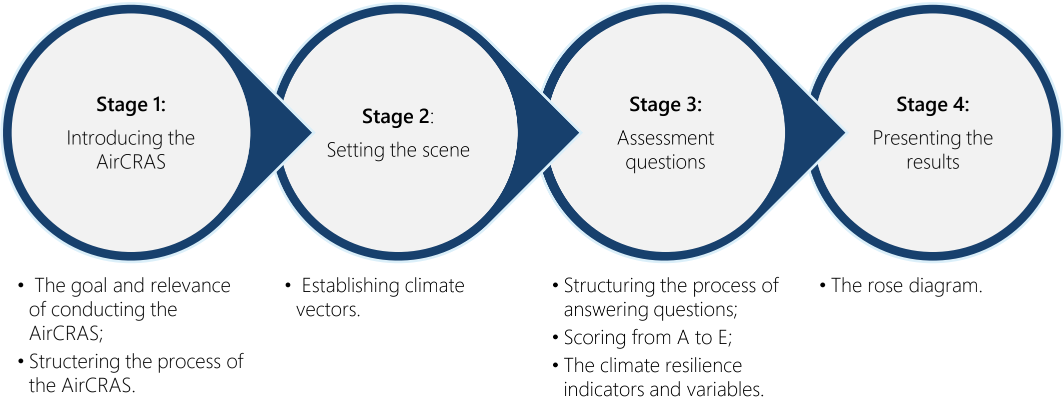

Figure 18: The user journey as presented in the third validation session.

- The AirCRAS only maps aspects that the airport authority has influence over. Consequently, the variable 'weather forecasting', was removed in response to the experts' recommendation since it is something that is outsourced to other companies;
- After a discussion about the indicators and variables being part of the category: 'organisation', it has been decided to restructure and rename a few of these indicators and variables. For example, the naming of the indicator: 'a supportive culture', had been changed into: 'effective sharing of information'.
- The variable regarding: 'warming stations' and 'heating' had been deleted in response to the experts' recommendation since it relates to a problem that rarely occurs;
- The expert recommended dividing the variable: 'reliable technology networks', into the variable 'robust utility networks' since this variable by itself sheds light into various important aspects;
- The expert recommended to state the sources from which the information is collected since substantiation of information will help to convince experts of the correctness of the information. Not only the sources should be provided along with the AirCRAS, but also a summary should be provided at the beginning of the AirCRAS about the sources that were used to collect the information;
- The rose diagram does not show how the results came into being. Hence, detailed information about the results per category is provided to facilitate reflection;
- Since the result is presented on a 5-scale score (from A to E), scores are rounded. Which means that an average score of 2.6 and 3.4 are both rounded to a 3 and thus appointed label C. However, to provide insight into the actual score, the scoring mechanism was slightly adapted, see Chapter 4, Figure 15.
- An open text box is attached to each of the assessment questions so that the expert panel can explain the answer they provided. The given explanation will be used later when the results of the AirCRAS are presented, to reflect on the score and discuss the level of ambition that they aim to reach;
- In consultation with the expert, it was decided to add discussion points that stimulate open dialogues regarding the realised scores versus the ambition level of the airport authority.

Table 19 presents the climate resilience indicators and variables as presented in the second validation session. Below, detailed feedback in response to the climate resilience indicators and variables is summarized.

Table 19: Climate resilience indicators and variables as presented in the third validation session.

<table>
<tr><th>Category</th><th>Indicators</th><th>Variables</th></tr>
<tr><td rowspan="6">Organisation</td><td rowspan="4">Effective leadership and management</td><td>Adequate commitment of upper management</td></tr>
<tr><td>Adequate strategies</td></tr>
<tr><td>Adaptive leadership</td></tr>
<tr><td>Effective engagement with stakeholders</td></tr>
<tr><td rowspan="2">A culture supportive of resilience</td><td>Effective empowerment of employees</td></tr>
<tr><td>Effective sharing of information</td></tr>
<tr><td rowspan="5">Operations</td><td rowspan="2">Adaptive procedures</td><td>Adaptive approach, landing and take-off procedures</td></tr>
<tr><td>Adaptive ground procedures</td></tr>
<tr><td rowspan="3">Adequate resources</td><td>Adequate equipment</td></tr>
<tr><td>Competent employees</td></tr>
<tr><td>Adequate employee availability</td></tr>
<tr><td rowspan="8">Infrastructure</td><td rowspan="6">Effective systems</td><td>Effective drainage and runoff systems</td></tr>
<tr><td>Effective ventilation, heating, and cooling systems, and warming stations</td></tr>
<tr><td>Effective warming stations</td></tr>
<tr><td>Effective technology networks</td></tr>
<tr><td>Accurate weather forecasting</td></tr>
<tr><td>Accurate monitoring of permafrost depth and land subsidence</td></tr>
<tr><td rowspan="2">Robust infrastructure</td><td>Robust ground transportation networks</td></tr>
<tr><td>Robust (under)ground infrastructure</td></tr>
</table>

- The variable regarding: 'warming stations' and 'heating' had been deleted in response to the experts' recommendation since it relates to a problem that rarely occurs;
- The expert recommended dividing the variable: 'reliable technology networks', into the variables 'reliable CNR systems', and 'reliable utility networks' since this variable by itself sheds light into various important aspects. This recommendation had been implemented;
- The AIRCRAS only maps aspects that the airport authority has influence over. Consequently, the variable 'weather forecasting', was removed in response to the experts' recommendation since it is something that is outsourced to other companies.
- Finally, after a discussion about the indicators and variables being part of the category: 'organisation', it has been decided to restructure and rename a few of these indicators and variables. For example, the naming of the indicator: 'a supportive culture', had been changed into: 'effective sharing of information'. Other changes that are made in response to the feedback can be found in Appendix E.

Figure 10 presents the final climate resilience indicators and variables.

APPENDIX F | An overview of the assessment questions

This appendix provides an overview of all assessment questions.

Table 20: The assessment questions.

Categories (3)	Indicators (6)	Variables (17)	Statement	Question
Organisation	Effective leadership	Adequate financial resources	The proper level of investment in resilience varies from company to company and industry to industry. Proper investment levels are relative to the risks, which depends on many aspects e.g. geography and the airport's general reputation (Sheffi and Rice 2005). The organisation should allocate adequate financial resources to address vulnerabilities and to be able to adapt to changing circumstances. Hereby it's important to routinely review the suitability of financial resources, taking account of the impact of any changes in the organisation and its context (ISO 2017).	To what extent are adequate financial resources made available for improving the climate resilience of the airport.
		Adequate resilience strategies	A climate-resilient should have response strategies in place to cope with relatively high-likelihood, identifiable risks. For example, airports experiencing changing icing conditions should include snow and ice removal targets e.g. keeping a specific number of runways open (ACRP 2012; GTAA 2014). Yet, airports also have to prepare for unforeseen or unknown types of disruptions by formulating values, a clear purpose, and a vision regarding climate resilience, that provides strategic direction and clarity to decision making. For example, climate resilience language should be included in the business continuity plans, business continuity policy, business continuity objectives, design guidelines and maintenance plans (San Diego International Airport 2019; ISO 2017).	To what extent are climate resilience strategies in place and are clear responsibilities defined regarding who is in charge of executing particular tasks and adhering to the strategies?
	Effective sharing of information	Effective empowerment of employees	A climate-resilient airport should empower its employees to identify and communicate threats and opportunities and to take individual action that will improve climate resilience. Fostering creativity and innovation helps to engage and empower employees (ISO, 2017). In their early stages, disruptions may seem innocent. But gauging the magnitude of a large disruption early, requires a mindset that continuously asks questions prevailing wisdom and requires a culture that allows "maverick" information to be heard, understood and acted upon (Sheffi and Rice 2005). A culture of empowerment – granting authority to people to do what is needed – should extend to all levels of the organisation to respond quickly and effectively to extreme weather events.	To what extent employees are empowered to identify, communicate and act on improving the climate resilience of airports?
		Effective collaboration with internal parties	A climate-resilient airport should ensure that knowledge and information is effectively shared with all relevant internal parties to enable sound decision making (EUROCONTROL, 2013). To do so, the information should be accessible and understandable, and the organisation should promote communication and cooperation between departments (ISO, 2017). Accelerating a company's information flow and its decision-making processes is an important factor in the detection and fast response. For example, during longer periods of unusual weather conditions the airport will benefit from more effective collaboration, information-sharing and face-to-face meetings, rather than primarily relying on operational conference calls (GTAA, 2014).	To what extent the organisation is effectively sharing information internal parties?
		Effective communication with external parties	Airports are operating in a multi-stakeholder environment where many are dependent on the effective functioning of the airport system and vice versa. Therefore, climate resilience depends on collaboration with external parties and successful engagement with stakeholders (being, for example, airlines, ground handlers and surrounding) (ISO 2017). Therefore, the airport understands and strengthens its relationships with relevant external parties, and monitors the organisation's context (ISO 2017).	To what extent the airport authority is engaging with stakeholders?
		Effective evaluation	A climate-resilient airport should prevent itself from repeatedly making the same mistakes but instead, learn from its past and with that, increase the resilience after an extreme weather event. To do so, the airport authority should encourage the evaluation of disruptions and the sharing of lessons learned about success and failure (ISO 2017).	To what extent is the airport authority encouraging the evaluation of disruptions?
Operations	Adaptive procedures	Adaptive runway procedures	As air temperature increases at constant pressure, air expands and becomes less dense (Coffel, Thompson, and Horton 2017). However, at lower air densities, a higher airspeed is required to produce a given lifting force. For a given runway and aircraft, there is a temperature threshold above which takeoff at the aircraft's maximum takeoff weight (MTOW) is impossible due to runway length or performance limits on tire speed or braking energy. Above this threshold temperature, a weight restriction (entailing the removal of passengers, cargo, and fuel) must be imposed to permit takeoff (Ibid.).	To what extent the airport acting regarding the changing weight restriction?
			Due to changing precipitation, takeoff and landing conditions may become hazardous which may result in closure or reduction of runway capacity. Furthermore, changing precipitation causes reduced visibility which leads to increased application of low visibility procedures (ICAO 2018a; Pendakur 2017).	To what extent is the airport acting regarding the effects of changing precipitation on runway procedures?
			Changes to, or deviation from, the prevailing wind direction and wind shear at airports could affect runway utilisation and schedules. Flights might be cancelled, delayed or redirected when crosswinds are too strong for aircraft to safely take off or land (Heathrow Airport, 2011). In turn, this could reduce airport and aircraft operating efficiency, capacity and safety. Changing wind may also reduce flight arrival and departure punctuality (ACI 2018; EUROCONTROL 2013). Low-level wind shear warning and detection systems would mitigate the risk to low levels (NACO 2017).	To what extent the airport is acting regarding the effects of changing wind on runway procedures?
		Adaptive apron procedures	As global temperatures increase, lightning is projected to also increase. Consequently, lightning-induced ramp closures are a necessity to ensure the safety of outdoor personnel servicing gate-side parked aircraft. However, ramp closures cause notable air traffic impacts on both departures and arrivals. The inability to ready aircraft for departure during ramp closures will result in a delayed gate pushback time. Prolonged or multiple successive ramp closures can create a backlog of departing aircraft that will have to queue up for taxiing out after operations resume again, which yields additional delays. Besides, delays can also be found for arriving flights in form of increased taxi-in times, which is a consequence of unavailable gates that remain occupied by aircraft unable to get ready for departure (FAA, 2013).	To what extent the airport is dealing with the effects of increasing lightning strikes on its ground operations?
			Additionally, temperature changes may influence the types of precipitation experienced in a geographical area. For example, in cold regions, there may be combinations of snow, freezing rain, rain or melt events. These changes in precipitation cause a variety in runway conditions (e.g. wet, dry, frost, dry snow, wet snow, wet ice) (ICAO, n.d.). That brings along challenges for aircraft operations since the braking deceleration of aircraft depends on the runway condition. In response, apron procedures might need to change according to the recently developed guidelines. ICAO developed the Global Reporting Format for Runway Surface conditions, providing an overarching conceptual understanding of the surface friction characteristics that contribute to controlling an aircraft via the critical tire-to-ground contact area. The intent is to provide broad and fundamental guidance related to support maintenance of surface friction characteristics and the global reporting system and format for assessing and reporting runway surface conditions applicable since 5th of November 2020 (ICAO, n.d.).	To what extent the airport can accurately report runway conditions?
	Adequate resources	Adequate equipment	Depending on the geographical location, a climate-resilient airport should ensure that enough de-icing equipment and the right quality of equipment is available. The need for equipment can change in some areas due to an increased intensity of freezing rain necessitating the use of de-icing products. As a knock-on effect, an increase in the use of de-icing fluids may increase concentrations in run-off, potentially triggering increases to the surcharge agreements (ACRP, 2012). In other areas, increased temperatures may lead to a reduction in de-icing. Other areas may experience more intense and more frequent snowfall which may also lead to a change in requirements for de-icing equipment (EUROCONTROL, 2013).	To what extent the airport authority does ensure that the right equipment, the right quality of equipment and enough equipment is available concerning changing precipitation?
		Competent employees	A climate-resilient airport should prepare its employees for dealing with extreme weather events by practising relevant procedures (e.g. using simulations) (EUROCONTROL 2013; GTAA, 2014; Heathrow Airport, 2011). Training may have an ignition financial outlay but by improving resilience they may eventually reduce financial costs (ICAO 2018a, p.59; EUROCONTROL 2013).	To what extent the airport offers regular training to its employees to prepare them for dealing with extreme weather events?
		Sufficient employee availability	A climate-resilient airport should ensure that enough competent employees are available at the airport during extreme weather events (in case of disruption of ground transportation networks) (NATS, 2011). For example, there could be staffing issues during heavy snow events if personal cannot reach airports or control centres. By using Land Rovers to shuttle staff to work and providing hotel accommodation close to work for key personnel (Ibid.).	To what extent the airport authority is ensuring that enough employees are available during an extreme weather event?
Infrastructure*	Effective systems*	Effective drainage and runoff systems*	A climate-resilient airport should have effective drainage and runoff systems in place that are suitably sized to deal with future runoff peaks (ICAO, 2018b). Due to sea level rise failure of drainage systems could cause the failure of pollution control systems with risks of contaminating groundwater (Heathrow Airport, 2011; ACI World, 2011).	To what extent the drainage and runoff systems can deal with increased volumes of water?
		Effective ventilation and cooling systems*	Due to more frequent and intense high-heat days, there is a higher peak demand for cooling which stresses existing cooling systems potentially beyond existing cooling capacities (Heathrow Airport, 2011; IPCC, 2014). A climate-resilient airport should have effective systems in place for cooling and ventilation of terminal areas and aircraft. Besides, back-up and additional measures for cooling and ventilating terminal areas should also be considered (ICAO 2018a).	To what extent the airport has effective and enough cooling and ventilation systems in place?

		Effective warning systems*	An important part of reducing the impacts of disruption is quick detection. The earlier the warning, the more a company can do in preparation. Detection also means perceiving the scope and magnitude of the disruption. Temperature and smoke sensors can warn of a fire, and many industrial sites connect these sensors automatic fire suppression, fire evacuation alarms, and emergency responders. Similarly, tsunami sensors and earthquake early warning systems automatically activate sirens and evacuation alert. Additionally, warning systems for heatwaves can be installed, because due to temperature change heatwaves are more likely to occur and can contribute to increased risk of fire at airport facilities (Heathrow Airport 2011). Such warning systems should be placed on effective locations and should be tested regularly.	To what extent the airport has effective warning systems for heatwaves in place?
		Effective utility networks*	A climate-resilient airport should ensure that utility networks including water pumps and communication, navigation and surveillance (CNS) systems, are always in working order. Therefore, among others, these systems need to be maintained well and there should be enough buffer and spare capacity available. Two climate vectors might impact the effectiveness of utility networks: sea level rise, and increased intensity of storms. First, often utility networks are low-lying infrastructure and are vulnerable to the effects of sea level rise (ICAO 2018a). Besides, increased intensity of storms put strains on commercial power, landlines, and cell phones. Increased intensity of storms may damage electrical systems, so lights and navigational aids should be ready to work when needed (ACRP 2012).	To what extent is the utility network in place effective and redundant?
	Robust infrastructure*	Robust ground transportation networks*	A climate-resilient airport should ensure that the airport is available at all times for employees, passengers and freight. The existing ground transportation networks should be able to withstand the impacts of extreme weather events without damage or loss of function. In case the network is affected, alternative route opportunities should exist. Ground transportation networks (for example, the metro or train, roads) are vulnerable to the effects of sea level rise because ground transportation is often low-lying infrastructure (ICAO 2018a). Besides, increased precipitation and increased intensity of storms can lead to blockage of ground transportation links (International Transport Forum 2015).	To what extent the airport authority is ensuring adequate airport access for employees, passengers and freight, at all times?
		Robust (under)ground infrastructure*	To protect infrastructure and vulnerable areas from the effects of sea level rise, various measures can be taken (ACRP, 2014; ICAO, 2016a; San Francisco Bay Conservation and Development Commission, 2017; IPCC, 2013): (1) Increase platform level; (2) Relocating vulnerable infrastructure; (3) Building or reinforcing flood defences; (4) Retaining or introducing natural barriers. The airport can choose to either prevent inundation from happening by taking the above-described measures, or the airport can allow a certain degree of inundation as long as safety is not compromised (ICAO, 2018b).	To what extent the current airport infrastructure is protected from the future effects of sea level rise?
			More frequent or more intense precipitation leads to increased risk of flooding and flood damage to both runways and infrastructure. Besides, increased snowfall may cause flooding in the thaw seasons (ICAO 2018a).	To what extent the airport is protecting its infrastructure from the future effects of changing precipitation?
			Warmer temperatures may cause permafrost to thaw, which can destabilize and damage ground infrastructure and contribute to erosion (ACRP 2012; EUROCONTROL 2013; ICAO 2016a; Pendakur 2017). In areas affected by permafrost thaw, adaptation and resilience measures are being taken, including, reinforcement or elevation of runways and access roads, and relocation of facilities. For example, in Alaska (USA), a few coastal communities are relocating and moving their airports due to permafrost thaw and the subsequent erosion of land (ACRP 2012).	To what extent the airport is protecting its infrastructure from permafrost thaw?
			Extreme heat causes asphalt pavements to rut and bleed (Transportation Research Board, 2008). Besides, changes to air density caused by rising temperature affect aircraft lift and the ratio of lift to weight, which may affect the required runway length to maintain normal operations (Boston-Logan International Airport 2016; Heathrow Airport 2011; ICAO 2016a; NATS 2011; Pendakur 2017).	To what extent the airport is protecting its infrastructure from the future effects of temperature change?
			Due to desertification, there is an increased risk of soil erosion around the apron and runways (ICAO, 2018a). Therefore, the airport authority should take measures to control erosion (for example, planting vegetation that requires little water and does not attract wildlife). Besides, airports planners and designers may need to design windbreaks to reduce dust and sand (ICAO 2018b).	To what extent the airport is protecting its infrastructure from future effects of desertification?

*dependent on a specific climate vector.

APPENDIX G | A mock-up of the AirCRAS

Appendix G visualises the AirCRAS using pictures, and thereby shows the information as presented to its users. The AirCRAS as visualised in the appendix is filled in (and so, presents the answers) for the particular case of Singapore Changi Airport. Due to visualisation purposes, this appendix only presents the first two questions. Other assessment questions are given in Appendix F.

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1 2 3 4
Setting the scene

Setting the scene

Establishing the climate vectors experienced by the airport in question

The exposure of an airport to a particular climate vector is dependent on the geographic location of the airport. The relevance of the climate vectors for the airport in question, should be assessed based on the judgement of the expert panel group. The expert panel group must decide which (out of the following seven climate vectors) will be considered in the assessment questions.

✓ **Sea level rise**
Sea level rise is caused by both increases in ocean warming and loss of mass from glaciers and ice sheets. Sea level rise can increase flooding (both in frequency and in area flooded), contribute to greater coastal land erosion, and, in some areas, cause permanent seawater inundation (IPCC, 2013).

✓ **Increased intensity of storms**
Overall, storms are projected to become stronger as the climate changes. In some areas, storms also become more frequent. The types of storms discussed in the documents reviewed include both winter storms and tropical cyclones (also classed as hurricanes or typhoons depending on the region in which they occur), extra-tropical cyclones, arctic cyclones, convective systems, and lightning (ICAO, 2018a).

✓ **Temperature change**
The global average annual temperature is rising (IPCC, 2014). More frequent occurrence and longer-lasting high-heat days are also projected for some regions, particularly in the summer months (EUROCONTROL, 2013; International Transport Forum, 2015). Besides, higher temperatures cause significant decreases in air density (ACRP, 2012).

✓ **Changing precipitation**
Precipitation is any form of water - liquid or solid - falling from the sky. It includes rain, sleet, snow, hail and drizzle plus a fewer common occurrences such as ice pellets, diamond dust and freezing rain (ICAO, 2018a). This AirCRAS will consider changes in types and intensities of precipitation leading to e.g. floods and changing runway conditions.

○ **Changing icing conditions**
This climate vector covers ground icing, which is icing accumulated while an aircraft is on the ground (Heathrow Airport, 2011; ICAO, 2016). This climate vector does not cover ice that may form as a result of precipitation (e.g., hail), which is addressed in the changing precipitation vector. However, although freezing rain is a form of precipitation, there is some reference to it as it can contribute to the need for de-icing and it was often addressed alongside de-icing in the literature reviewed.

✓ **Changing wind**
Changing wind includes changes or deviation in the prevailing wind direction and speed (ICAO, 2018a). Effects include low-level wind shear, which is defined as ' a change in wind speed and/or direction in space, including updrafts and downdrafts' (NACO, 2017).

○ **Desertification**
Desertification is the process in which more land becomes desert. Climate change is contributing to desertification by leading to many dry regions becoming drying and hotter and having more dust or sand in the air. Unprecedented heatwaves are already being recorded in many regions especially in the tropics. Desertification is also responsible for increased water scarcity and increased frequency of weather events such as high-intensity tropical cyclones and sandstorms in many regions (ICAO, 2018b).

Next

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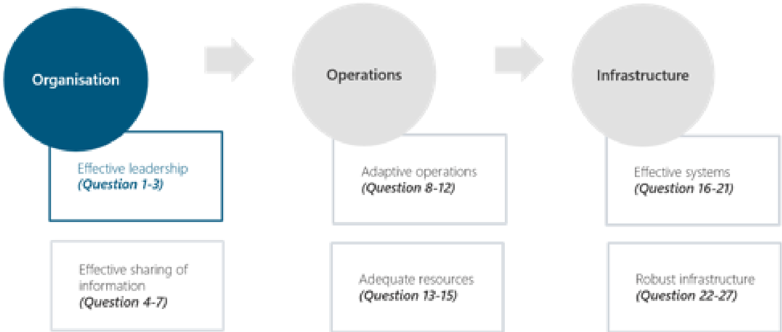
Organisation

Indicator: Effective leadership



1 Variable: Adequate financial resources.

The proper level of investment in resilience varies from company to company and industry to industry. Proper investment levels are relative to the risks, which depends on many aspects e.g. geography and the airport's general reputation (Sheffi and Rice 2005). The organisation should allocate adequate financial resources to address vulnerabilities and to be able to adapt to changing circumstances. Hereby it's important to routinely review the suitability of financial resources, taking account of the impact of any changes in the organisation and its context (ISO 2017).

To what extent are adequate financial resources made available for improving the climate resilience of the airport.

	A	B	C	D	E	
Very much	O	O	O	O	O	Not at all

Explain why:

[Continued on the next page]

2 Variable: Adequate strategies.

A climate-resilient should have response strategies in place to cope with relatively high-likelihood, identifiable risks. For example, airports experiencing changing icing conditions should include snow and ice removal targets e.g. keeping a specific number of runways open (ACRP 2012; GTAA 2014). Yet, airports also have to prepare for unforeseen or unknown types of disruptions by formulating values, a clear purpose, and a vision regarding climate resilience, that provides strategic direction and clarity to decision making. For example, climate resilience language should be included in the business continuity plans, business continuity policy, business continuity objectives, design guidelines and maintenance plans (San Diego International Airport 2019; ISO 2017).

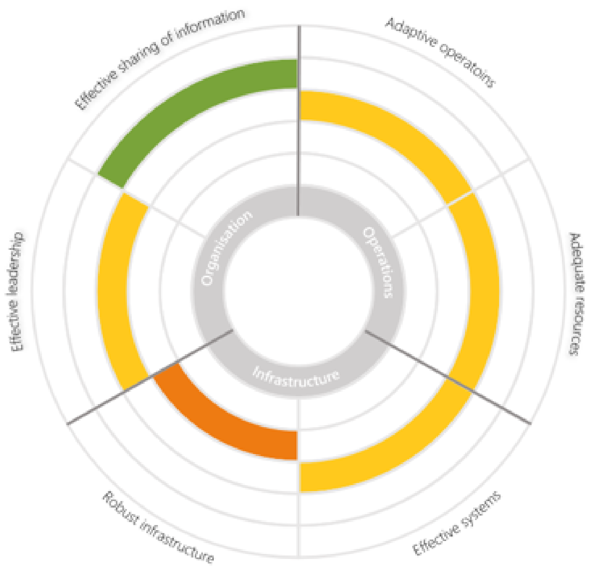
To what extent are climate resilience strategies in place and are clear responsibilities defined regarding who is in charge of executing particular tasks and adhering to the strategies?

	A	B	C	D	E	
Very much	O	O	O	O	O	Not at all

Explain why:

Next

Overview of the results



Organisation

Indicator 1: Effective leadership — Label C^+

- *Adequate financial resources*
  [Answer to open question]
- *Adequate resilience strategies*
  [Answer to open question]

Indicator 2: Effective sharing of information — Label B^+

- *Effective empowerment of employees*
  [Answer to open question]
- *Effective collaboration with internal parties*
  [Answer to open question]
- *Effective collaboration with external parties*
  [Answer to open question]
- *Effective evaluation*
  [Answer to open question]

1) Discuss the key issues that the airport currently experiences
2) Discuss the airports' level of ambition

[Continued on the next page]

Operations

Indicator 3: Adaptive procedures Label C

- *Adaptive runway procedures*
  [Answer to open question]
- *Adaptive apron procedures*
  [Answer to open question]

Indicator 4: Adequate resources Label C^+

- *Adequate equipment*
  [Answer to open question]
- *Competent employees*
  [Answer to open question]
- *Sufficient employee availability*
  [Answer to open question]

3) Discuss the key issues that the airport currently experiences

4) Discuss the airports' level of ambition

Infrastructure

Indicator 5: Effective systems Label C^-

- *Effective drainage and runoff systems*
  [Answer to open question]
- *Effective ventilation and cooling systems*
  [Answer to open question]
- *Effective warning systems*
  [Answer to open question]
- *Effective utility networks*
  [Answer to open question]

Indicator 6: Robust infrastructure Label D^+

- *Robust ground transportation networks*
  [Answer to open question]
- *Robust (under)ground infrastructure*
  [Answer to open question]

5) Discuss the key issues that the airport currently experiences;

6) Discuss the airports' level of ambition

----

7) Discuss the level of risk the airport is wiling to accept

8) Discuss the priorities, constraints, and the level of detail for the follow up in-depth resilience study.

Save results