DERICK MOREIRA BAUM

AIRSPACE CAPACITY ARTIFICIAL INTELLIGENCE MODEL IN UAM ENVIRONMENT BASED ON THE AIRSPACE COMPLEXITY

São Paulo
2021

DERICK MOREIRA BAUM

AIRSPACE CAPACITY ARTIFICIAL INTELLIGENCE MODEL IN UAM ENVIRONMENT BASED ON THE AIRSPACE COMPLEXITY

Thesis presented to School of Engineering of the University of São Paulo to obtain the Doctor of Science degree.

São Paulo
2021

DERICK MOREIRA BAUM

AIRSPACE CAPACITY ARTIFICIAL INTELLIGENCE MODEL IN UAM ENVIRONMENT BASED ON THE AIRSPACE COMPLEXITY

CORRECTED VERSION

Theses presented to School of Engineering of the University of São Paulo to obtain the Doctor of Science degree.

Concentration Area:
Computer Engineering

Adviser:
Prof. Dr. João Batista Camargo Jr.

São Paulo
2021

DERICK MOREIRA BAUM

Este exemplar foi revisado e alterado em relação à versão original, sob responsabilidade única do autor e com a anuência de seu orientador.

São Paulo, 08 de dezembro de 21

Assinatura do autor________________________________

Assinatura do orientador____________________________

FICHA CATALOGRÁFICA

Baum, Derick Moreira
AIRSPACE CAPACITY ARTIFICIAL INTELLIGENCE MODEL IN UAM ENVIRONMENT BASED ON THE AIRSPACE COMPLEXITY / D. M. Baum -- versão corr. -- São Paulo, 2021.
199 p.

Tese (Doutorado) - Escola Politécnica da Universidade de São Paulo. Departamento de Engenharia de Computação e Sistemas Digitais.

1.Mobilidade Aérea Urbana (UAM) 2.eVTOL 3.Capacidade do Espaço Aéreo 4.Complexidade do Espaço Aéreo 5.Interligência Artificial I.Universidade de São Paulo. Escola Politécnica. Departamento de Engenharia de Computação e Sistemas Digitais II.t. Departamento de Engenharia de Computação e Sistemas Digitais II. t.

São Paulo
2021

ACKNOWLEDGMENTS

Esta jornada de trabalho está próxima de seu encerramento e tenho muito a agradecer e certamente algumas palavras representadas em uma folha não refletirão a minha gratidão.

Primeiramente, nada acontece neste mundo, independente da complexidade do evento, sem o consentimento de Deus: muito obrigado por ter me concedido o discernimento necessário para chegar até este momento.

Agradeço aos meus avós, Dona Leonor e Pedrão, por me ensinarem, com exemplos, como é aliar simplicidade a conhecimento e desejo a persistência. O maior desafio de minha vida tem sido fazer jus a tudo que me proporcionaram.

Agradeço à minha mãe por ter me mostrado, com exemplos, que com trabalho tudo é possível e que o nosso nome é o nosso maior legado.

Quando há alguns anos, compartilhei com a minha esposa Cátia e o meu filho Derick o desejo de realizar este projeto, mais do que uma opinião eu pedi silenciosamente que não me deixassem sucumbir. Também de forma silenciosa, os dois me apresentam diariamente, com exemplos, a arte da perseverança e demonstram a todo momento que não se começa um projeto sem ter a certeza de que será possível terminá-lo. Saibam que quando olho em seus olhos, tudo se torna possível. É um privilégio tê-los a meu lado. Na verdade, ainda há muito a ser dito e o que me resta é me conformar, pois mesmo que escreva um livro aqui, não apresentarei tudo o que sinto.

Agradeço ao professor João Batista por ter me aceitado de braços abertos como meu orientador e por ter se tornado um amigo querido. É um exemplo de resiliência e objetividade. Nunca ouvi uma palavra sequer de sua boca que não fosse de motivação e de direcionamento. Muito obrigado pelo convívio, pelo aprendizado e pela paciência.

Agradeço aos professores Paulo Cugnasca e Jorge Rady por estarem sempre dispostos a ouvir nossas opiniões e novos projetos, compartilhando sem qualquer reserva o conhecimento e os direcionamentos necessários. Saibam que, assim como o professor João, sempre me fizeram sentir como parte de uma família.

Agradeço ao Euclides Neto por compartilhar tantas ideias, experiências e projetos e por me dar a oportunidade de compartilhar também as minhas ideias,

São Paulo
2021

ACKNOWLEDGMENTS

experiência e projetos. Assim, nasceu uma relação de trabalho muito produtiva e uma amizade verdadeira.

Agradeço ao Felipe Ferrare pela contribuição a esta pesquisa, desenvolvendo uma inovadora ferramenta, essencial para a geração de resultados.

Agradeço aos amigos do Safety Analysis Group (GAS) pelos ensinamentos e orientações, por compartilharem tantas experiências e pelo excelente convívio que tivemos. Saudades das longas conversas do grupo, alternando entre a busca da solução de um problema, das discussões do dia a dia e das conversas sem qualquer pretensão.

Agradeço à Escola Politécnica, à USP e ao GAS pelo acesso irrestrito a todo equipamento, modelagem ou instalação que precisei.

Agradeço à Força Aérea Brasileira, em especial ao DECEA, pois sem o aprendizado obtido com todos os cursos realizados, as práticas exercidas no Controle de Tráfego Aéreo em diferentes localidades do Brasil e o convívio com os excelentes profissionais, seria impossível chegar a esse dia.

São Paulo
2021

RESUMO

Quando consideramos o tráfego aéreo convencional, onde os pousos ocorrem normalmente em aeroportos ou helipontos, encontramos todos os critérios necessários para a realização dos voos (regras de tráfego aéreo), para os procedimentos de pouso e decolagem, estrutura do espaço aéreo e para os aeroportos. Estes critérios são desenvolvidos por órgãos como a ICAO e a FAA. Considerando qualquer porção de espaço aéreo, visando manter os níveis de segurança aceitáveis (safety), caberá à autoridade aeronáutica a definição da capacidade deste espaço aéreo, normalmente apresentada em quantidade máxima de tráfegos que poderão voam simultaneamente. Para isso, utilizam modelagem matemática adequada, normalmente baseada na carga de trabalho do controlador de Tráfego Aéreo (ATCo). No entanto, consenso entre os pesquisadores, é que a complexidade do espaço aéreo deverá ser considerada, pois impacta diretamente a carga de trabalho do ATCo e consequentemente a capacidade do espaço aéreo. Tem sido um constante desafio estabelecer a relação entre a complexidade do espaço aéreo e a capacidade do espaço aéreo. No entanto, nos deparamos com um desafio maior ainda que é pensarmos em estratégias para viabilizamos a realização e o crescimento de uma nova demanda: UAM (Urban Air Mobility) . Em muitas partes do mundo, a cada ano, o tráfego terrestre aumenta, resultando em tempos de deslocamento mais longos, com custos econômicos significativos. Além de diversas estratégias para resolver o problema de congestionamento de tráfego (criação de viadutos, novas vias ou restrições de tráfego em determinados horários e locais), um conceito que começou com o uso de helicópteros e com amplo desenvolvimento tecnológico, é a Mobilidade Aérea Urbana (UAM) , definido como operações de tráfego aéreo seguras e eficientes em uma área metropolitana para aeronaves tripuladas e não tripuladas. Nesta pesquisa, o eVTOL (electric vertical takeoff and landing) será a aeronave considerada no ambiente UAM que poderá realizar pousos e decolagens nos mais diferentes lugares, que serão chamados de TOLA (takeoff and landing área). Uma das principais preocupações de pesquisadores sobre o assunto é considerar que atual estrutura de controle do espaço aéreo, de estrutura espaço aéreo, assim como as regras de tráfego aéreo utilizadas atualmente poderão ser fatores que impeçam o crescimento do UAM. Este trabalho tem o objetivo de apresentar um Modelo de Inteligência Artificial de Capacidade do Espaço Aéreo no Ambiente UAM com Base na Complexidade do Espaço Aéreo. No entanto, nesta ambiente não foi considerada a presença do ATCo, sendo proposta a utilização de ferramenta computacional para as instruções de controle de tráfego aéreo. Para que o objetivo fosse alcançado, foram apresentados critérios para a criação de espaço aéreo controlado em ambiente UAM e regras de tráfego aéreo específicas para o ambiente UAM. Foram apresentados também novos conceitos, como por exemplo, Capacidade Dinâmica do Espaço Aéreo e um índice de limite de complexidade aceitável (complexity Treshold).

Palavras chave: Mobilidade Aérea Urbana (UAM), eVTOL, Capacidade do Espaço Aéreo, Complexidade do Espaço Aéreo, Inteligência Artificial.

ABSTRACT

When we consider conventional air traffic, where landings normally occur at airports or helipads, we find all the necessary criteria for carrying out flights (air traffic rules), for landing and take-off procedures, and airspace structure. These criteria are developed by International Entities such as ICAO and FAA. Aeronautical authorities must define the airspace capacity for any portion of the airspace to maintain acceptable safety levels. This normally involves determining the maximum amount of traffic that can fly simultaneously. For this, they use adequate mathematical modeling, usually based on the workload of the Air Traffic Controller (ATCo). However, researchers agree that airspace complexity must also be considered, as it directly impacts the ATCo workload and, consequently, the airspace capacity. Establishing the relationship between airspace complexity and airspace capacity is a challenging task. On top of that, we face the even greater challenge of envisioning strategies that enable the consolidation and growth of a new demand: UAM (Urban Air Mobility). Every year increases in ground traffic worldwide have resulted in longer commute times with high economic costs. In addition to several strategies to solve the problem of traffic congestion (creation of viaducts, new lanes, or traffic restrictions at certain times and locations), the concept of Urban Air Mobility (UAM) has emerged to encompass safe and efficient air traffic operations in a metropolitan area for manned and unmanned aircraft. This research examines eVTOL (electric vertical takeoff and landing) aircraft in the UAM environment. These aircraft can perform landings and takeoffs in a wide range of places, which will be called TOLA (takeoff and landing area). However, researchers worry that the current airspace structure and air traffic rules may not meet the demands of the UAM.This work aims to present an Artificial Intelligence Model of Airspace Capacity in the UAM Environment Based on Airspace Complexity. The presence of ATCo was not considered in this environment, with a computational tool being used for air traffic control instructions instead. Criteria for creating the controlled airspace in a UAM environment were presented, as well as specific air traffic rules. This work also introduces new concepts, such as Dynamic Airspace Capacity and an Acceptable Complexity Threshold Index.

Keywords: Urbain Air Mobility (UAM), eVTOL, Aispace Capacity, Airspace Complexity, Artificial Intelligence.

LIST OF FIGURES

LIST OF FIGURES

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES

LIST OF TABLES

LIST OF EQUATIONS

LIST OF ABBREVIATIONS AND ACRONYMS

ACC	Area Control Center
ACFT	Aircraft
ACI	Adjusted Capacity index
AGL	Above Ground Level
ARC	Area Chart
AMAN	Arrival Manager
AMOC	ATFM modelling capacity
ANSP	Air Navigation Service Provider
APP	Approach Control
ARTCC	Air Route Traffic Control Center
AS	Alert Service
ATC	Air Traffic Control
ATCo	Air Traffic Controller
ATM	Air Traffic Management
ATS	Air Traffic Service
ATZ	Aerodrome Traffic Zone
AWY	Airway
BVLOS	Beyond Visual Line-of-Sight
BN	Bayesian Network
C2	Command and Control
CB	Cumulonimbus
CBR	Community Based Rules
CM	Complexity Metric
CG	Complexity Generator
CI	Complexity Index
CNS/ATM	Communication, Navigation and Surveillance/Air Traffic Management
ConOps	Concept of Operations
CPT	Conditional Probability Table
CRCT	Collaborative Routing Coordination Tool
CTAS	Center TRACON Automation System
CTR	Control Zone
DCB	Demand Capacity Balancing

LIST OF ABBREVIATIONS AND ACRONYMS

DD	Dynamic Density
DECEA	Brazilian Airspace Control Department
DRAT	Data Reduction and Analysis Toolkit
ENRC	Enroute Chart
ETMS	Enhanced Traffic Management System
eVTOL	Electric Powered Vertical Take-off and Landing
FAA	Federal Aviation Administration
FANS	Future Air Navigation System
FIR	Flight Information Region
FIS	Flight Information Service
FT	Feet
GCS	Ground Control Station (or System)
GNSS	Global Navigation Satellite System
hPa	hectopascal
IAC	Instrument Approach Chart
ICAO	International Civil Aviation Organization
ICI	initial Capacity Index
IFR	Instrument Flight Rules
KT	Knots
LAANC	Low Altitude Authorization and Notification Capacity
LFR	Low- Level Flight Rules
METAR	Meteorological Aerodrome Report
OCCA	Outside Conventional Controlled Airspace
OCCAP	Outside Conventional Controlled Airspace Provider
OCH	Obstacle Clearance Height
ODM	On Demand Mobility
MSL	Mean Sea Level
MVFR	Marginal Visual Flight Rules
NAS	National Airspace System
NM	Nautical Mile
PBN	Performance Based Navigation
PIC	Pilot in Command

LIST OF ABBREVIATIONS AND ACRONYMS

PSU	Providers of Services for UAM
RNP	Required Navigation Performance
RPAS	Remote Pilot Aircraft System
RWY	Runway
SAR	System Analysis Recording
SID	Standard Instrument Departure
SITRAER	Air Transportation Symposium
STAR	Standard Terminal Arrival Route
SWIM	System-Wide Information Management
TAAM	Total Airspace and Airport Modeler
TBO	Trajectory Based Operations
TLS	Tactical Load Smoother
TMA	Terminal Area Control
TML	Technology Maturity Level
TOLA	Takeoff and Landing Area
TUS	Trajectory-Base UAM Operations Simulator
TUSO	Trajectory-Base UAM Operations Simulator + Optimizer
TWR	Aerodrome Control Tower
TWY	Taxiway
UAM	Urban Air Mobility
UAS	Unmanned Aircraft System
UASP	Urban Airspace Service Provider
UATM	Urban Air Traffic Management
UAV	Unmanned Aerial Vehicle
UTM	Unmanned Aircraft System Traffic Management
VAC	Visual Approach Chart
VFR	Visual Flight Rules
VLL	Very Low Level
VLOS	Visual Line-of-Sight
VTOL	Vertical Take-off and Landing
eVTOL	electric Vertical Take-off and Landing
WAC	World Aeronautical Chart

CONTENTS

CONTENTS

1. INTRODUCTION

Air transportation is not only a large-scaled service production industry supporting the worldwide economic and social growth but also a key driver for the development of local industries such as tourism, international commerce, and construction.

The ATC (Air Traffic Control) must first authorize aircraft to enter controlled airspaces. Additionally, to perform landings and take-offs at airports, aircraft must carry out the approach and departure procedures developed by the aeronautical authorities and defined by the ATCs. In all countries — whether or not signatories of the ICAO (International Civil Aviation Organization) — the capacity of airports and the airspace is one of the primary concerns of aeronautical authorities and must be consistent with existing aircraft and passenger.

Therefore, the aeronautical authority shall define the maximum permitted aircraft capacity in all portions of the airspace under its responsibility. To achieve this, it will consider several variables of interest and use appropriate mathematical modeling.It is important to emphasize that the success of the any initiatives to improve current and future airspace capacity relies upon a reliable definition and measure of airspace capacity (MAJUMDAR; OCHIENG, 2002).

When we talk about airspace, according to Majumdar and Polak (2001a) capacity of an ATC sector can be defined as the maximum number of aircraft that are controlled in a particular ATC sector in a specified period while still permitting an acceptable level of controller workload. Majumdar and Ochieng (2002) define that a safer measure of capacity is based on air traffic controller workload than on internationally specified spatial separation.

(MOGFORD, R.; GUTTMAN, J.; MORROW, S.; KOPARDEKAR, 1995) indicates that the workload experienced by air traffic controllers is affected by the complex interaction of situation in the airspace, the state of the equipment, and the state of the controller. Considering air traffic situation in the airspace, (MOGFORD, R.; GUTTMAN, J.; MORROW, S.; KOPARDEKAR, 1995) and (RODGERS; MOGFORD, 1998) define a relationship between air traffic control workload and sector characteristics, i.e. ATC complexity factors. It is unanimous among researchers that this workload is directly affected by complexity (CHRISTIEN et al., 2002a)

Complexity is a measure of the difficulty that a particular air traffic situation poses to the air traffic controller (MECKIFF; CHONE; NICOLAON, 1998).

Sector complexity (also known as “air traffic complexity,” “cognitive complexity,” and sometimes “dynamic density”) is a term used to describe a set of factors presumed to affect the difficulty experienced by a controller when controlling traffic (MANNING; PFLEIDERER, 2006). Complexity factors often include such variables as the presence of climbing or descending aircraft, aircraft mix (different types of aircraft having different performance characteristics), special use airspace activity, and presence of severe weather (MANNING; PFLEIDERER, 2006).

For conventional air transport (that which uses airports for landings and take-offs, performs the specific procedures for these airports, and uses the available airspace structure) there are several models of airspace capacity and complexity (TOBARUELA et al., 2014) (WANG; GONG; WEN, 2015) (KOPARDEKAR; MAGYARITS, 2003) (SUÁREZ, N;LÓPEZ,, P; PUNTERO, E;RODRIGUEZ, 2014) (LAUDEMAN et al., 1998) (OCHIENG, W.; MAJUMDAR, 2002) (DECEA, 2014) which consider the following assumptions:

a) Human factors (ATCo) (HOPKIN, 1982) (TOBARUELA et al., 2014) (SUÁREZ, N;LÓPEZ,, P; PUNTERO, E;RODRIGUEZ, 2014).
b) Conventional Air Traffic Rules such as separation between aircraft (DECEA, 2016a) (DECEA, 2016b) (ICAO, 2001a) (ICAO, 2005) (ICAO, 2001b); and
c) Airspace Standard Structure (EUROCONTROL, 2015) (EUROCONTROL, 2005).

The same existing ATM concepts apply to the management of this structure (aircraft handling, creation of airspaces, procedures for landings and take-offs at aerodromes, etc.) (EUROCONTROL, 2015) (ICAO, 2016a) (DECEA, 2021).

Even though researchers have studied the complexity and capacity of airspace since the early 1960s, several challenges remain in developing and improving models and analyzing different scenarios under the set of conventional assumptions described above. Facing these challenges is necessary for increasing airspace capacity to meet projected increases in demand.

However, due to various economic, social and technological factors, aircraft appear with different performances and sizes, manned or unmanned, with the need to fly in segregated or non-segregated airspaces and to perform landings and take-offs in the most diverse locations.

With the steady growth of the UAS (Unmanned Aircraft System) fleet, especially the small UAS (sUAS) flying at low altitudes, there was a need for management for this type of operation, like ATM. The concept of Unmanned Aircraft System Traffic Management (UTM) was then developed and with it, the challenge of making it coexist with ATM (RAJU; RIOS; JORDAN, 2018) (JIANG et al., 2016) (MURAKAMI et al., 2019) (COURT, 2015) (KOPARDEKAR et al., 2016) (EUROCONTROL, 2018) (JANG et al., 2017) (KOPARDEKAR, 2014). In (BULUSU; POLISHCHUK, 2017) modeling of airspace capacity considering the UTM is proposed.

It is noteworthy that, so that sUAS flights do not interfere with general aviation, countries have adopted structures and mandatory authorizations from aeronautical authorities to prohibit flights in areas close to airports.

UAS that will fly at high altitudes in non-segregated airspaces should not be disregarded. These aircraft will use the same airspace and airport structure as other conventional aircraft. Although managed by the same ATM principles, several researches are being developed in order to enable the safe inclusion of these aircraft in non-segregated airspace (NETO et al., 2017a) (BAUM et al., 2019) (HOBBS; LYALL, 2016) (NEUBAUER et al., 2015) (ICAO, 2011) (FERREIRA et al., 2018)

Now consider a specific type of UAS, VTOL (Vertical Take-off and Landing)[1], driven by the needs of the community, several companies are dedicated to improving VTOL aircraft and developing the concept of electric Vertical Take-off and Landing (eVTOL). These new technologies have led to the concept of UAM (BOOZ; ALLEN; HAMILTON, 2018) (POSTORINO; SARNÉ, 2020) (NASA, 2018) which in turn requires a notion of management analogous to ATM and UTM — in this case, we call it UATM (Urban Air Traffic Management)(EMBRAER; ATECH; HARRIS, 2019).

The density of projected operations requires the integration of vehicles — manned or unmanned — into an air traffic control system that provides flexibility and equitable access to shared airspace resources. Enabling safe and efficient UAM operations in the NAS (National Airspace System) necessitates a large paradigm shift of the current air traffic control system towards higher levels of autonomy (BOSSON; LAUDERDALE, 2018).

[1] In this work, VTOL will be considered as a UAS.

Several works have proposed airspace structures and ways to manage UAM flights, such as (EMBRAER; ATECH; HARRIS, 2019) (VASCIK; HANSMAN, 2018)(BIJJAHALLI; SABATINI; GARDI, 2019) (VASCIK et al., 2018)(NETO et al., 2021) and in (BOSSON; LAUDERDALE, 2018) (WU; ZHANG, 2021) (PATTERSON; ANTCLIFF; KOHLMAN, 2018) (NETO et al., 2019b)(FERRARE et al., 2021) are proposed separations between aircraft using simulation or analysis of real flights.

Although (BOSSON; LAUDERDALE, 2018) discusses aircraft separation strategies and (EMBRAER; ATECH; HARRIS, 2019) examines aircraft management, the literature still lacks proposals for new air traffic rules consolidating new separations and new airspace structures as well as novel airspace capacity models for the UAM environment and updated air traffic control concepts

1.1. Motivation

According to (BOOZ; ALLEN; HAMILTON, 2018), the goals of UAM are to decongest road traffic, improve mobility, reduce transport time, decrease pollution, reduce strain on existing public transport networks and reduce traffic accidents.

There will be 70+ manufacturers worldwide including Boeing, Airbus and Bell Helicopters, over $1 billion investment made as of September 2018, and high profile events (BOOZ; ALLEN; HAMILTON, 2018). Projections for the use of the UAM are presented in (HOLDEN; GOEL, 2016)(UBER, 2018)(UBER, 2016).

The technological development of eVTOL has enabled its large-scale manufacture, with performances that will meet the initial needs of the market (ELEVATE, 2018). However, the growth potential of the UAM may be compromised without a solid structure for its development.

While VTOL aircraft presented opportunities for creating a new form of transportation, reducing congestion and overcoming the geographic constraints of ground mobility modes, a number of operation challenges hindered their success, including (VASCIK; HANSMAN, 2017):

a) Availability of geographically distributed ground infrastructure co-located with areas of customer demand.
b) Integration of urban air transportation operations with Air Traffic Control (ATC) and the potential need for a new, automated ATC system to manage airspace below 3000 ft.

c) Murky legal and regulatory jurisdictions for low altitude airspace.
d) Acquiring widespread community acceptance of vehicle noise; and
e) Lack of a computerized customer booking and demand scheduling system.

The ability of UAM aircraft to reliably access and conduct high density operations within controlled airspace constitutes an Air Traffic Control (ATC) constraint. Current ATC procedures are anticipated to be insufficient to handle a large number of new UAM aircraft as a result of air traffic controller workload limitations and the required aircraft separation (VASCIK; HANSMAN, 2018).

Given the continuous growth of the UAM, we need studies that examine the airspace structure, air traffic control, air traffic rules and airspace capacity models associated with the UAM environment.

1.2. Objectives

Considering the UAM projections, concerns arise, one of which is related to the airspace structure considering the UAM environment.

If we think of using in UAM the same concepts used in general aviation (Air Traffic Rules, Airspace Structure and Air Traffic Control), the projected growth in demand will certainly be unfeasible. Thus, it is necessary to propose a reduction in horizontal and vertical separation, as well as new approach and take-off procedures in the respective Take-off and Landing Areas (TOLA). TOLAs refers to the airports, heliports, vertiports, "skyports", or some other form of ground infrastructure.

This work aims to present an Airspace Capacity Artificial Intelligence Model in a UAM Environment Based on the Airspace Complexity. In order to achieve this goal, it was necessary to propose a New Air Traffic System Framework.

1.3. Contribution

The Main contribution of this research are:

a) Strategy for the development of controlled airspace, considering the UAM environment.

b) Framework for flight authorization, proposing the use of a computational tool for the development of air traffic control.
c) Air Traffic Rules specifics to the UAM Environment.
d) Concept of Dynamic Airspace Capacity.
e) Airspace Capacity Model based on Airspace Complexity.
f) Analytical Model of Airspace Complexity; and
g) Complexity Threshold definition.

1.4. Work Structure

The proposed structure of the work will be:
Chapter I - motivation and objectives; Chapter II - complexity concepts and complexity models applied in different areas; Chapter III – complexity and airspace capacity models; Chapter IV - discussion of complexity models applied to air traffic. In this chapter, will be presented the reference model for the development of this work; Chapter V - the concepts of UAM and UAS, considering that this work will propose a complexity model for application in UAM environment with unmanned vehicles; Chapter VI - capacity model prerequisite framework. Before developing and applying the model, some questions must be answered; Chapter VII - the capability model based on the complexity of the airspace. In this chapter all the necessary concepts are presented; Chapter VIII - discussion of the results found and defined complexity threshold; Chapter IX - Analytical Complexity Model; Chapter X – final consideration and future works.

In order to present relevant concepts about air traffic, it is presented in Appendix A - air traffic concepts, air traffic rules and airspace structure and key concepts.

2. COMPLEXITY BACKGROUND

2.1. Definition of Complexity

The technological maturity level (TML), a concept presented in (BAUM et al., 2019) related to perception, and proposed for use in air traffic control, is defined as a systematic metrics / measurements approach that supports assessments of ATCo's familiarity with an aircraft in particular. The levels represent the familiarity, which may increase throughout the years of aircraft operation (i.e., considering the increase of liability, social acceptance, and operational exposure).

Simon (1976) argues that complexity can be associated with the structure of a system and linked to the perception of those who manipulate it – an idea that relates to the presented concept of TML.

Scholars have proposed many different ways of assessing complexity. In fact, a variety of different measures would be required to capture all our ideas about what is meant by complexity and by its opposite, simplicity (WILEY; GELL-MANN, 1995).

Different forms and definitions of complexity are presented in (LEMES, 2012). In (MITCHELL, 2009) is presented defining and measuring complexity as:

1) Size;
2) Entropy: Shannon
3) Algorithmic Information Content: Kolmogorov
4) Logical Depth
5) Thermodynamic Depth
6) Computational Capacity
7) Statistical Complexity
8) Fractal Dimension
9) Degree of Hierarchy: complex systems are composed of subsystems

First, we need to highlight the difference between complexity and complicated. “Complexity” is essentially different from “complicated.” To show this, it is necessary to present the concept of chaos. According to Stacey (1993), apud (LEMES, 2012), when there is no agreement on the subject and the level of uncertainty about it is high, it is said that one works in a region of anarchy or chaos. Situations where you are far from an agreement and close to certainty, or far from certainty and close to an agreement, are considered regions where you work on complicated issues. Complexity arises between the complicated and the chaotic (figure 1).

In complicated systems the interactions between the many parts are governed by fixed relationships. This allows reasonably reliable prediction of technical, time, and cost issues. In complex systems, such as the air transport system, interactions between the parts exhibit self-organization, and local interactions give rise to novel, nonlocal, emergent patterns. Complicated systems can often become complex when the behaviors change, but even systems of very few parts can sometimes exhibit surprising complexity (INCOSE, 2015).

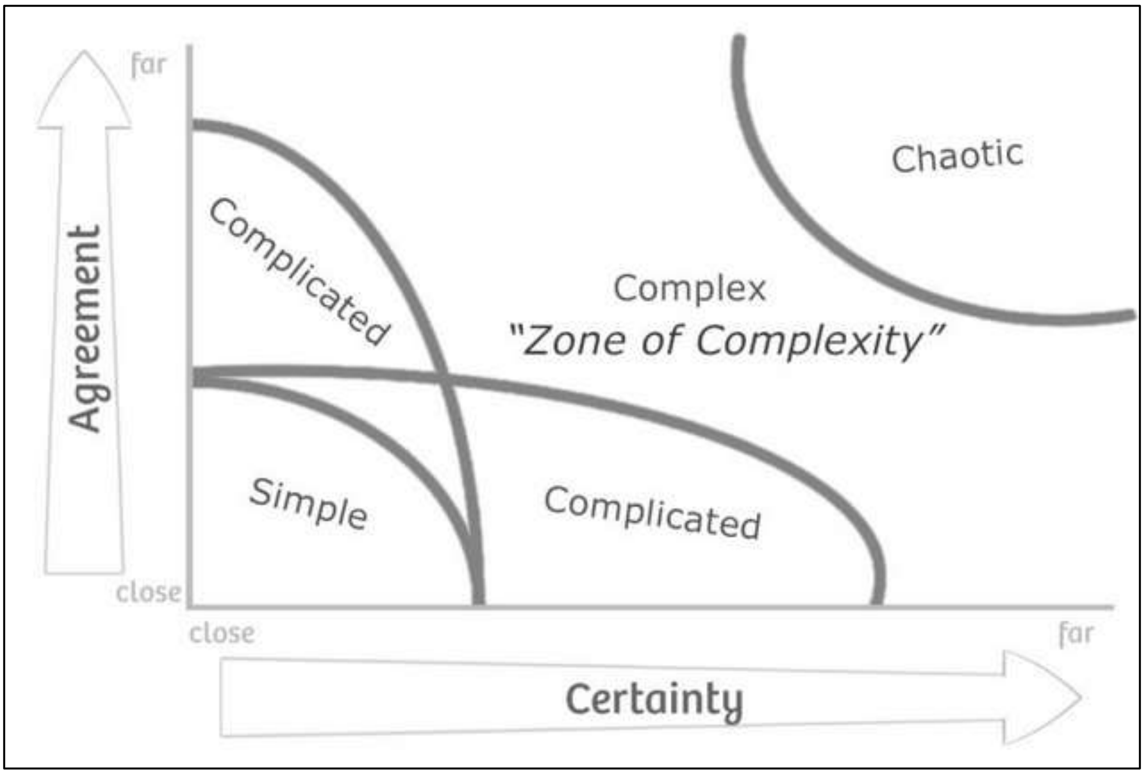

Figure 1 – Stacey matrix.

Source: (STACEY,1993, apud LEMES, 2012).

There are a lot of definitions of a complex system (LADYMAN; LAMBERT; WIESNER, 2012). The definition of greatest interest for this work is that a complex system is one whose evolution is very sensitive to initial conditions or to small perturbations, one in which the number of independent interacting components is large, or one in which there are multiple pathways by which the system can evolve.

The proposed complexity model requires us to understand the interdependence between all system variables to measure complexity.

Contemporary researchers in architecture, biology, computer science, dynamical systems, engineering, finance, game theory, etc., have defined different measures of complexity depending on their fields. . In the present work, complexity will be an indicator based on the probabilities of the scenarios under study and can take the following values: very high complexity, high complexity, acceptable complexity, low complexity, and insignificant complexity.

(LLOYD, 2001) presents three questions that researchers frequently ask to quantify the complexity of something (house, bacterium, problem, process, investment scheme) under study :

1. How hard is it to describe?

Difficulty of description. Typically measured in bits.

2. **How hard is it to create**?

Difficulty of creation. Typically measured in time, energy, money, etc.

3. **What is its degree of organization?**

Degree of organization. This may be divided up into two quantities:

- a) Difficulty of describing organizational structure, whether corporate, chemical, cellular, etc.
- b) Amount of information shared between the parts of a system as the result of this organizational structure.

Just as there are different definitions of complexity, it is natural to expect that there are also different ways of measuring it. (Lloyd, 2001) apud (LEMES, 2012), for example, features 40 different types of measures of complexity and points out that the list is incomplete. How we measure complexity depends on our choice of complexity model. Next, different complexity models applied to different areas of knowledge will be presented Models of Complexity applied to Different Areas

2.1.1. Cyber Physical Systems

According to (SINHA, 2014) there are three main dimensions of complexity that emerge in the context of system design and development: Structural Complexity, Dynamic Complexity and Organizational Complexity. Structural complexity pertains to the underlying system architecture or, more generally, the enabling infrastructure. Dynamic complexity refers to the complexity of the system behavior or process running on the underlying infrastructure. Organizational Complexity relates to the system development process and the organizational structure of the development team. The Complexity Typology for Engineered Systems is presented in figure 2.

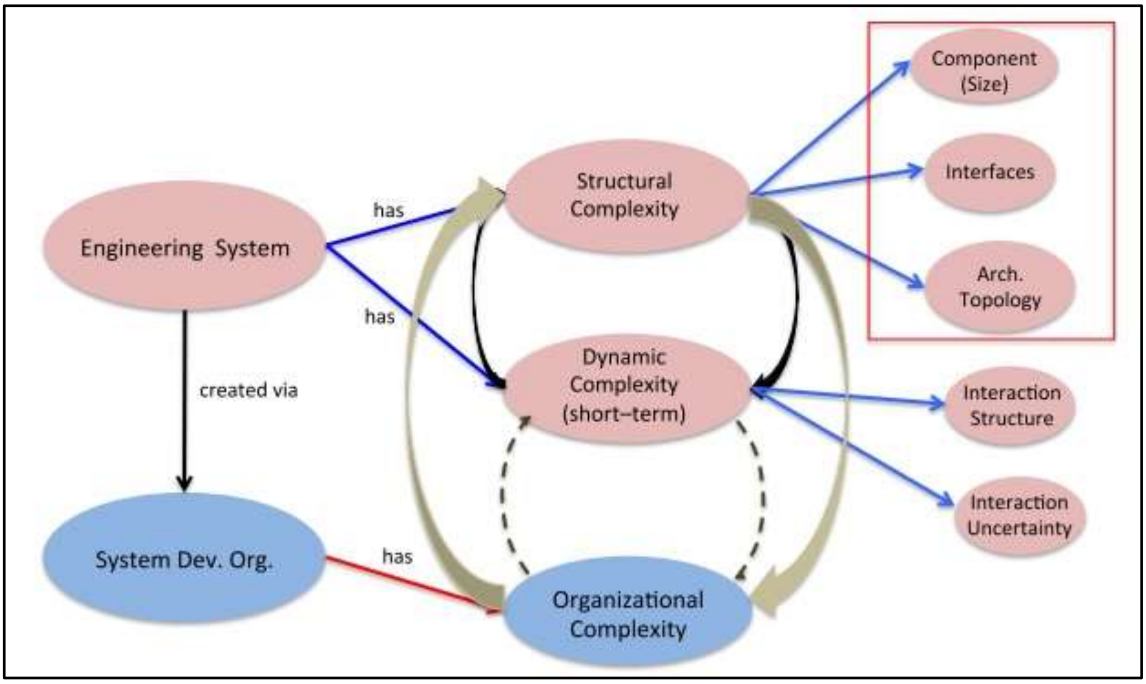

Figure 2 - Complexity Typology for Engineered Systems.

Source: (SINHA, 2014).

To meet the purposes of this research, only the structural and dynamic complexities will be presented. In (SINHA, 2014) and (WECK, KAUSHIK SINHA, 2016), it is presented a formula to estimate the structural complexity of an engineered complex system (equation 1):

Equation 1: Structural Complexity

$$\textit{STRUCTURAL COMPLEXITY}= \underbrace{\sum_{i=1}^{n}\alpha_i}_{\mathbf{C1}} + \left(\underbrace{\sum_{i=1}^{n}\sum_{j=1}^{n}\beta_{i,j}A_{i,j}}_{\mathbf{C2}}\right)\underbrace{\frac{E(A)}{n}}_{\mathbf{C3}} \quad :$$

Where:

- C1: sum of complexities of individual components alone;
- C2: number and complexity of each pair-wise interaction; and
- C3: effect of architecture or the arrangement of the interfaces. C3 is represented by E (A) (the sum of its singular values[7], defined as matrix energy), divided by ***n*** (the number of components).

Dynamic complexity is a function of three fundamental components: inherent uncertainty in system responses (C1); inherent uncertainty in the pair-wise dependency relationships among system responses (C2); and dependency structure among those system responses (C3), presented in (2).

Equation 2: Dynamic Complexity

$$DYNAMIC\ COMPLEXITY = \underbrace{\sum_{i=1}^{n} H(Y_i)}_{C_1} + \underbrace{\left(\sum_{i=1}^{n}\sum_{j=1}^{n} \beta(i,j).A(i,j)\right)}_{C_2}\underbrace{\left(\frac{E(A)}{n}\right)}_{C_3}$$

Where:

- C1 is calculated using the concept of Shannon information entropy (is an average measure of uncertainty of a random variable). Then entropy H(Y) is given by equation 3.

[7] Singular values of matrix A are the n square roots eigenvalues of matrix A^T A, $\sigma_i = \sqrt{\lambda i}$.

Equation 3: Shannon Information Entropy

$$H(Y) = -\sum_{i=1}^{n} p(y).\ln\,[p(y)]$$

- C2 is product of pair-wise dependency relationships and adjacency matrix.

An example of adjacency matrix is presented in figure 3.

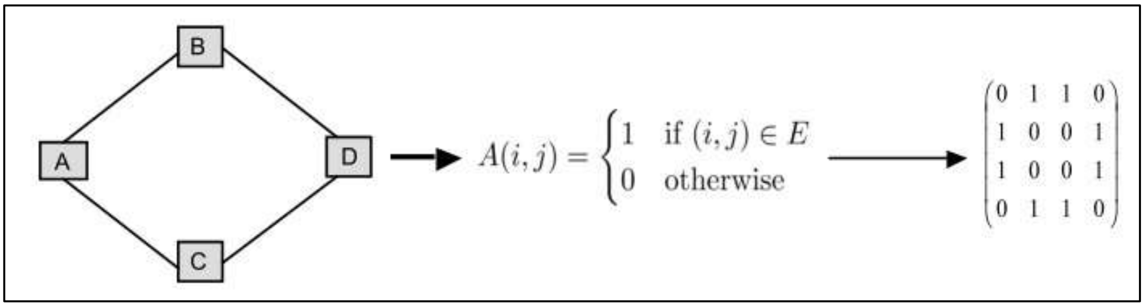

Figure 3: Example of adjacency matrix.

- C3 is represented by E (A) (the sum of its singular values, defined as matrix energy), divided by ***n*** (the number of components).

The effect of the connectivity or the network structure among system components acts as a scaling factor and is captured as the sum of singular values of the binary adjacency matrix (SINHA, 2014).

Given a matrix A, m x n, the matrix A^T A, n x n, is a symmetric matrix with n equal or distinct non-negative real eigenvalues, λ_1, λ_2,..., λ_n. .

2.1.2. Complexity, Coupling, and Criticality (C3)[8] as Risk Indicators in System Design

In order to define risk indicators in system projects applied to aircraft, Lemes (2012) considered in his work three different concepts: COMPLEXITY, COUPLING, AND CRITICALITY.

---

[8] Original title is Complexidade, Acoplamento e Criticalidade (C2A) como indicadores de risco em projetos de sistemas.

He presented a structural complexity approach, introducing that the complexity of a system is a consequence of the complexity of its connections, and the complexity of a connection is measured using the concepts of information theory. According to (PERROW, 1984), systems are not linear or complex, only their interactions are.

Based on the interactions, to measure the complexity was used the formula proposed by Shannon, according to (SHANNON; WEAVER, 1964). Shannon introduced the concept of informational entropy. The entropy of a random variable X with probability p(x), x ∈ S, the entropy H (s) of a random variable S is defined by equation 4.

Equation 4: Entropy H (s)

$$H(S) = -\sum_{i=1}^{|S|} p_i . log_2 p_i$$

H (s) corresponds to the amount of information existing in the connections between its elements, as presented in Equation 5.

Equation 5: Amount of information

$$\Gamma(S) = \sum_{i,j=1}^{|S|} \Gamma_{i,j} = -\sum_{i,j=1}^{|S|} p(x)_{i,j} . \log{}_2 (x)_{i,j}$$

Where:

- **Γ**(S) is equivalent to H(S);
- **Γ**i,j is the amount of information in each connection between of the elements of the system S;
- S is the set of connections between the elements of the system;
- $|S|$ is the total system connections;
- p(x) is the frequency in which a connection between elements i and j happens, where p is given by $\frac{n}{(S)}$. The value of n represents the number of system connections.

Coupling is defined by a set of information in the inputs between two system elements. Thus, the measure of coupling is the measure of these characteristics.

Criticality is an index that indicates the importance of a given connection concerning system safety. Criticality is the result of the classification of fault conditions identified for the system elements involved.

Based on this, (LEMES, 2012) presented a risk indicator based on structural elements of a system, according equation 6.

Equation 6: Risk Indicator

$$C^2A_{i,j} = \left(\Gamma_{i,j+}\ \Phi_{i,j}\right) * \Lambda_{i,j}$$

Where:

- C^2A is the Complexity, Coupling and Criticality Index
- i,j represents the connections of system S;
- $\Gamma_{i,\,j}$ is the i, j connection complexity;
- $\Phi_{i,\,j}$ is the i, j connection coupling; and
- $\Lambda_{I,\,j}$ is the i, j connection criticality

2.1.3. Quantitative Complexity Theory

Once defined, a metric for complexity becomes a property of the system just like mass, pressure, and temperature (MARCZYK, 2011) and that the Complexity Management is an advanced form of Risk Management (MARCZYK, 2014). In (MARCZYK, 2011) the Quantitative Complexity Theory (QCT) and the Quantitative Complexity Management (QCM) are presented. This model has been applied in different areas, such as medical (MARCZYK, 2015) and finance (DOMPIERI, 2014).

In QCT the complexity of a system described by a vector x of N components is defined as a function of its structure S and entropy E, as presented in equation 7.

Equation 7: Complexity in QCT

$$C = f(SoE)$$

Where:

- S ∈ R^{NxN} is an adjacency matrix that establishes the structure – also called topology;
- E ∈ R^{NxN} is an entropy matrix: Average amount of information exchanged between the system nodes. The entropy represents the uncertainty of the system and is characterized by means of the Shannon entropy; and
- $\boldsymbol{o}$ is Hadamard's matrix product;

Once the entropy and adjacency matrices have been obtained, one can calculate the complexity of a given system as the norm of matrix, as follows in equation 8.

Equation 8: Complexity as Norm of Matrix

$$\mathrm{C} = \|\mathrm{SoE}\|$$

A fundamental property of this metric is its upper boundary known as critical complexity (equation 9). In a similar way, one can calculate the minimum complexity (equation 10):

Equation 9: Critical Complexity

$$C_{crítica} = \|SoE_{max}\|$$

Equation 10: Minimum Complexity

$$C_{min} = \|SoE_{min}\|$$

E_{max} is the entropy matrix in which the relations between the parameters of a system are scattered and deprived of structure, and E_{min} is the entropy matrix in which the system in question is almost totally deprived of uncertainty and functions in a deterministic way, dominating its structure. The distance between the minimum complexity and critical complexity is called resilience (MARCZYK, 2011). The "uncertainty" of the system is characterized by means of the Shannon entropy.

2.2. Systems and Systems of Systems

According (ISO/IEC/IEEE, 2015), a system is defined as a combination of interacting elements organized to achieve one or more stated purposes or as an integrated set of elements, subsystems, or assemblies that accomplish a defined objective (INCOSE, 2015). These elements include products (hardware, software, firmware), processes, people, information, techniques, facilities, services, and other support elements. In many cases, the combination of systems, called systems of systems (SoS), should be identified.

In (SIEGFRIED, 2013), SoS is defined as an assembly of systems that are independently acquired and then operated in order to maximize the performance of the global operation of the grouped systems at certain periods. SoS is an open system that can be affected by external events. Figure 4 presents a SoS as a Hierarchy System. We must observe that System Element can be atomic (i.e., not further decomposed), or they can be systems on their own merit (i.e., decomposed into further subordinate system elements).

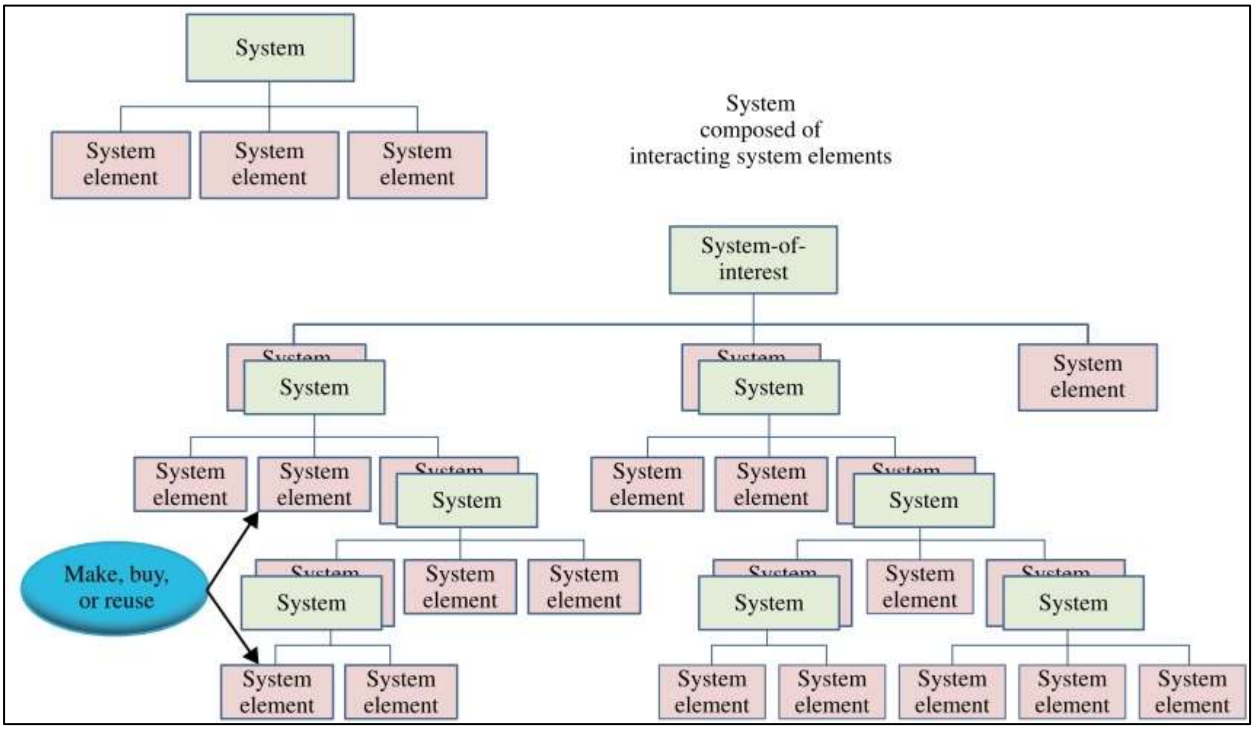

Figure 4 - Hierarchy within a system.
Source: (ISO/IEC/IEEE, 2015).

A practical example about transport system is presented in figure 5, where we observe the relationship between Air Traffic Control System and Aircraft System, Air Traffic Control System and Airport System, and Aircraft System and Fuel Distribution System.

In this work, which aims to develop the airspace complexity model, interactions will be established between different systems, such as air traffic control and meteorology, air traffic control and aircraft, and aircraft and meteorology, among others.

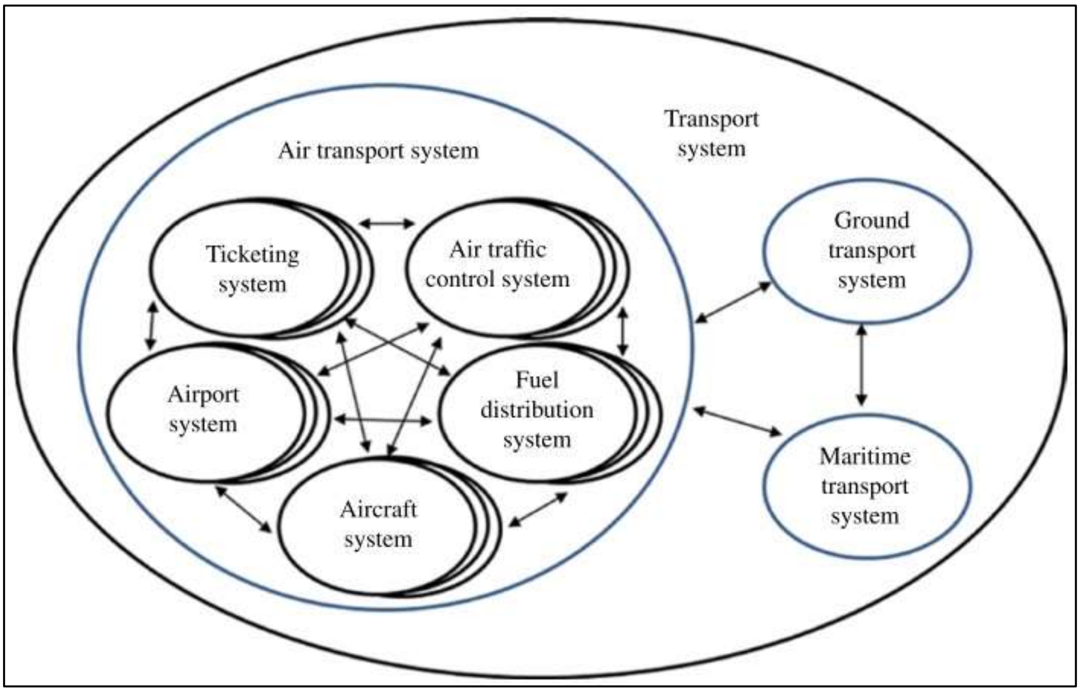

Figure 5 - Systems and systems of systems within a transport system of systems.
Source:(INCOSE, 2015).

A lot of dimensions of SoS are presented in the literature, as follows (NIELSEN et al., 2015):

a) **Autonomy**: the extent to which a constituent system's behavior is governed by its own rules rather than by others external to the constituent. This is seen as a result of individual ownership of the systems;

b) **Independence:** capacity of constituent systems to operate when detached from the rest of the SoS;

c) **Distribution**: the extent to which constituent systems are dispersed so that some form of connectivity enables communication or information sharing;

d) **Evolution**: Many SoSs are long-lasting and subject to change, whether in the functionality, the quality of that functionality, or in the structure and composition of constituent systems;

e) **Dynamic Reconfiguration**: capacity of a SoS to undertake changes in its structure and composition, typically without planned intervention;

f) **Emergence of Behavior:** behaviors that arise as a result of the synergistic collaboration of constituents;

g) **Interdependence:** mutual dependency that arises from the constituent systems having to rely on each other in order to fulfil the common goal of the SoS; and

h) **Interoperability**: ability of the SoS to incorporate a range of heterogeneous constituent systems. This involves the integration and adaptation of interfaces, protocols, and standards to enable bridging between legacy and newly designed systems.

3. MODELS OF COMPLEXITY AND CAPACITY

In order to present relevant concepts about air traffic, it is presented in Appendix A - air traffic concepts, air traffic rules and airspace structure and key concepts.

First of all, it is worth mentioning that although many technologies have been developed over time, the complexity variables identified in the systems, in general, are the same presented in the literature since the beginning.

To talk about any airspace, we need to talk about flights. Safety of flights is of paramount concern, and Air Traffic Control (ATC) is a primary activity for this issue. Studies have examined potential future scenarios for the ATC system and concluded that that ATC performance and safety will degrade with higher air traffic load (MOGFORD, R.; GUTTMAN, J.; MORROW, S.; KOPARDEKAR, 1995)

When we look into the growth of air transport, we concern ourselves with the capacity of the system as a whole, especially airports and airspace capacity or a portion of the airspace, called ATC (air traffic control) sector. Considering that the focus of this work is airspace, capacity of an ATC sector can be defined as the maximum number of aircraft that are controlled in a particular ATC sector in a specified period of time while still permitting an acceptable level of controller workload (MAJUMDAR; POLAK, 2001a).

Hence, it is crucial that we know the relationship between ATCo workload and airspace capacity. According to (MAJUMDAR; POLAK, 2001b) in high air-traffic-density areas a safer measure of capacity is based on ATCo workload (i.e., the mental and physical work done by the controller to control traffic), which considers that the only way to measure ATCo's workload is the number of traffics. To disregard how traffic and airspace configuration are presented would result in a very simplistic model.

Considering that ATCo workload defines airspace capacity, it is fundamental to know factors affecting this workload when we think about increasing or maintaining airspace capacity. Figure 6 presents these factors, which are called complexity factors (also known as “air traffic complexity,” “cognitive complexity,” and sometimes “dynamic density”) (OCHIENG, W.; MAJUMDAR, 2002).

This approach emphasizes that – although there may be objective, measurable features of sectors and aircraft – the concept of ATC complexity is subjectively defined by the controller. It is developed from the controller's perception of and interaction with the sector and the air traffic within it (MOGFORD, R.; GUTTMAN, J.; MORROW, S.; KOPARDEKAR, 1995).

.

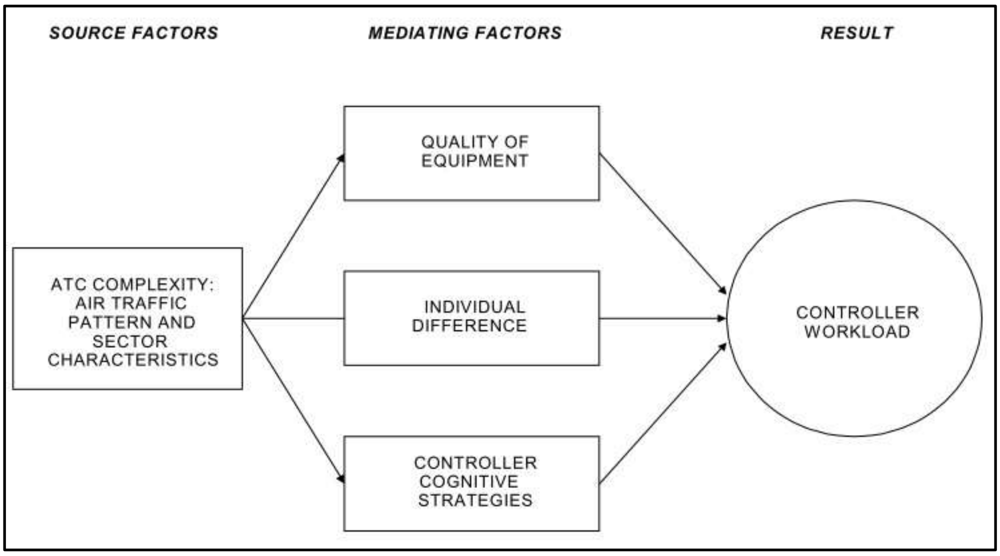

Figure 6 – Factors affecting controller workload

Source: (MOGFORD, R.; GUTTMAN, J.; MORROW, S.; KOPARDEKAR, 1995)

The concern with factors that impact ATCo's workload is old, and different approaches have been proposed since then to address this issue. Since the beginning of the 1960s, several researchers have been dedicated to studying and establishing the relationship between factors classified as complexity variables and their influence on the ATCo workload. This is because, as previously presented, they recognize that ATCo's workload is usually the factor that limits airspace capacity.

According (TOBARUELA et al., 2014) Workload measurements can either be direct or indirect. Direct measurement techniques focus on obtaining workload indicators from the ATCo (e.g. discussions); is the measurement of work performed on tasks. Indirect techniques estimate ATCo workload based on other indicators (e.g. complexity metrics).

In (MOGFORD, R.; GUTTMAN, J.; MORROW, S.; KOPARDEKAR, 1995)(OCHIENG, W.; MAJUMDAR, 2002) we found a systematic review of the literature that presents studies developed by several researchers, analyzing the impact of factors on the workload of the ATCo. Table 1 presents a list of works and complexity factors studied.

Table 1- Factors that affect ATCo Workload

Variable	Author
AIRCRAFT	
Traffic density/ Number of flights	Davis (1963); Arad (1963, 1964); Buckley et al. (1983); Stein (1985); Eurocontrol (2000).
Traffic mix	Davis (1963); Mogford et al. (1993)
Separation Standards/Longitudinal, sequencing, spacing	Arad (1963, 1964); Schmidt (1976); Mogford et al. (1993)
Aircraft speeds	Arad (1963, 1964); Schmidt (1976); Delahaye et al. (2000)
Traffic flow rate	Schmidt (1976)
Cruising traffic	Schmidt (1976); Eurocontrol (2000)
Confliction	Buckley et al. (1983)
Occupancy	Buckley et al. (1983)
Delay	Buckley et al. (1983)
Buckley et al. (1983)	Buckley et al. (1983)
Aircraft clustering	Stein (1985)
Angle of intersection between routes Schmidt	Schmidt (1976)
Hourly traffic	Hurst & Rose (1978)
Peak Traffic	Hurst & Rose (1978)
Climbing/ Descending traffic	Mogford et al. (1993); Eurocontrol (2000)
Horizontal conflicts	Siddique (1973)
Ascending conflicts	Magill (1997)
Military flights	Mogford et al. (1993)
Airline hubbing	Mogford et al. (1993)
Aircraft position	Delahaye et. al (2000)
SECTOR	
Sector Size	Arad (1963, 1964); Mogford et al. (1993); Eurocontrol (2000)
Sector/ flow design	Sector/ flow design; Arad (1963, 1964); Stein (1985)
Number of flight levels	Schmidt (1976)
Coordinations	Mogford et al. (1993)
Number of intersections	Courilis & Schmidt (1973)
Boundary location	Courilis & Schmidt (1973)
Airway configuration	Courilis & Schmidt (1973)
Number of intersecting flight paths Mogford	Mogford et al. (1993)
Complex routing	Mogford et al. (1993)
Restricted areas	Mogford et al. (1993)
COMBINATION	
Radio and radar coverage	Mogford et al. (1993)
Frequency congestion	Mogford et al. (1993)
Communications	Buckley et al. (1983)
Required procedures	Mogford et al. (1993)
Weather	Mogford et al. (1993)

Source: (MOGFORD, R.; GUTTMAN, J.; MORROW, S.; KOPARDEKAR, 1995)(OCHIENG, W.; MAJUMDAR, 2002).

In (COMENDADOR et al., 2018) a list of “complexity generators” selection was proposed based on a proposal and review by experts. This list has been divided into seven categories, as shown in table 2.

Table 2- List of Complexity Generators

CATEGORY	COMPLEXITY GENERATOR REVIEW
AIRSPACE	Number of main flows
	Number of interaction points Presence/proximity (crossing points)
	Presence/proximity of restricted airspace
	Distribution of crossing points and their proximity to airspace boundaries
	Airspace Geometry
	Airspace Volume
CONFLICTS	Angle of convergence in conflict situation
	Number of conflicts predicted
	Number of opposite heading
	Degrees of freedom of the controller in the resolution strategy of the conflict (e.g. procedural or supporting tools limitations)
	Minimum vertical/ horizontal (the lower of the two) distance between flights at conflict point
	Proximity of potential conflicts to sector boundary
FLOW ORGANISATION	Altitude distribution
	Speed distribution
	Flows and Routes distribution: Number, geometry (orientation relative to sector shape, merges, crossings…)
	Vectoring and operational restrictions Related
OPERATIONAL PROCEDURES	Related with coordination procedures
	Related with "vectoring and operational restrictions"
	Separation Standards
	Coordination procedures Traffic
	Related with "vectoring and operational restrictions"
	Separation Standards
	Coordination procedures Traffic
TRAFFIC	Number aircraft entering
	Number of aircraft changing altitude
	Distribution of flight time per aircraft under ATCo responsibility in the given timeframe
	Related with "speed distribution" Related
	Average sector flight time
	Fraction of aircraft climbing Fraction, in cruise, descending
	Total number of flights in the timeframe Flight
	Flight level difference between crossing flights
	Time difference at crossing points
TRAFFIC MIX	Aircraft type mix (performance)
	Proportion of arrivals, departures, and overflights
OTHERS	Risk of technical failures
	Level of aircraft intent knowledge
	Weather conditions

Source: (COMENDADOR et al., 2018).

Below, different complexity models applied to air traffic will be presented.

3.1. Model of Complexity and Capacity applied to Air Traffic

3.1.1. Dynamic Density

The search for an air traffic controller workload metric based on air traffic characteristics has led to the development of a model called dynamic density that proposes a metric that includes both traffic density (a count of aircraft in a volume of airspace) and traffic complexity (a measure of the complexity of the air traffic in a volume of airspace) (LAUDEMAN et al., 1998).

The general form of the proposed equation is presented in (LAUDEMAN et al., 1998)

Equation 11: Dynamic Density

$$DD = \sum_{i=1}^{n} W_i \, TC_i + TD + CI$$

Where *DD* is dynamic density, TC_i is the ith traffic complexity factor, W_i is the ith factor weighting, *i* is the number of traffic complexity factors, *TD* is traffic density, and *CI* is the air traffic controller intent. However, although it was presented in the formula, (LAUDEMAN et al., 1998) does not consider CI, due to the possibility of a substantial amount of variance in observed controller activity. One implication of the elimination of the CI term is the limitation of the workload measure to observable behavior.

The choice of complexity factors was based on an informal interview process with subject matter experts, as follows:

- Heading Change (HC): Number of Aircraft that made a heading change of greater than 15 degrees during a sample interval of two minutes.
- Speed Change (SC): The number of aircraft that had a computed airspeed change of greater than 10 KT or 0.02 Mach[9] during a sample interval of two minutes.
- Altitude Change (AC): The number of aircraft that made an altitude change of greater than 750 feet during a sample interval of two minutes.

[9] Mach is based a sound speed.

- Minimum Distance 0-5 NM (MD5): The number of aircraft that had a Euclidian distance of 0-5 NM to the closest other aircraft at the end of each two minutes of interval.
- Conflict Predicted 0-25 NM (CP25): The number of aircraft predicted to be in conflict with another aircraft whose lateral distance at the end of each two minute sample interval was 0 – 25 NM.
- Conflict Predicted 25-40 NM (CP40): The number of aircraft predicted to be in conflict with another aircraft whose lateral distance at the end of each two minute sample interval was 25 – 40 NM.
- Conflict Predicted 40-70 NM (CP70): The number of aircraft predicted to be in conflict with another aircraft whose lateral distance at the end of each two minute sample interval was 40 – 70 NM.
- TD: amount of traffic divided by Airspace Volume.

The dynamic density equation is presented in (12) (LAUDEMAN et al., 1998).

Equation 12: Dynamic Density – aplication

$$D = W_1(HC) + W_2(SC) + W_3\,(AC) + W_4\,(MD5) + W_5(MD10) \\ + W_6(CP25) + W_7(CP40) + W_8(CP70) + W_{td}TD$$

The dynamic density equation was programmed into the Center TRACON Automation System (CTAS) and used in Denver ARTCC (Air Route Traffic Control Center) as a scenario. Factors weights were computed in a multiple regression analysis in which traffic density and all the traffic complexity factors were forced into the equation. The dynamic density factors, the computed normalized weights (B), and the statistical significance (Sig T) of each factor weight are shown in table 4. are shown in table 4. The B weights are normalized with a mean of zero and a standard deviation of 1. The statistical significance of each weight was computed with a T test that compared the mean of the computed weight with a zero mean.

According to table 3, after multiple regression analysis, the computed normalized weights (B) are presented no-significant SC (0.15) and CP25 (0.10).

Considering SC, it is possible that the low weighting of the speed factor is an artifact of the types of sectors that were analyzed. This term might capture a significant amount of the variance in observed activity in a low "altitude sector with a large proportion of arrival traffic. There are typically a high percentage of aircraft changing speed in arrival sectors as they slow down for final approach to an airport. The no significance of the conflict prediction term for a current range of 0-25 NM is possibly the result of its relatively low base rate, as two converging aircraft are relatively unlikely to close to less than 25 NM of each other in an airspace in which all aircraft are under radar control.

Table 3- Regression factor weights with statistical significance values.

Traffic density	Regression		
	B	T	Sig T
	0.79	5.79	0.00
Traffic factors	**Regression**		
	B	T	Sig T
HC	2.17	3.06	0.00
SC	0.15	0.34	0.73
AC	0.88	1.78	0.08
MD 5	1.02	1.84	0.07
MD 10	1.18	3.94	0.00
CP 25	0.10	0.14	0.89
CP 40	1.85	2.59	0.01
CP 70	1.85	2.85	0.00

Source: (LAUDEMAN et al., 1998).

The dynamic density equation is presented in equation 13.

Equation 13: Dynamic density after multiple regression

$$DD = 2.17(HC) + 0.88\,(AC) + 1.02\,(MD5) + 1.18(MD10) \\ + 1.85(CP40) + 1.85(CP70) + 0{,}79(TD)$$

According to (KOPARDEKAR, 2001), ETMS (Enhanced Traffic Management System) monitor alert is used as a strategic planning tool to identify and predict sector traffic complexity, based solely on aircraft count, identifying a sector complexity threshold. It is widely recognized, however, that this threshold measurement is often an insufficient and/or inaccurate prediction of sector traffic complexity. In (KOPARDEKAR, 2001) the importance of DD is reinforced. Figure 7 presents potential applications, requirements, and benefits of a DD metric.

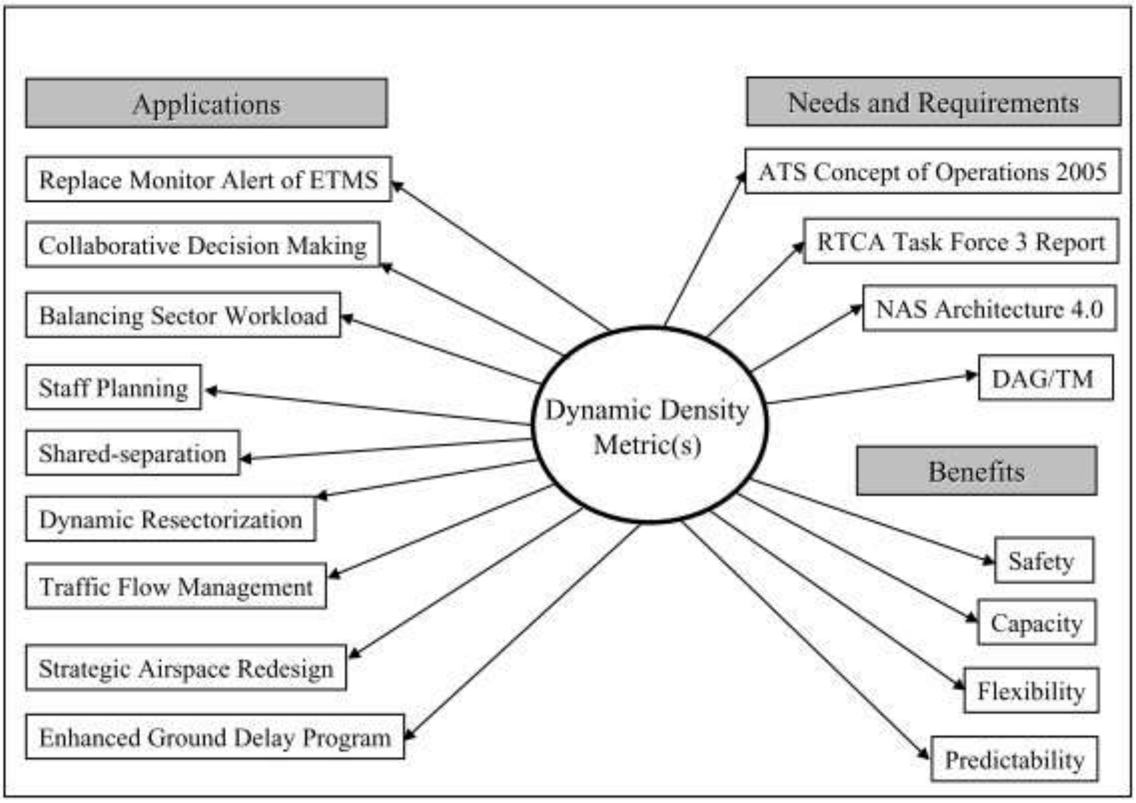

Figure 7 - Potential applications, requirements, and benefits of a DD metric.

Source:(KOPARDEKAR, 2001).

In (SRIDHAR; SHETH; GRABBE, 1998), it is shown a dynamic density analysis at the Dallas/Fort Worth (ZFW) ARTCC using CTAS. The authors present the conclusion that dynamic density represents only the traffic flow conditions and could be improved by incorporating effects of structural characteristics like airway intersections as well as other dynamic flow events, such as weather. There is also a need for developing measures of airspace complexity that can be used for addressing not only the physical aspect but also the cognitive aspect of controller workload.

In 1999, the FAA William J. Hughes Technical Center (WJHTC), NASA Ames Research Center, and Metron Aviation formed a partnership to research DD, where each organization had its own ideas about what variables contributed to DD, although many similarities existed (KOPARDEKAR; SCHWARTZ, 2007) (KOPARDEKAR; MAGYARITS, 2003).

In (KOPARDEKAR; MAGYARITS, 2003), there were the first validation exercises that examined all DD metrics using the same common data set to identify their applicability, strengths, and weaknesses. The DD research activities were performed in three phases: The first two phases involved developing and refining the DD metrics, selecting traffic samples, and collecting subjective complexity ratings from controllers and supervisors at multiple ARTCCs (Air Route Traffic Control Center)[10] across the country on the complexity of those traffic samples. Phase III was focused on data analysis and used ETMS (Enhanced Traffic Management System), developed by FAA, for data collection and CRCT (Collaborative Routing Coordination Tool), developed by MITRE, to compute the DD variables.

Denver ARTCC was used collecting complexity ratings from controllers and supervisors. To select traffic samples were used four ARTCC (Atlanta, Cleveland, Denver, and Fort Worth) as a simulation scenario and realizing data analysis. An optimal DD metric was developed that included a comparison of the DD output for the complexity classification and a regression analysis to determine the significant DD metrics. This study concludes that the model can be further developed and tested with techniques such as neural networks and genetic algorithms and recommends the use of CTAS as a data source because of its accuracy.

In (MASALONIS; CALLAHAM; WANKE, 2003) using traffic characteristic metrics that could eventually enable Traffic Flow Management (TFM) personnel to strategically prevent overloads using triggers other than predicted sector traffic count.

In a second validation of DD, was used Cleveland ARTCC as scenario, according to (KOPARDEKAR; SCHWARTZ, 2007), SAR (System Analysis Recording) as a data source, and DRAT (Data Reduction and Analysis Toolkit) developed by FAA. It was found seventeen significant variables, considered complexity factors, and their corresponding weights (estimates), t-values, and p-values and concluded that SAR

[10] Performs the role of the ACC (area control center).

was shown to be a better data source. Just like the previous study, this one suggests other techniques to improve the model.

3.1.2. Macroscopic Wokload Model (MWL)

As discussed earlier, it is understood that complexity affects ATCo's workload, existing different models, with different complexity variables, for example, as presented in (CHRISTIEN et al., 2002b). In (CHRISTIEN et al., 2002b) is presented a model of workload calculation, including complexity in a workload model, called Complexity Flight and Complexity of interactions, according to (14). Single aircraft tasks are, for example, ensure coordination and check trajectories and Aircraft interaction tasks are, for example, conflict search and conflict resolution.

Equation 14: Workload - Complexity Flight and Complexity Interaction

$$WL = WlFL_{tasks} + WlFL_{complexity} + WlINT_{tasks} + WlINT_{complexity}$$

Considering within the ATC sector in the chosen period, where:

- WL is the workload;
- FLs are the number of flights;
- INT are the number of interactions.
- FL_{tasks} and INT_{tasks} representing all operational tasks.
- $FL_{complexity}$ and $INT_{complexity}$ representing the impact of complexity.

The higher $WlFL_{Complexity}$ and $WlINT_{complexity}$ are the higher complexity is. For example, in a sector S where conflicts are difficult to solve (lack of space…) WlINTcomplexity will be high. As a consequence, for a given number of flights and interactions, workload will be higher in this sector S than in a less complexity sector.

The complexity indicators, presented in table 4 and 5, were chosen and the simulations performed in fast time ATFM simulator, called AMOC (ATFM MODELLING CAPACITY), developed by Eurocontrol.

Table 4- Complexity flight

Number and type of flights by time period (each 10 minutes during 24h from midnight)(over-flight, entry)
3 Peak hours (3 consecutive hours with the maximum of flights in the day)
Amount of climbing/descending traffic
Proximity of a centre boundary

Source: (CHRISTIEN et al., 2002b).

Table 5- Complexity of Interactions

Number and type of conflicts
Multiple crossing points
Small angle convergence routes
Aircraft performance mix (jets, props...)
Separation standards
Time between conflict detection and conflict resolution
Flow entropy
Density

Source: (CHRISTIEN et al., 2002b)

3.1.3. Tactical Load Smoother (TLS)

The Program for Harmonised ATM Research in Eurocontrol (PHARE), which was initiated in 1989, is a co-operative effort between European research establishments National Air Traffic Services (UK), Centre d'Etudes de la Navigation Aérienne (France), Deutche Forschungsanstalt für Luft und Raumfahrt (Germany), Nationaal Luchten Ruimtevaartlaboratorium (Netherlands) and the Eurocontrol Experimental Centre.

One of the results of PHARE was presented in (MECKIFF; CHONE; NICOLAON, 1998), which introduced the concept of TLS (Tactical Load Smoother). A key notion in the TLS is of complexity, and though the notion of ATCo workload has always been difficult to define, it is clearly related to complexity in some way. It is assumed that workload is a function of three elements: the geometrical nature of the air traffic; operational procedures and practices used to handle the traffic; and the characteristics and behavior of individual controllers (experience, orderliness, etc.).

The complexity calculation is based on:

- Aircraft position in the sector is defined as:

$$S(sector)=\begin{Bmatrix} in\ center \\ close\ to\ edge \\ very\ close\ to\ edge \end{Bmatrix}$$

- Attitude of an individual aircraft:

$$A(aircraft)=\begin{Bmatrix} 4D\ FMS \\ 3D\ FMS \\ NO\ FMS \end{Bmatrix} x \begin{Bmatrix} steady \\ climbing \\ descending \end{Bmatrix} x \begin{Bmatrix} slow \\ medium \\ fast \end{Bmatrix}$$

Where FMS is Flight Management System.

-

- Situation of an aircraft relative to a sector:

$$AS(aircraft\ sector)=\begin{Bmatrix} correct\ level \\ incorrect\ level \end{Bmatrix} x \begin{Bmatrix} long\ crossing \\ average\ crossing \\ short\ crossing \end{Bmatrix}$$

- Relation between a pair of aircraft:

$$AA(aircraft_1,\ aircraft_2)=\begin{Bmatrix} in\ trail \\ crossing \\ head\ on \end{Bmatrix} x \begin{Bmatrix} both\ level \\ both\ climbing \\ both\ descending \\ steady\ and\ climbing \\ steady\ and\ descending \\ climbing\ and\ descending \end{Bmatrix}$$

Therefore, overall complexity for each ATC sector is presented in equation 15.

Equation 15: Overall Complexity

$$Complexity = S(sector)x\prod_{i=1}^{n} A(aircraft_i)x\prod_{i=1}^{n} AS(aircraft, sector)x\prod_{i=1}^{n}\prod_{j>1}^{n} AA(aircraft_i\, , aircraft_j)$$

Each of the values in the complexity formulation is a constant identified after interviews with controllers. For computational purposes:

- all constants are greater than or equal to unity; and
- the values of in_centre, 4d_fms, steady, slow, correct_level and long_crossing is set to unity.

This model presents instantaneous complexity called Sector Load Window according to figure 8 and areas of potential complexity for a specific instant in time, called Complexity Map, figure 9.

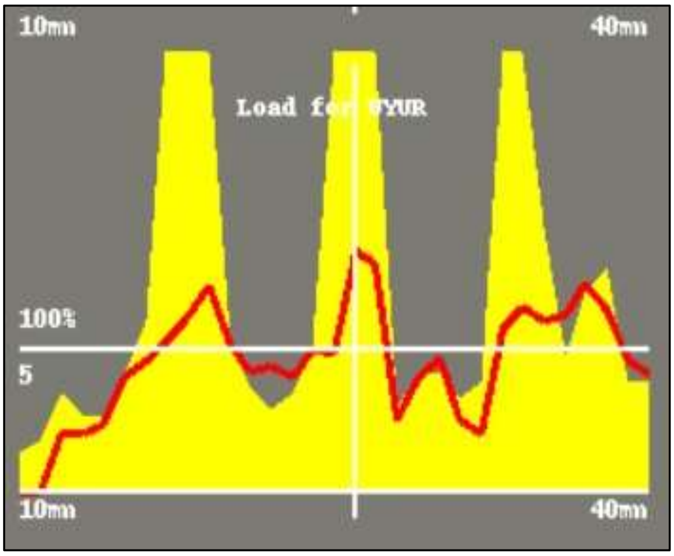

Figure 8 - Sector Load Window.
Source: (MECKIFF; CHONE; NICOLAON, 1998).

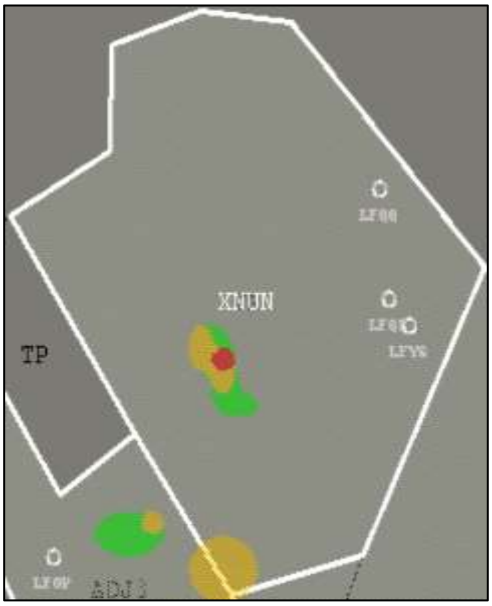

Figure 9 - Complexity Map.
Source: (MECKIFF; CHONE; NICOLAON, 1998).

3.1.4. Dynamical System

(DELAHAYE; PUECHMOREL, 2000) presents a complexity indicator based on the linear dynamical system theory using the concept of topological entropy (Kolmogorov-entropy), which is a disorder indicator of the distribution of the aircraft in the considered airspace.

The Single European Sky ATM Research (SESAR) has chosen a complexity model called Lyapunov Algorithm based on dynamic System Modelling of Aircraft Trajectories to develop an air complexity assessment tool. This model is presented in (DELAHAYE; PUECHMOREL, 2014) both as linear and non-linear modeling.

Linear dynamical system modeling enables us to generate an aggregate metric associated with any traffic situation and can recognize any global organization pattern. The key is to model a set of aircraft trajectories by a linear dynamical system that is defined by the following equation 16:

Equation 16: Linear Dynamical System

$$\dot{\vec{X}} = A.\vec{X} + \vec{B}$$

where $\vec{X}$ is the state vector of the system, presented in equation 17.

Equation 17: State Vector of System

$$\vec{X} = [x \quad y \quad z]^T$$

This equation associates a vector speed $\dot{\vec{X}}$ to a position in the space coordinate $\vec{X}$.

The eigenvalues of the matrix A control the evolution of the system. The real part of those eigenvalues is related to the convergence or the divergence property, such that when the eigenvalue has a positive real part, the system is in expansion mode, and when the real part is negative, the system is in contraction mode. Depending on the eigenvalues, a dynamical system can evolve in contraction, expansion, rotation, or a combination of those three modes. Figure 10 presents these situations.

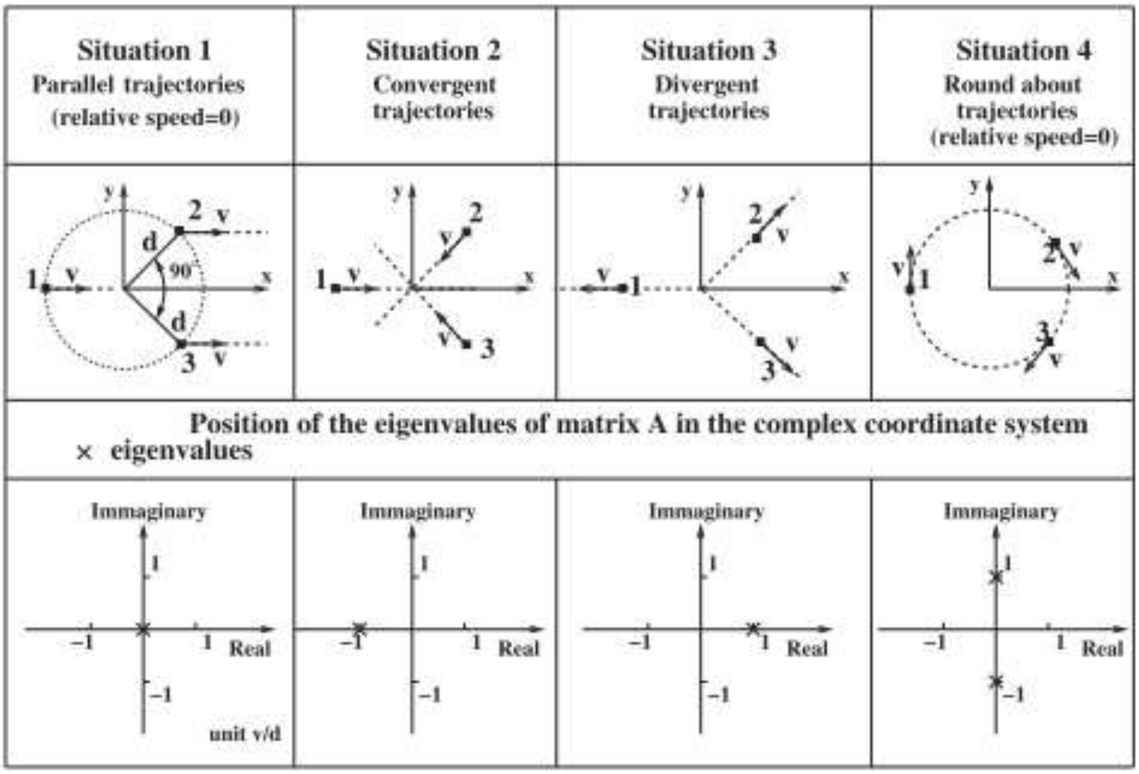

Figure 10 - Eigenvalues for several typical situations.

Source: (DELAHAYE; PUECHMOREL, 2014).

It gives an aggregate measure of a given traffic situation but is not able to identify high or low complexity areas in the airspace.

For such purpose, a complexity metric has been developed based on non-linear dynamical system, and the metric chosen for complexity computation relies on a measure of sensitivity to the initial conditions of the underlying dynamical system called Lyapunov exponents. In order to figure out what the Lyapunov exponents are, let us consider a point and look at its evolution when transported by the dynamical system.

Let $\vec{x}_0$ be fixed (initial point) and let γ be a point trajectory of the dynamical system associated with the vector field $\vec{f}$ given by equation 18.

Equation 18: Dynamical System associated with vector f

$$(t, \vec{x}_0) = \vec{x}_0 + \int_0^t \vec{f}(u, \gamma(u, \vec{x}))du$$

If the three space dimensions are considered (x,y,z), then

$$\mathrm{u}= (x - \mathrm{x}_0)\mathrm{i} + (y - y_0)j + (z - z_0)k.$$

Assume now that the trajectory is disturbed by a small perturbation, as shown in figure 11.

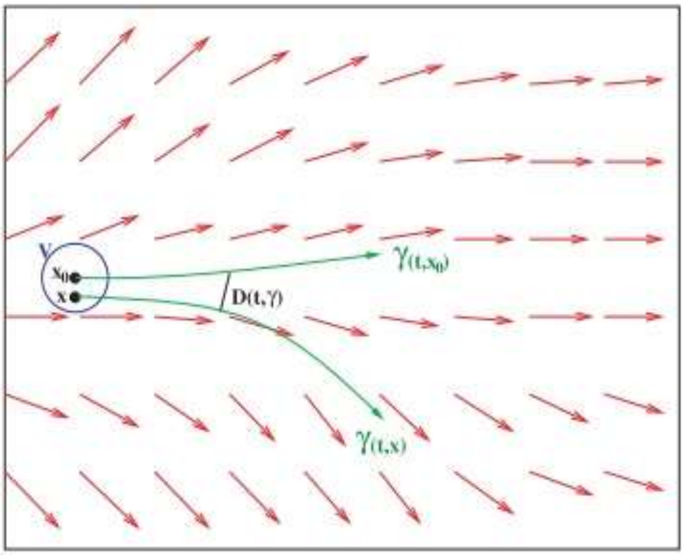

Figure 11 - Time evolution of a reference trajectory and a perturbed trajectory.

Source:(DELAHAYE; PUECHMOREL, 2014).

The figure 12 shows an example of Lyapunov exponents map for which full organized miles in trail trajectories cross two random traffic situations. Highly complex regions are identified, represented by the difference in tonality of the map colors.

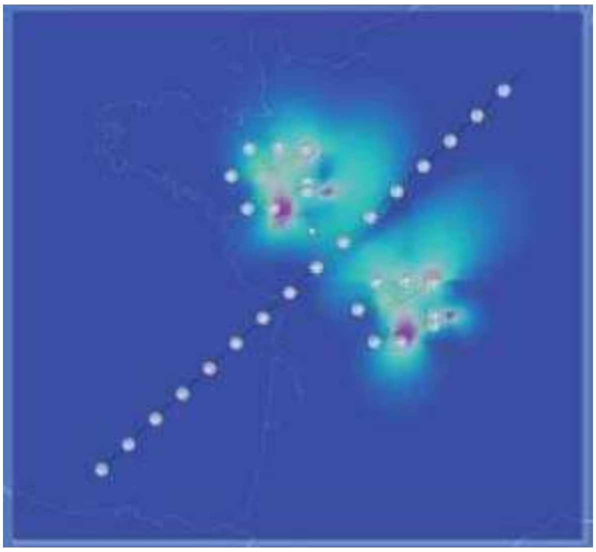

Figure 12 - Miles in trail traffic between disordered areas complexity.

Source: (DELAHAYE; PUECHMOREL, 2014).

3.1.5. Bayesian Model

In (PEPPER; MILLS; WOJCIK, 2003) was presented a method of accounting for uncertain weather information at the time of TFM (Traffic Flow Management) decisions, based on Bayesian decision network. The difficulty in creating a usable Bayesian Decision Network Highlights How To Difficult It is to learn to make better strategic TFM decisions from past decision-make experience.

As presented in (COMENDADOR et al., 2018), the complexity metrics applied to ATM and the opinion of sector experts have allowed us to identify elements called Complexity Generators, which can be key to the definition of complexity in Capacity Management. In addition, the application of causal models has led to the development of a methodology to evaluate the effect of the trajectory uncertainty on the results of the complexity evaluation metrics, depending on the complexity generators (CG) selected in each ATM application.The uncertainties related to the CG were proposed and reviewed by ATC experts.

To development the complexity model, (COMENDADOR et al., 2018) proposes the use of Bayesian Networks, which, for having the capacity to model the propagation of multi-directional uncertainty forward and backward, can be helpful in both predicting a system’s performance and diagnosing the causes of some system outcome. Bayesian Networks (BN) have been selected in this case to assess the uncertainty propagation for complexity in ATM because they present the following features (COMENDADOR et al., 2018):

- Are useful to capture and analyze causality and influence in relationships.
- Are primarily used to update the probability distribution over the states of a hypothesis variable.
- Provide a convenient and coherent way to represent uncertainty in uncertain models and are increasingly used for representing uncertain knowledge.
- Due to the conditional dependence relationships of the variables within the network, BNs offer the ability to either predict or diagnose.
- Allow for qualitative cause and effect assessment as well as for quantitative updates on the probability distribution of non-observable variables.

(COMENDADOR et al., 2019) presents a Bayesian Network Modelling of ATC Complexity Metrics for Future SESAR Demand and Capacity Balance Solutions. The BN models have been built and validated following a process called Engineering of Expert–based Knowledge Engineering of Bayesian Network (EKEBN). This process comprises three main steps:

- Structure building: consisted of the identification of the variables and causal relationships and the states or values that each variable could take.
- Uncertainty quantification: deals with the conditional probabilities that quantify the relationships between variables. Conditional probability tables (CPTs) were obtained via expert’s elicitation as well from data and results in existing literature. Model validation: checks the BN resulting from the two previous steps and determines whether it is necessary to revisit any of the previous steps.

- Validation followed a Model Walkthrough approach, which used real case scenarios prepared by domain experts to assess the BN model predictions.

The process is iterative until a complete BN is built and validated. Figure 13 presents steps in the construction of a generic Bayesian Network for complexity.

As a result, it was presented (COMENDADOR et al., 2019):

- Assessment of how trajectory uncertainty is translated into complexity uncertainty.
- Identification of the complexity generators that generate greater uncertainty in the complexity results.
- The set of complexity generators recommended as inputs in the complexity metrics.
- Reducing the level of uncertainty, it reduces complexity.
- An evaluation of the adaptability of current complexity metrics.

(KNORR; WALTER, 2011) states that complexity metrics quantify the perceived workload experienced by the controller in various traffic situations.

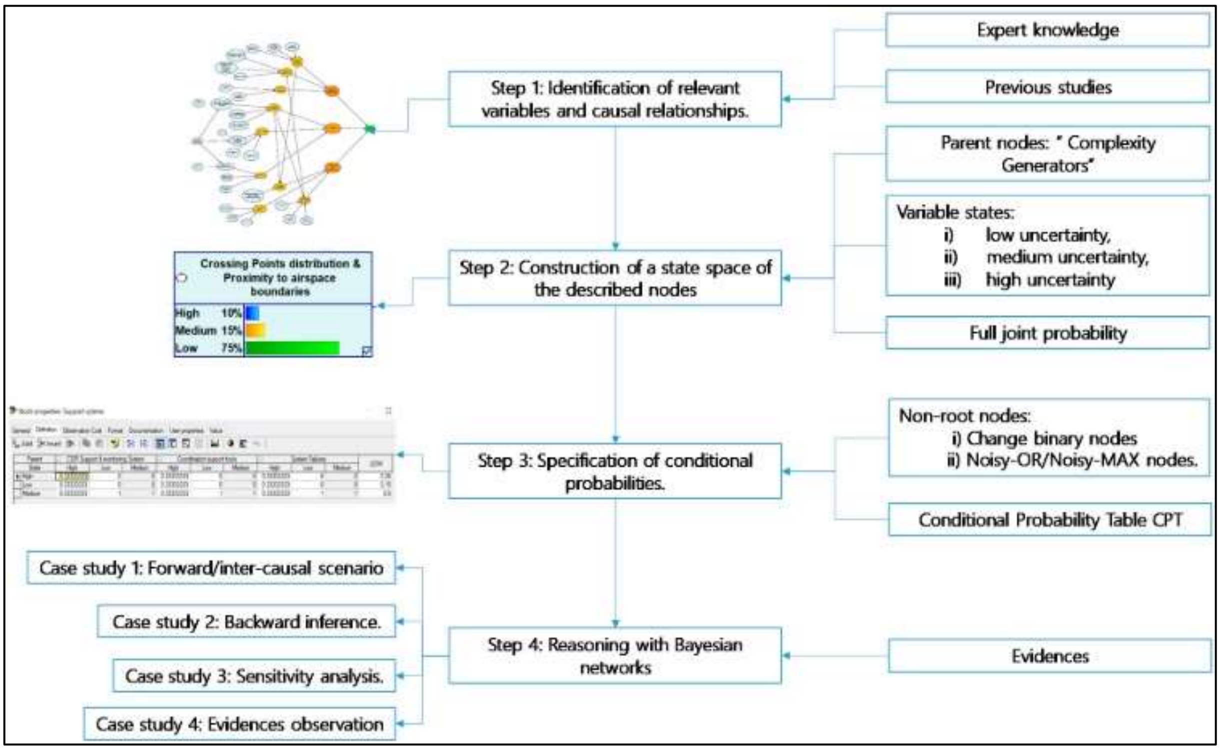

Figure 13: a generic Bayesian Network for complexity.
Source: (COMENDADOR et al., 2019).

Below is a breakdown of the steps shown in figure 13:

- Step 1: Identification of all the variables that will make up the model, as well as establishing the relationships between them. Consider, for example, that we want to establish an “x” indicator. After consulting the team of experts, we initially select the variables a, b, c, d that will compose the model. The team of experts identified that these variables are connected to three other variables k, l, m (nodes); however, considering that these factors k, l, m are different from each other, the influence of variables a, b, c, d on the variables k, l, m must be different from each other. Finally, the variables k, l, m are connected to the indicator “x” (figure 14);

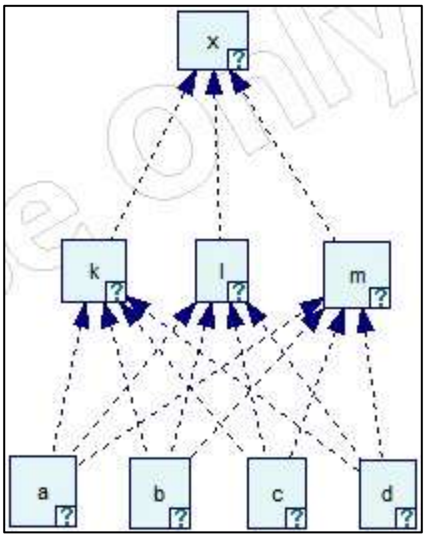

Figure 14: Identification of variables and causal relationships.

- Step 2: Construction of state space. This involves defining the possible states of each variable in the model, as illustrated in figure 15 (for example, the variables a, b, c, and d can be classified as low, medium, or high).

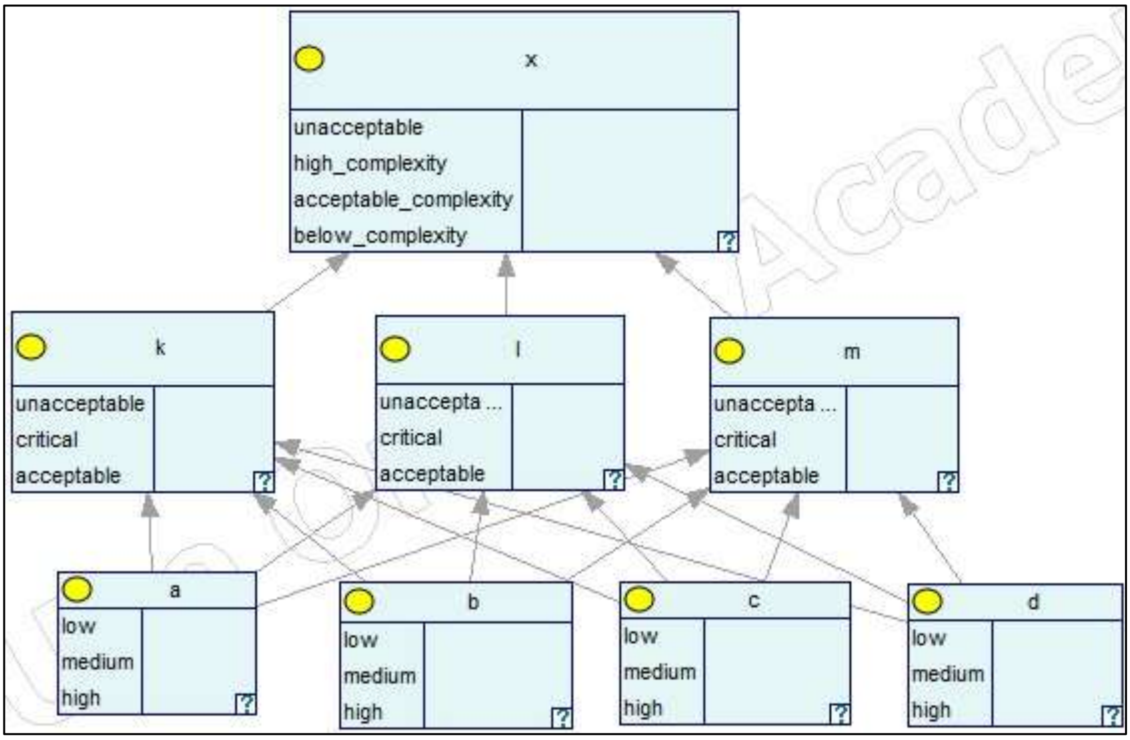

Figure 15: Construction of state space.
Source: Proposed by the author.

- Step 3: The conditional probabilities of each state space will be established. Different strategies can be used, such as expert team or computer simulation modeling[11]. Figure 16 presents an example of conditional state space probabilities.

[11] The present work uses computer simulation to define the conditional probabilities of each state space.

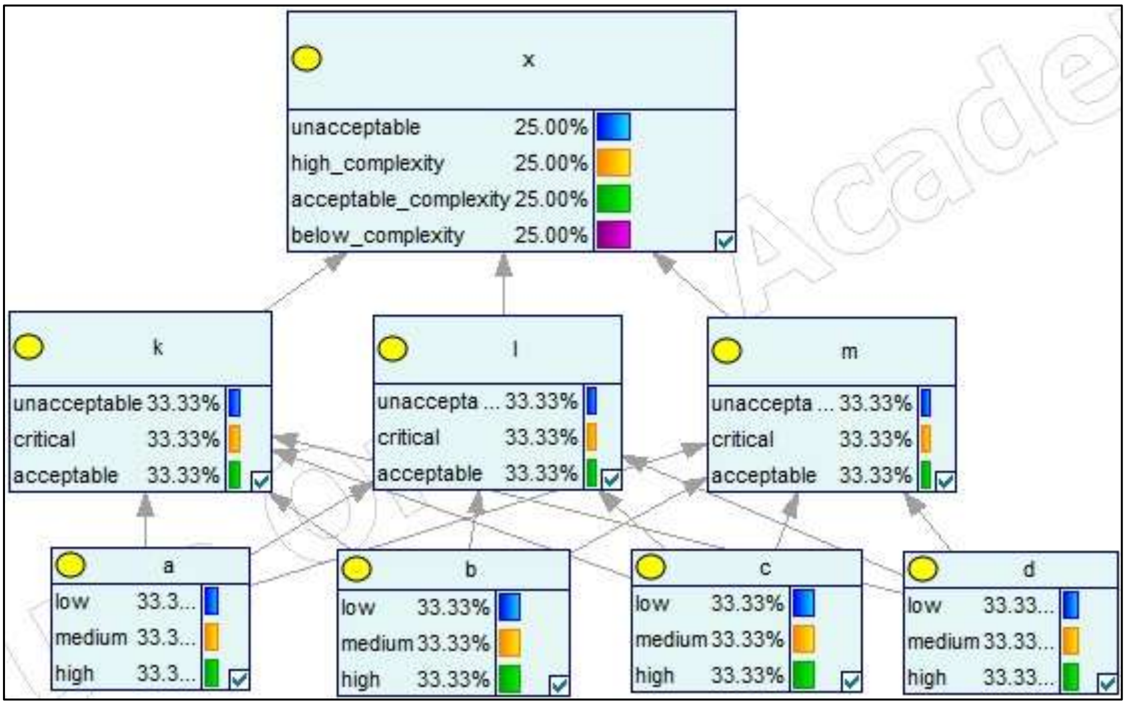

Figure 16: Conditional probabilities of state space.

- Step 4: After using the Model Walkthrough approach to validate the model, where we compare the BN model results with experts' expectations, inferences can be made using the Bayesian network. For example, we could estimate the complexity of "x" when the variables a, b, c, and have high quantities

3.1.6. Brazilian Airspace Capacity

In Brazil, the DECEA (Department of Airspace Control) is responsible for measuring the capacity of ATC sectors (DECEA, 2014), according to analytical model presented in equation 19.

Equation 19: Capacity of ATC Sectors

$$\mathrm{Nref} = \frac{\mathrm{T} * \alpha_{\mathrm{n}}}{(\mathrm{Tcom} + \mathrm{TTS}) * 1{,}30}$$

Where:

• Nref is the measured reference capacity of an ATC Sector, which is the air traffic volume that an Air Traffic Controller (ATCo) is able to operate simultaneously.

• T is the average time of permanence of an aircraft in a sector (in seconds).

• α_n is the convergence factor that has the role of minimizing discrepant effects in large sectors.

• Tcom is the average time of communication between the ATCo (transmission and reception) with the aircraft (in seconds).

• TTS is the average time spent by the ATC in secondary duties (in seconds), such as coordination tasks, filling the flight progress strip, updating radar screens and any other possible unavoidable activity to air traffic control, except for the use of communication channel with the aircraft;

• 1,30 is the cognitive factor that refers to the ATCos mental state during the time spent in the tasks of planning, organizing the air traffic and managing the surveillance radar.

This model is based on the workload of the ATCo, where it is expected that sectors that require a lot of communication between ATCo and pilot, represented in the formula by Tcom, have a lower capacity, theoretically having more complexity in the activities. Although ATCo has the perception of some factors that make his or her routine more complex, the DECEA does not have a defined complexity model, so the relationship between complexity and workload is not evident.

In order to determine the capacity of the ATC (Air Traffic Control) sectors, DECEA considers only optimum air traffic coordination and sequencing conditions. Thus, all operational teams are considered with the same operational performance; all radio navigation equipment and visual aids are considered, technically and operationally, without restriction; and all communications equipment (VHF / Telephony) are considered operational. The collected data must be avoided at times that demonstrate meteorological instability, military operations and festive events and holidays (DECEA, 2014).

3.1.7. UAS as Complexity Factor

Considering that ICAO has defined in (ICAO, 2015a) that it will treat UAS only as RPA (Remoted Piloted Aircraft) in non-segregated airspace, a concern of the ATCo is, in case of C2 link failure, to know what will be the procedure adopted by the aircraft.

UAS has a relatively unpredictable operating performance, increasing ATCo's workload, i.e. reducing airspace capacity. In (NETO et al., 2017b), this integration was modeled, considering UAS as ATC complexity variable. Using the DECEA model to calculate airspace capacity, the impact that this type of operation could have on the capacity of the system was presented.

The tool used for the simulations was TAAM, which is widely used for air traffic simulation as a fast-time gate-to-gate simulator. In TAAM, it is possible to measure the activities developed by ATCo using the time required to perform them and to define the types of aircraft used in the simulation. For each scenario, with a stipulated simulation time, the ATCo workload for performing all tasks was defined. Considering UAS as B737, we created several tasks for ATCo, such as the one presented in table 6.

Table 6 - Duration (in seconds) of additional activities for UAS integration

Activity	Pessimistic	Realistic	Optimistic
Surveillance for the RPA	40.05	30	19.95
Surveillance for other traffics in the RPA vicinity	40.05	30	19.95
Anticipation of instructions	13.34	10	6.66
Anticipation of Traffic Planning	14.15	10	5.85
Coordination to TWR about RPA traffic	15.07	10	4.93
Additional information to TWR	5.7	5	4.3
Receiving TWR requests	13.05	10	6.05
Run TWR requests	15.07	10	4.93

Source: (NETO et al., 2017b).

Considering that UAS is remotely piloted (RPAS), we also modeled situations where there was a loss of C2 (command and control) link between pilots and aircraft, as shown in Table 7. In this case, UAS may perform different procedures, such as landing at an alternate aerodrome, returning to the origin, or proceeding to the destination.

Table 7 - Duration (in seconds) of additional activities for UAS integration

Activity	Pessimistic	Realistic	Optimistic
Coordination to ACC about RPA traffic	34.01	25	15.99
Additional information to ACC	20.3	15	9.7
Planning Traffics	20.02	15	9.98
Information to traffics about RPA	38.4	30	21.6
Instructions to traffics	38.4	30	21.6
Information about RPA localization	68.4	50	31.6
Complementary information	4.15	10	5.85

Source: (NETO et al., 2017b)

For the modeling of task execution times, it was considered low familiarity of ATCo with the insertion of UAS into the non-segregated airspace. However, considering that this flight becomes familiar to ATCo, the workload will gradually decrease until it becomes the same one used to control conventional aircraft. This configuration will be treated as the system maturity level, called TML (Technology Maturity Level), according to(BAUM et al., 2018).

The TML is a systematic metric/measurement approach that supports assessments of the familiarity of ATCo with a particular aircraft. The levels represent the familiarity, which may increase throughout the years of aircraft operation (i.e., considering the increase of liability, social acceptance, and operational exposure). Thus, the type of aircraft, UAS, for example, may be referred to as its TML level to simplify the workload evaluation (BAUM et al.,2018). Considering (MARCZYK, 2014), fragility is a product of complexity by the uncertainty (equation 20). In this context, TML represents uncertainty in operation.

Equation 20: Uncertainty

$$Complexity\ X\ Uncentainty = Fragility$$

For each TML, a fator multiplication was presented, as shown in table 8.

Table 8 - TML multiplication factors

TML	Description	Multiplication Factor	Additional Activities
10	High Operation Certainty	1	X
9	Acceptable Operation Certainty	1.1	X
8	Considerable Operation Certainty	1.2	X
7	Extensive Exposure to Operations	1.3	X
6	Small Exposure to Operation	1.4	✓
5	Operation Beginner	1.5	✓
4	Pre-Operation	1.6	✓
3	Reduced Operation Uncertainty	1.7	✓
2	Considerable Operation Uncertainty	1.8	✓
1	High Operation Uncertainty	1.9	✓
0	Incipient Technology	2	✓

Source: (BAUM et al.,2018)

We consider different percentages of UAS in the fleets (fleet 1 to 6) and due to the variation in complexity, there is variation in the workload of ATCo as shown in Figure 33. Considering different AGES (treated in (BAUM et al., 2018) as periods), due to the increase of TML for UAS, that is, over time the greater the familiarity with the UAS and the workload of ATCo is smaller than currently presented, as shown in Figure 17 and 18.

Figure 17 - Variation of ATCo workload considering the increase of UAS Fleet with low TML.
Source:(BAUM et al.).

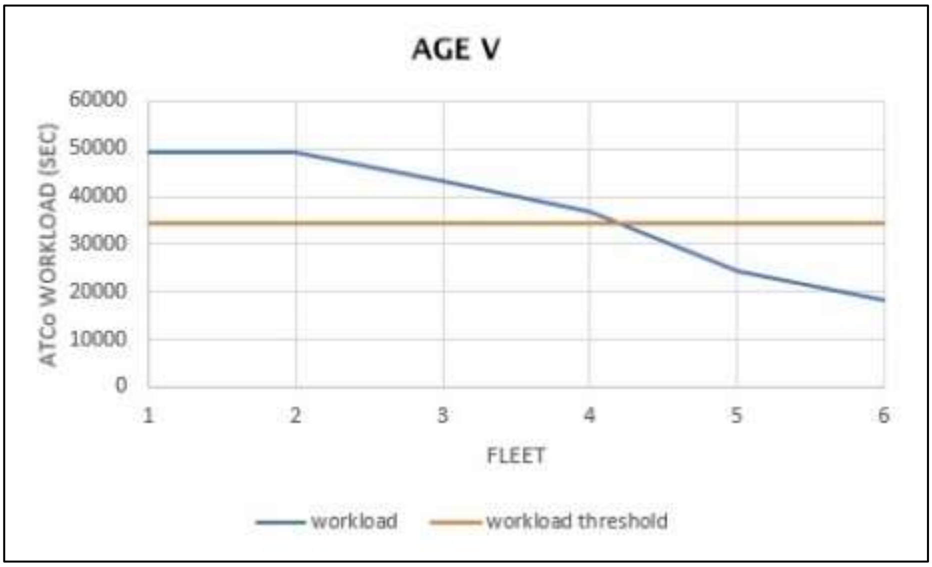

Figure 18 - Variation of ATCo workload considering the increase of UAS Fleet with high TML.
Source: (BAUM et al.)

In (BULUSU; POLISHCHUK, 2017) is presented a mathematical method for airspace capacity estimation for UAS traffic management. According (BULUSU; POLISHCHUK, 2017) conventional approaches using air traffic complexity measures based on controller workload become less relevant with the advent of automated unmanned aircraft systems and unmanned aviation needs unmanned traffic management to the extent possible.

Future UAS operations may be free flight by nature i.e. individual flights could prefer responsibility for determining their own courses independent of a global plan or system.

The generic capacity definition is the size of the largest de-confliction problem observed for a given traffic density. Assuming a minimum allowable separation between two UASs, the measure of the airspace capacity is therefore the range, where the probability that the computed metric exceeds the acceptable size of the largest de-confliction problem, shows a phase transition threshold, i.e., the capacity has been reached threshold capacity.

For this analysis, it is used a random geometric graph (RGG), defined as a graph whose nodes are n randomly placed points in a given region, and whose edges connect two vertices u and v if and only if the distance between them is less than r: |uv| < r. Each connected component of the graph thus represents a set of aircraft to be jointly de-conflicted (called a cluster),as shown in figure 19.

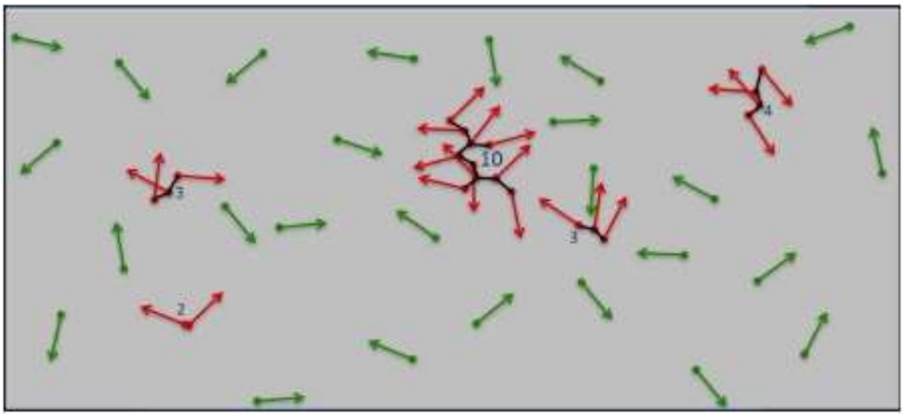

Figure 19: Airspace Snapshot with cluster sized indicated.
Source: (BULUSU; POLISHCHUK, 2017)

It is considered that UAS execute vertical take-off, and landing and flying on a fixed flight level, presented in figure 20, as proposed in (BULUSU; SENGUPTA; LIU, 2016).

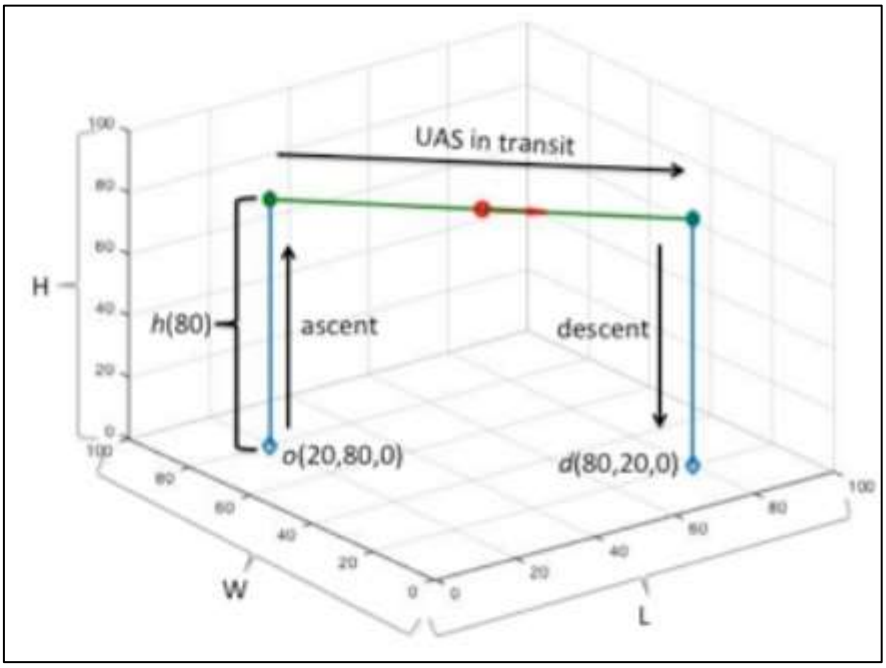

Figure 20: Typical UAS Flight.
Source: (BULUSU; SENGUPTA; LIU, 2016).

In (PANG et al., 2020) conducted airspace complexity studies considering FFO (Free Flight Operation) and TBO (Trajectory-Base Operation) concepts with the presence of UAS.

FFO has more movement freedom for aircraft to operate. However, with the increase of flight flexibility, the airspace complexity will rise accordingly, given the traffic density is unchanged. While for the TBO, the operational efficiency will be sacrificed due to the movement freedom constraints that aircraft only allow to operate based on waypoint. But, on the other hand, the TBO will help to reduce the airspace complexity by limiting the movement freedom of aircraft. For TBO, operations will be allocated in different altitude and route to avoid collisions and congestions.

3.2. Conclusion

The concepts presented in this chapter are foundational for the development of the model used in this research.

Considering that this work explores only the UAM environment, it proposes:

- To replace ATCo with a computational tool for issuing instructions to aircraft.
- That aircraft will be unmanned eVTOL (UAS).
- The need for defining airspace structure and air traffic rules.

- The need for understanding that complexity affects airspace capacity, without considering the presence of ATCo. The complexity variables composing the complexity model discussed later will be chosen based on the variables and models presented in the current chapter.

According to (BING, 2014), the interaction between aircraft depends on of air traffic flow and airspace structure. Thus, certain situations occurring in the same way in different sectors or different moments may present different levels of complexity. The concept of dynamic complexity captures precisely this idea.

Following the definitions presented by (BING, 2014) and (SIMON, 1976), apud (LEMES, 2012), the model will yield dynamic results based on different circumstances of air traffic flow and will feature a behavioral average for each scenario.

This work will consider the interaction between air traffic flow and airspace structure to construct a complexity index based on the behavioral average for each scenario, which will, in turn, be simulated one hundred times. Scenarios with the same variables and the same number of aircraft may present different complexity indices depending on the circumstances of air traffic flow.

4. DISCUSSION OF COMPLEXITY MODELS APPLIED TO AIR TRAFFIC

In order to present relevant concepts about air traffic, it is presented in Appendix A - air traffic concepts, air traffic rules and airspace structure and key concepts.

This research aims to present a capacity model based on the complexity of the airspace. For this, it is necessary to devise a strategy for defining complexity.

According to (MAJUMDAR; POLAK, 2001b), in areas of high air traffic density, a widely used measure of capacity is based on the workload of ATCo. It is, therefore, essential that the factors affecting workload are known — these are called complexity factors and encompass air traffic complexity, cognitive complexity, and dynamic density (OCHIENG, W.; MAJUMDAR, 2002).

Considering that all complexity models applied to air traffic have ATCo workload as one of the main variables of the system, we can see (author's italics):

1) Dynamic Density: it presents complexity variables and their respective weights. A complexity index is presented, using a linear regression method. However, the variables that make up the model vary from location to location and are presented in a static way, not being considered factors in real time. There is no correlation between the complexity index presented and its impact on airspace capacity.
2) Macroscopic Workload Model: it presents variables that assess the behavior of air traffic and airspace structure and does not establish a relationship with airspace capacity
3) Tactical Load Smoother: Although it presents a dynamic airspace index, it only considers variables related to aircraft trajectories and airspace structure. An ATCo workload dashboard is proposed.
4) Dynamic System: It presents a dynamic index of airspace complexity, considering only variables related to aircraft trajectories. No relationship is established between the presented complexity index and the airspace capacity.
5) Brazilian Airspace Capacity: Using mathematical modeling, it presents the capacity of airspace in terms of the number of aircraft that can fly

simultaneously. DECEA considers only the following variables: average time the aircraft is in the sector, time it takes for ATCo to perform their task and the estimated average time used for ATCo reasoning. The value shown is statistical and regardless of the present conditions is not changed (does not consider the current time). Although an airspace capacity is presented, the model does not have any index of complexity.

6) Bayesian Network: The assembly of the Bayesian network implies classifying variables of interest and relating them, usually using the literature review or experts. The result is a probability that a given state will happen according to the presented Bayesian network. Each complexity variable, as well as the complexity index, is composed of states, also defined in the literature or by experts. By setting a given state for one of the network's complexity variables, it is possible to understand the impact on the complexity index. Using a Bayesian network to calculate complexity, we can select variables with different levels and connect them — with the links leading to the outcome. Thus, it is possible to carry out forward and backward analyses on the model, verifying, for example, what the result will be by fixing the value of a given input variable. However, a disadvantage of the model is that it requires participation from experts and a considerable degree of subjectivity for selecting the variables and assembling the network. Another challenge is to present the model's validation processes.

The method of Bayesian Network (BN) integrates qualitative and quantitative analyses, which allows it to incorporate many types of information, such as backward reasoning, and inference in incomplete data sets. The above advantages make BN superior to other artificial intelligence methods in safety evaluation of civil aviation (WANG; GAO, 2013). BN can be constructed either manually, based on knowledge and experiences acquired from previous studies and literature, or automatically from data.

Bayesian estimation of conditional probabilities is important in a subjective estimation of risk as it allows the distributions of the aleatory model parameters in a model to be updated as new knowledge becomes available (GOODHEART, 2014).

Considering the interest in using BN for the development of the complexity model, advantages and disadvantages will be highlighted.

Advantages:

- BN makes it possible to select variables with different levels and connect them — with the links leading to the outcome. Thus, it is possible to carry out forward and backward analyses on the model, verifying, for example, what the result will be by fixing the value of a given input variable.
- It is possible to consider all the variables of interest in the model, based on the literature, connect them, and understand the impact of each variable on the others and on the model's outcome. Although validation can be challenging, the model is highly flexible.
- The model can be easily updated with new variables or updated results.
- There is the possibility of inserting the complexity model in TUSO (Trajectory-Base UAM Operations Simulator + Optimizer), allowing the complexity index to be made available in real time. TUSO is the proposed tool to present aircraft sequencing/separation solutions. The tool is under development and the proposal is that the model developed in this work be inserted in TUSO for dynamic reading of airspace capacity. The role of TUSO in this research will be discussed in greater depth later.

Disadvantages:

- For each variable that will compose the model, the conditional probabilities must be presented, requiring a tool to define these probabilities [12].
- The choice of variables that will compose the model will depend on experts or literature.
- The construction of the Bayesian network requires analysis by experts, as well as the validation of the model.

[12]. This research, as discussed later, uses Netlogo as the computational tool to define conditional probabilities."

Conclusion: Since it was possible to find reasonable solutions for each of the disadvantages above, the Bayesian Network is a powerful method for assembling the complexity model. Before the complexity model is presented, the theory of Bayesian Network is discussed in the next section.

Before the structure of the complexity model is presented, appendix B presents Bayesian Network Concepts

4.1. Bayesian Network Applications: A Literature Review

When developing a causal probabilistic model, i.e., a Bayesian Network (BN), it is common to incorporate expert knowledge of factors that are important for decision analysis but where historical data are unavailable or difficult to obtain. This happens, mainly, when development BN for practical application, such air traffic surveys.

In some cases, the distribution of some continuous variable in a BN is know from the data, but we wish to explicitly model the impact of some additional expert variable. (CONSTANTINOU; FENTON; NEIL, 2016) provide a method for eliciting expert judgment that ensures the expected values of a data variable are preserved under all known conditions, as presented in figure 21.

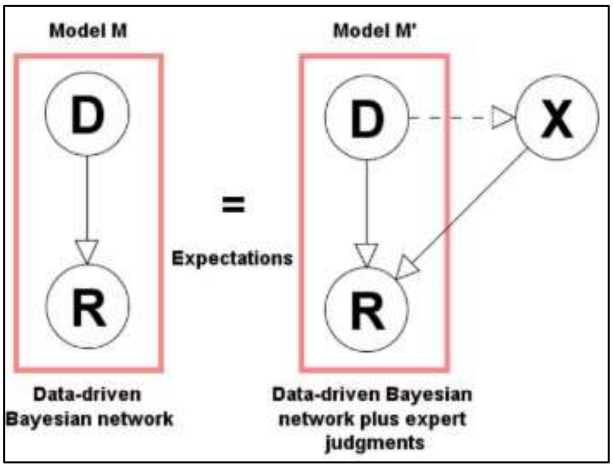

Figure 21: Concept where model M extend to model M’ and the expectations are preserved.
Source: (CONSTANTINOU; FENTON; NEIL, 2016).

Using BN, the number of publications in the most varied fields is considerable, so will be presented some works developed related to air traffic.

The Air Traffic Management (ATM) industry has long known that optimizing performance involves a delicate balance between different areas of performance. (RANIERI, 2015) proposed a model to identify and assess the magnitude of interdependencies between performance indicators, based on a probabilistic approach which takes into account the great variability in ANSPs performance due to both endogenous and exogenous factors as well as the uncertainty implied by future changes in the operational context. The model was built applying a combination of data-driven process with manual adjustments, based on experience and knowledge. Figure 22 shows the performance model’s structure.

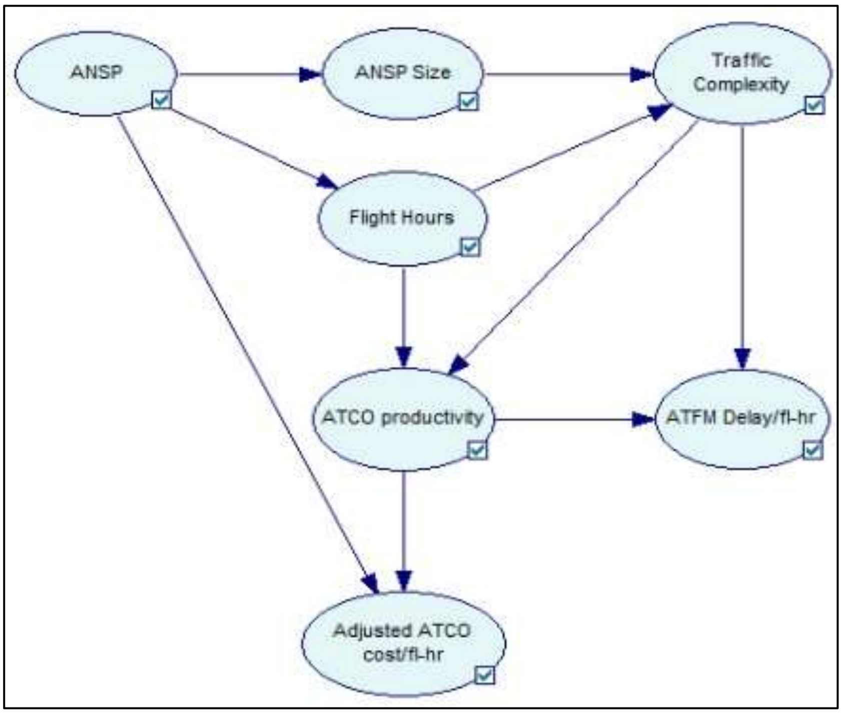

Figure 22: Performance model’s structure.
Source: (RANIERI, 2015).

(KAYA; INALHAN, 2014) presented a new model for predicting departure, en-route, and arrival delays simultaneously before departure as well as during the course of flight. The proposed model is a Dynamic Bayesian Belief Network (DBBN), considering temporal, operational, spatial (other delays at the same airport), traffic, and hidden variables. The propagation model provides the relationships between parameters effecting delays depending on time, space, and airport delay states. Using this, one can do a dynamic prediction of departure, en-route, and arrival delay at some specific time before the scheduled departure. It has been observed that as DBBN propagates its belief the accuracy of the predicted variable increases continuously.

In (PEPPER; MILLS; WOJCIK, 2003) was presented a method of accounting for uncertain weather information at the time of TFM (Traffic Flow Management) decisions, based on Bayesian decision network.

The air traffic control (ATC) system is critical in maintaining the safety and integrity of the National Airspace System (NAS) and requires the information fusion from various sources. (WANG et al., 2018) proposed hybrid network model called the Bayesian-Entropy Network (BEN) that can handle various types of information. The BEN method is a combination of the Bayesian method and the Maximum Entropy method. The Maximum Entropy method introduces constraints and is given as an exponential term added to the classical Bayes' theorem.

(COMENDADOR et al., 2018) and (COMENDADOR et al., 2019) proposed a method to Capacity Optimization in Trajectory-Based Operations. The objective is to identify the impact of trajectories' uncertainty, called complexity metrics, in existing complexity methodologies. The analysis of the main complexity metrics that have been developed for the application in ATM, together with the opinion of sector experts, has allowed identifying the elements (called Complexity Generators), which can be key to the definition of complexity in Capacity Management.

According (COMENDADOR et al., 2018) BN have been selected to assess the uncertainty propagation for complexity in ATM because their following capabilities:

- Are useful to capture and analyze causality and influence relationships.
- Are primarily used to update the probability distribution over the states of a hypothesis variable.
- Provide a convenient and coherent way to represent uncertainty in uncertain models and are increasingly used for representing uncertain knowledge.
- Due to the conditional dependence relationships of the variables within the network, BNs offer the ability to either predict or diagnose; and
- Allow for qualitative cause and effect assessment as well as for and quantitative updated on the probability distribution of non-observable variables.

A runway incursion is a major concern of the dynamics of aircraft movement at an airport. In (ICAO, 2016b) defines that runway incursion is any occurrence at an aerodrome involving the incorrect presence of an aircraft, vehicle or person on the protected area of a surface designated for the landing and take-off of aircraft.

(GOODHEART, 2014) proposed a method for structuring a Bayesian network using quantitative and qualitative event analysis in conjunction with structured expert probability estimation is outlined and results are presented for propagation of evidence through the model as well as for causal analysis.

For this analysis (GOODHEART, 2014) uses an Assessment of the adequacy of elicited data has been mentioned briefly in previous discussions of feedback and over-fitting, both of which serve as tools for evaluation of expert-derived data. Feedback was presented to expert panelists to confirm that the assumed distribution form is a reasonable representation of each expert’s ideas, as presented in figure 23. Using this set of variables, an initial model structure was constructed from 58 variables within the organizational, operational, human factors, weather, and technological domains, and after iterative review by experts.

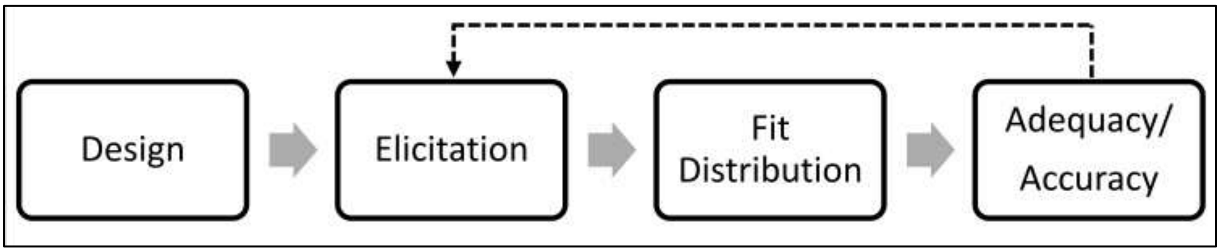

Figure 23: Expert elicitation process overview.
Source: (GOODHEART, 2014).

Another concerning factor for air transport is flight delays, as they impact the entire system, causing inconvenience and potentially generating unnecessary expenses. Flight delays and safety are the principal contradictions in the sound development of civil aviation. In (WANG; GAO, 2013) it was proposed the safety assessment model of civil aviation by BN, which considered the composition of civil safety risk based on flight delays, the randomness of civil aviation safety risk variation, the change rules of civil aviation safety risk based on flight delays.

The fact is that aviation is an extremely complex segment that involves a considerable number of variables and players. Most decisions in aviation regarding systems and operation are currently taken under uncertainty, relaying in limited measurable information, and with little assistance of formal methods and tools to help decision makers to cope with all those uncertainties. (VALDÉS et al., 2018) proposed three main ways in which Bayesian networks are currently employed for scientific or regulatory decision- making purposes in the aviation industry, depending on the extent to which decision makers rely totally or partially on formal methods: the Bayesian reasoning assumes the entire process of evaluation and decision, Bayesian methods can be used just to estimate probability distributions and, Bayesian methods can be used to select or parameterize input distributions for a probabilistic model.

Considering the mission planning process of UAVs, there are many assessment indicators, complex constraints, high system integration, and close correlation with specific mission characteristics. (WANG et al., 2019) proposed a mission planning quality assessment method based on static Bayesian network, which realizes an objective and quantitative assessment of mission planning results. Considering the concern of manned and unmanned aircraft flights in the same airspace, (CORRÊA, 2008) proposed a model based on Bayesian networks in order to obtain estimates of uncertainties for risks caused by random events, such as the unexpected approach of a another aircraft.

5. URBAN AIR MOBILITY (UAM) AND UNMANNED AERIAL SYSTEM (UAS)

5.1. General Concepts

In many parts of the world, each year, ground traffic increases resulting in longer commute times with significant economic costs. (SCHRANK; EISELE; LOMAX, 2019) presented the trends about congestion from 1982 to 2017, as shown in table 9, and it comes evident that congestion is a persistently growing problem. The metrics used were:

- *Yearly delay per auto commuter – The extra time spent during the year traveling at congested speeds rather than free- flow speeds by private vehicle drivers and passengers who typically travel in the peak periods.*
- *Travel Time Index (TTI) – The ratio of travel time in the peak period to travel time at free-flow conditions. A Travel Time Index of 1.30 indicates a 20-minute free-flow trip takes 26 minutes in the peak period[13].*
- *Planning Time Index (PTI) – The ratio of travel time on the worst day of the month to travel time in free-flow conditions. Wasted fuel – Extra fuel consumed during congested travel.*
- *Congestion cost – The yearly value of delay time and wasted fuel by all vehicles.*

Truck congestion cost - The yearly value of extra operating time and wasted fuel for commercial trucks.

Table 9 – Congestion Impacts

Measures of...	1982	2000	2012	2017	5-Yr Change
... Individual Congestion					
Yearly delay per auto commuter (hours)	20	38	47	54	15%
Travel Time Index	1.10	1.19	1.22	1.23	1 Point
Planning Time Index (Freeway only)	--	--	--	1.67	--
"Wasted" fuel per auto commuter (gallons)	5	16	20	21	5%
Congestion cost per auto commuter (2017 $)	$610	$920	$970	$1,080	11%
... The Nation's Congestion Problem					
Travel delay (billion hours)	1.8	5.3	7.7	8.8	14%
"Wasted" fuel (billion gallons)	0.8	2.5	3.2	3.3	3%
Truck congestion cost (billions of 2017 dollars)	$1.8	$7.0	$14.5	$19.5	35%
Congestion cost (billions of 2017 dollars)	$15	$75	$150	$179	19%

Source: (SCHRANK; EISELE; LOMAX, 2019).

[13] A 30% surcharge on travel time. In the case of a 20 min travel, it will take 26 minutes.

In addition to several strategies to solve the problem of traffic congestion (creation of viaducts, new roads or traffic restrictions at certain times and locations), a concept that started with the use of helicopters and evolved to a broader technological development is Urban Air Mobility (UAM).

UAM is defined as safe and efficient air traffic operations in a metropolitan area for manned aircraft and unmanned aircraft systems (THIPPHAVONG et al., 2018). An example to UAM is that there are over 400 helicopters traveling between a network of more than 250 helipads in São Paulo, Brazil (VASCIK; HANSMAN, 2017). According (BRADFORD; KOPARDEKAR, 2020) (UAM) enables highly automated, cooperative, passenger or cargo-carrying air transportation services in and around urban areas .

The literature also presents the ODM (On Demand Mobility) as a multi-modal transportation capacity in which individuals have access to immediate and flexible high-speed transportation, which can incorporate air travel, to take them safely and efficiently from one location to another over ranges from approximately 10 to miles (PATTERSON; ANTCLIFF; KOHLMAN, 2018), considering manned or unmanned aircraft. Due to the way it is presented in the literature, we will consider ODM to be synonymous with UAM.

Although the first aircraft used in the UAM concept were helicopters using the conventional concepts of air navigation and air traffic control, such as the São Paulo helicopter control area, ODM (on demand mobility) for Aviation is an emerging concept that leverages increased connectivity through smartphones to enable the real-time matching of consumers and service providers for multimodal, point-to-point transportation via networks of novel vertical takeoff and landing (VTOL) aircraft (VASCIK; HANSMAN, 2017). Aviation technologies and concepts have reached a level of maturity that may soon enable an era of on-demand mobility fueled by quiet, efficient, and largely automated air taxis (MUELLER; KOPARDEKAR; GOODRICH, 2017).

Several projects are under development for application at UAM. An example is eVTOL (Electric Vertical Take Off and Landing), considerably cheaper compared to helicopters, which can be used for inspection, transportation of valuables and people, with a market potential of US $ 74 billion and 23,000 units by 2035 (PORSCHE, 2018). The forecasts are that, with the use of 4000 eVTOL, 55,000 air taxi flights will take place every day in the United States (BOOZ; ALLEN; HAMILTON, 2018).

While eVTOL aircraft presented a compelling case to constitute a new form of transportation, reduce congestion, and overcome the geographic constraints of ground mobility modes, their success was hindered by a number of operational challenges including (VASCIK; HANSMAN, 2017):

- Availability of geographically distributed ground infrastructure co-located with areas of customer demand;
- Integration of urban air transportation operations with Air Traffic Control (ATC) and the potential need for a new, automated ATC system to manage airspace below 3000 ft;
- Murky legal and regulatory jurisdictions for low altitude airspace;
- Acquiring widespread community acceptance of vehicle noise; and
- Lack of a computerized customer booking and demand scheduling system.

In (VASCIK; HANSMAN, 2017) was presented TOLA (“Takeoff and Landing Area) concept: any location an ODM aircraft may depart from or arrive at. Depending upon the VTOL capabilities of future aircraft, the generic term TOLA may represent a wide variety of infrastructure ranging from an airport to a heliport or even perhaps a parking lot or empty road. Numerous terms for novel takeoff and landing infrastructure for ODM aircraft have been proposed in the literature: vertiport, vertipad, pocket airport, skypark, skynode and skyport.

The scalability of ATC is expected to become an increasingly more significant issue for aviation due to the proliferation of UAS for both commercial and hobbyist purposes as well as the anticipated emergence of large-scale UAM systems that aim to provide passenger services within metropolitan areas (VASCIK et al., 2018). These new vehicles will frequently operate within 915 m (3000 ft) of the ground, in close proximity to one another or obstacles, and under the auspices of less experienced or even amateur onboard or remote pilots. As a result of these characteristics, the emerging UAS and UAM industries are anticipated to challenge the safe and efficient management of the National Airspace System (NAS) through current ATC methods.

According (PATTERSON; ANTCLIFF; KOHLMAN, 2018) ATC interaction was perceived as a potential challenge because as ODM Aviation networks increase in scale, their need for low altitude ATC services may substantially increase compared to the volume of flights handled today by air traffic controllers. As a result, the workload may exceed the current system's capacity to support. If this were to occur, an air traffic controller may not permit some ODM operations to enter controlled airspace.

According to (VASCIK; HANSMAN, 2018) the ability of UAM aircraft to reliably access and conduct high density operations within controlled airspace constitutes an Air Traffic Control (ATC) constraint. Current ATC procedures are anticipated to be insufficient to handle a large number of new UAM aircraft as a result of air traffic controller workload limitations and the required separation minima.

The Furthermore, current separation standards within controlled airspace likely prohibit operations of significantly greater density than current-day operations (VASCIK; HANSMAN, 2017).

If we think about the evolution of demand at UAM, we find that the use of the conventional airspace structure, as well as the separations used (radar or not radar), in addition to the existing ground infrastructure, will compromise the growth of this concept.

Then, there is a need to develop concepts that specifically deal with UAM, understanding the technical and operational characteristics of the aircraft that make up the UAM environment.

5.2. Concept of Operations (ConOps)

Based on Los angeles case study, with twelve reference missions, one Concept of Operations (ConOps) is proposed in (VASCIK; HANSMAN, 2017) for ODM aviation flight, describing of sequence of steps for ODM Aviation, as presented table 10.

Table 10: Concept of Operations for ODM aviation

ConOps Step	Description
Initiation	Customer Submits a travel request
1	Aircraft routed to nearest TOLA
2	Customer takes ground transportation from origin to TOLA
3	Customer arrives at TOLA and is prepared for takeoff Sought
4	Flight Segment
5	Aircraft arrives at destination and customer disembarks
6	Customer takes ground transportation to final destination
7	Aircraft charges batteries

Source:(VASCIK; HANSMAN, 2017).

For each of the steps presented at ConOps, some Potential Operational challenges are identified (table 11). This research will highlight the flight segment.

Table 11: Potential Operational challenges

Mission Conops Steps		Potential Operational Change
0	Customer submits a travel request	None
1	Aircraft routed to nearest TOLA (Takeoff and Landing Area)	1. Where are ODM aircraft staged? 2. How is TOLA congestion and priority handled?
2	Customer takes ground transport from origin TOLA	3. Where are private automobiles parked? 4. How close is a TOLA to the customer origin location?
3	Customer arrives at TOLA and is prepared for takeoff	5. How does a customer access the TOLA? 6. What is the turn-time for the aircraft at the TOLA? prepared for takeoff 7. How is TOLA safety and security provided?
4	Flight Segment	8. How do ODM aircraft interact with ATC to access controlled airspace? 9. How do ODM aircraft fly safety with increased densities of vehicles in the airspace, particularly sUAS? 10. How do ODM Aviation address noise annoyance to bystanders?
5	Aircraft arrives at destination and customer disembarks	11. How is TOLA congestion and priority handled? 12. Is an alternative safe landing location available and what are the energy reserve requirements? 13. How does a customer egress from the TOLA? 14. What is the turn-time for the aircraft at the TOLA? 15. How is TOLA safety and security provided?
6	Customer takes ground transport to final destination	16. How close is a TOLA to the customer destination?
7	Aircraft recharges batteries	17. What is the required time for aircraft charging?

Source: (VASCIK; HANSMAN, 2017)

In (EMBRAER; ATECH; HARRIS, 2019) is proposed a concept Urban Air Traffic Management (UATM). Similar to ATM, the concept of UATM arises as a system that will use strategically designed airspace structures and procedures to ensure urban flights remain safe and efficient while minimizing the impact on ATM (EMBRAER; ATECH; HARRIS, 2019). Figure 24 shows the airspace structure considering ATM, UATM and sUAS.

UATM is a system that will use strategically designed airspace structures and procedures to ensure urban flights remain safe and efficient while minimizing the impact on ATM.

Figure 24: ATM, UATM and sUAS.
Source: (EMBRAER; ATECH; HARRIS, 2019).

According (EMBRAER, 2019) is proposed that the urban airspace of the future will be structured with routes, corridors, and boundaries that will define where UAM aircraft may fly with procedures and airspace structures will remain the foundation of airspace management. In (EMBRAER; ATECH; HARRIS, 2019) was proposed a single entity, an urban airspace service provider (UASP), that will be responsible for managing low-altitude urban air traffic. In close collaboration with ATM, USSs, and UATM stakeholders, the UASP will deliver a suite of services. It will also manage traffic in the cruise phase of flight as aircraft operate between skyports.

The table 12 describes each service and its role in supporting the UATM system.

Table 12: UATM System

	UATM SERVICE AIRSPACE
FOUNDATIONAL SERVICES: that must be established before UAM operations begin UATM	AIRSPACE AND PROCEDURE DESIGN: Creating urban airspace routes, corridors, and procedures
	INFORMATION EXCHANGE Exchanging airspace and flight information with all stakeholders
OPERATIONAL SERVICES: Services that are delivered on a daily basis to manage airspace and flights	FLIGHT AUTHORIZATION Authorizing registered aircraft and pilots for flight in UATM airspace
	FLOW MANAGEMENT Spacing aircraft to maintain the integrity of the UATM operation
	DYNAMIC AIRSPACE MANAGEMENT Managing routes, corridors, and airspace boundaries dynamically
	CONFORMANCE MONITORING Ensuring flights conform to flight and assisting pilots during off-nominal situations

Source: (EMBRAER; ATECH; HARRIS, 2019).

With the need to provide a common frame of reference to support the FAA, NASA, industry and other stakeholder, (BRADFORD; KOPARDEKAR, 2020) proposed a Concept of Operations (COnOPs 1.0), considering the aircraft performance of eVTOL[14] .

As presented in (BRADFORD; KOPARDEKAR, 2020), UAM aircraft operate between UAM aerodromes (“aerodromes”) within UAM Corridors – a performance-based airspace of defined dimensions in which aircraft abide by UAM specific rules, procedures, and performance requirements.

In table 13, according (BRADFORD; KOPARDEKAR, 2020), is presented a comparison between the Initial UAM Operations, ConOps 1.0 operations and Mature State Operations. For this, must be observed the following key indicators:

- Operational time: representation of the density, frequency, and complexity of UAM operations. Time evolves from a small number of low complexity operations to a high density and high rate of complex operations.
- UAM structure (airspace and procedural): the level of complexity of infrastructure and services that support the UAM environment. Structure

[14] In this research we use VTOL indiscriminately, understanding that the operational behavior is similar to eVTOL.

evolves from current helicopter routing to UAM-specific corridors and associated performance requirements and procedures that reduce operational complexity.

- UAM driven regulatory changes: existing regulations may evolve from current regulations to address the needs for UAM operations' structure and performance.
- UAM CBRs (Community Bases Rules): CBRs augment the UAM-driven regulations to establish the expectations of UAM Operators and PSUs (Providers of Services for UAM). CBRs are developed by industry based on FAA guidelines and require FAA approval to address elements covered by FAA authority (e.g., NAS safety, DCB, equitable access to airspace, security).
- Aircraft automation level: the level of PIC (Pilot in Command) engagement with the UAM aircraft enabling systems. The following categories describe the evolution of aircraft automation:
  - Human-within-the-Loop (HWTL):
    - Human is always in direct control of the automation (systems).
  - Human-on-the-Loop (HOTL):
    - Human has supervisory control of the automation (systems).
    - Human actively monitors the systems and can take full control when required or desired.
  - Human-over-the-Loop (HOVTL):
    - Human is informed, or engaged, by the automation (systems) to take action.
    - Human passively monitors the systems and is informed by automation if, and what, action is required.
  - Human is engaged by the automation either for exceptions that are not reconcilable or as part of rule set escalation.
- Location of the PIC (Pilot in Command): the physical location of the PIC. UAM operations will evolve from a PIC onboard the UAM aircraft to remote UAM PICs.

Table 13: Initial UAM Operations, ConOps 1.0 operations and Mature State Operations

	Initial UAM Operations	ConOps 1.0 Operations	Mature State Operations
Operational tempo[15]	Low.	The operational tempo is low; however, the operational time will have increased to a point that requires changes in the existing regulatory framework and procedures.	The operational tempo increases significantly. Higher operational time needs drive the maturity for the other indicators.
UAM structure (airspace and procedural)	Implementation of existing helicopter infrastructure (e.g., routes, helipads, rules and regulations, ATC services). No UAM unique structures or procedures exist.	Operations of UAM aircraft occur within defined UAM Corridors from specific aerodromes based on UAM performance requirements. There is minimal UAM Corridor structure or intersections. ATC tactical separation services are not provided for operations within the UAM Corridors. Tactical separation is allocated to the UAM operators, PICs, and PSUs.	UAM operations continue to occur within UAM Corridors from aerodromes. The UAM Corridors may form a network to optimize paths between an increasing numbers of aerodromes; the internal structure of the UAM Corridors may increase in complexity, and the necessary performance parameters for UAM participation may increase.
UAM driven regulatory changes	Initial UAM operations are conducted consistent with the current rules, regulations, and local agreements.	Changes to ATM regulations and new UAM regulations that enable operations within UAM Corridors.	Additional UAM driven regulations may be necessary to enable operations within UAM Corridors.
UAM CBRs	No CBRs, only existing agreements such as Letters of Agreement (LOAs).	CBRs are defined by industry to meet industry standards or FAA guidelines when specified. CBRs will require FAA approval.	The complexity of CBRs and involvement in the FAA establishing guidelines or approving CBRs may increase.
Aircraft automation level	Consistent with current, manned helicopter technologies.	PICs actively control the aircraft with UAM-specific capabilities. Location.	Automation improvements may lead to HOVTL capabilities.
Location of the PIC	Onboard.	Onboard.	Remote.

Source: (BRADFORD; KOPARDEKAR, 2020).

To assess what determines the capacity limit of a sector, air traffic control literature was reviewed, and various influence factors were identified: Controller workload, separation minima, traffic sequencing, weather airspace geometry, special use airspace, ATC ConOps (i.e., procedure and route design), and Communication, Navigation, and Surveillance (CNS) capabilities.

5.3. Weather Constraints

Weather constraints represent a critical and complex component of characterizing the UAM market. Weather can influence many components of UAM, including operations, service supply, passenger comfort, community acceptance, infrastructure, and traffic management (REICHE; BRODY; MCGILLEN, 2018).

Weather is an ever-present concern for aircraft, both in open space and urban environments. However, in the confined spaces and dense populations that urban centers represent, hazards associated with weather take on special concern.

[15] The density, frequency, and complexity of operations.

According to (GREENFELD, 2019), Urban canyons can result in high-speed winds that could destabilize a UAM vehicle and Urban buildings can increase the blinding effects of heavy rain, snow, or fog placing an extra burden on the C2 (Communication and Control) system to operate efficiently to prevent mishaps. Excessive precipitation could degrade or even block RF signals. Flying blindly is unacceptable, and this possibility needs to be given sufficient study and its consequences incorporated in operating rules.

In (REICHE; BRODY; MCGILLEN, 2018) was defined impact for each weather condition captured in METAR (Meteorological Aerodrome Report) observations. Using extensive expertise in aviation weather as well as available literature on weather influence on UAS and UAM vehicles to define scores for each weather condition captured in METAR observations. “Impact Scores” is from 1 (minimally impactful, little reduction in operations) to 10 (significantly impactful, potential cessation of operations), as shown in table 14.

After evaluated variability of the average impact score distributions, as well as the impact scores themselves, it was determined that an average impact score threshold of 3 provided a robust delineation between minimal and significant potential impacts to UAM operations.

Table 14: Impact Scores for each weather condition from METAR

Weather Condition	Score	Weather Condition	Score
Drizzle	1	Wind 20-25 KT	7
Rain	1	Smoke (<3 NM)	7
MVFR (Marginal VFR) Ceiling[16]	1	LIFR (Low Instrument Flight Rules) Ceiling	7
Haze	1	IFR Visibility	7
Ice Crystals	1	Wind ≥25KT	8
Sand Whirls	1	Sleet	8
Sand	2	Squalls	8
Snow Grains	2	Fog	8.5
Temp≤32^{0}F	3	Freezing Fog	8.5
Temp≥100^{0}F	3	Freezing Drizzle	9
IFR Ceiling	4	Thunderstorms	9
Dust	5	Dust Storm	10
Snow	5	Funnel Cloud/Tornado	10
Sandstorm	5	Freezing Rain	10
Wind 15-20KT	5	Hail	10
Mist (vis≥ $\frac{5}{8}NM$)	6	Volcanic Ash	10
Snow Pellets	6		

Source: (REICHE; BRODY; MCGILLEN, 2018).

[16] Minimum Ceiling to VFR is 1500 ft (450m).

According (EMBRAER; ATECH; HARRIS, 2019), the UATM airspace will be a dynamic place where the status of skyports, corridors and routes will change rapidly. The information exchange will derive data from numerous sources, such as aircraft sensors, weather sensors, skyports, pilots, ATM systems, and USSs. Real-time data regarding weather in the low-altitude airspace will be particularly critical. During the course of daily operations, the UASP will open, close, and move routes, corridors, and airspace in response to traffic demands, weather conditions, emergencies, or any other situation that requires changes to the airspace structure and procedures.

Regarding eVTOL, according (VASCIK; HANSMAN, 2017) there is a need for research and operational experience to identify how the performance of electric aircraft and novel aircraft configurations will degrade in inclement weather such as cold temperatures, reduced visibility, high winds, precipitation and icing conditions.

According to (BRADFORD; KOPARDEKAR, 2020), in the event that aircraft performance is inadequate to maintain required separation within the UAM Corridor due to forecasted or current weather, UAM operators are responsible to take appropriate strategic and tactical action to ensure separation is maintained (e.g., do not take off, exit the UAM Corridor and operate per appropriate airspace rules).

6. CAPACITY MODEL PREREQUISITE FRAMEWORK

In order to present relevant concepts about air traffic, it is presented in Appendix A - air traffic concepts, air traffic rules and airspace structure and key concepts.

6.1. Initial Considerations

The terminology used to present a UAM environment will follow (EMBRAER; ATECH; HARRIS, 2019): UATM.

The proposed Airspace Capacity model will only make sense if implemented in controlled airspace. Thus, before implementing the model, prerequisites must be presented based on the questions below:

1) Will it be a UTM, UATM or ATM environment?
2) What are the aircraft performances? Will they be considered manned or unmanned?
3) What is the airspace structure where the model will be implemented: will it be segregated or not, what are its dimensions and route structure?
4) Which air traffic rules will be considered in the model?
5) What is the level of automation of air traffic control?

6.2. Capacity Model prerequisite framework

Before the proposed airspace capacity model is presented, several questions must be answered first.

6.2.1. Question 1: Will it be a UTM, UATM or ATM environment?

As shown in chapter 6, given the high demand potential of the UAM, many challenges arise with its growth. Although the Concept of Operations has been proposed for the UAM scenario, many of its issues have yet to be studied. This research contributes to the literature by considering the UATM environment to implement its airspace capacity model.

6.2.2. Question 2: What are the aircraft performances? Will they be considered manned or unmanned?

This research only considers the presence of eVTOL in the proposed airspace to develop its capacity model. During the simulations will be considered different performances, which will be explained in more detail later.

According to (ELEVATE, 2018), VTOL are vehicles that have vertical takeoff and landing capacity with short duration hover.

The performance in each phase of the flight was proposed by (ELEVATE, 2018) and is shown in figure 25 and table 15.

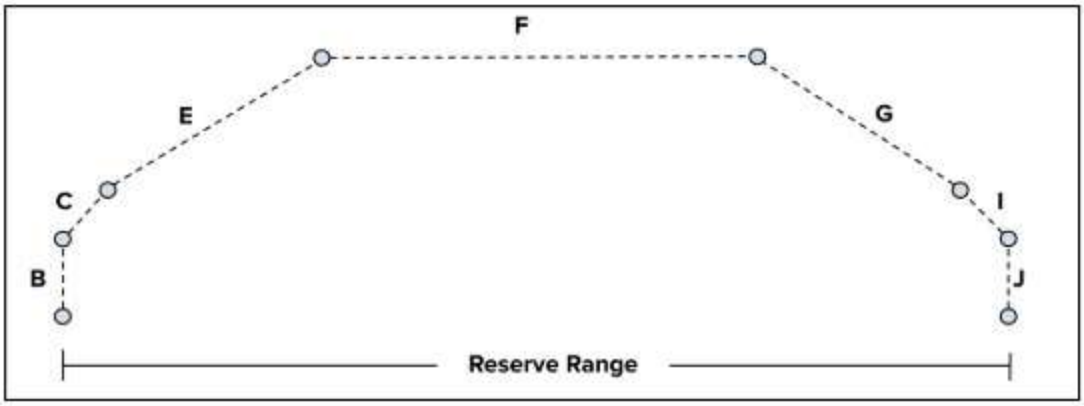

Figure 25: Aircraft performance profile.
Source: (ELEVATE, 2018).

Table 15: The performance in each phase.

	Segment	Vertical Speed (ft/min)	Horizontal Speed (KT)	AGL Ending (ft)
B	Hover Climb	0 to 500	0	40
C	Transition + Climb	500	0 to 1.2* Vstall	300
E	Accel + climb	500	1.2*Vstall to 150	1000
F	Cruise	0	150	1000
G	Decel+Descend	500	150 to 1.2*Vstall	300
I	Transition+Descend	500 to 300	1.2*Vstall to 0	40
J	Hover Descend	300 to 0	0	0

Source: (ELEVATE, 2018).

The initials UAV (unmanned aerial vehicle) are now generally used to denote the aircraft element of the UAS. However, UAV is sometimes interpreted as “uninhabited air vehicle” to describe the situation where the overall system is “manned” in that it is commanded by a human somewhere in the chain — and, as such, it is not exclusively autonomous(R. AUSTIN, 2010). In this case, we say that the aircraft is being remotely piloted (RPA)

Every UAV flight must be under the command of a UAV Commander. The UAV Commander is a qualified person who is in overall charge of, and responsible for, a particular UAV flight or flights. The UAV Commander can (AUSTIN, 2010):

- be in direct control of the vehicle by remote controls;
- co-located with the UAV-p[17]; and
- monitor the state and progress of the vehicle at the flight deck location in the GCS (Ground Control Station or system).

The UAV-p is a qualified person who is actively exercising remote control of a nonautonomous UAV flight or monitoring an autonomous UAV flight.

Additionally, (ICAO, 2015a) presents Autonomous Aircraft as an unmanned aircraft that does not allow remote pilot intervention in the management of the flight.

According to (ICAO, 2015a) all unmanned aircraft, whether remotely piloted, fully autonomous or combinations thereof, are subject to the provisions of Article 8 of the Convention on International Civil Aviation:

> No aircraft capable of being flown without a pilot shall be flown without a pilot over the territory of a contracting State without special authorization by that State and in accordance with the terms of such authorization. Each contracting State undertakes to insure that the flight of such aircraft without a pilot in regions open to civil aircraft shall be so controlled as to obviate danger to civil aircraft (ICAO, 2013).

This research treats VTOL as unmanned and — although (BRADFORD; KOPARDEKAR, 2020) proposes the location of PIC (Pilot in Command) as remote in Mature State Operation — considers that VTOL is a fully autonomous UAS

Question 3: What is the airspace structure where the model will be implemented: will it be segregated or not, what are its dimensions and route structure?

This work considers flights outside conventional airspace, where there is potential for high UAM flight demand. Although it examines UATM environments, it

[17] UAV pilot.

proposes a particular controlled air space called OCCA (Outside Conventional Controlled Airspace). The ATC analogous for OCCA will be OCCA Control (OC).

According to (ANTCLIFF; MOORE; GOODRICH, 2016), high incomes, long commutes, severe ground geographic constraints, severe highway congestion during peak commute times, high housing costs, and weather conditions are indicators for ODM (On Demand Mobility) potential.

This research considers the distribution of income and concentration of helipads to define OCCA. Figures 26 and 27 show the following locations with the highest concentration of income in São Paulo: Santo Amaro, Itaim Bibi, Moema, Jardim Paulista, Alto de Pinheiros, Vila Leopoldina, Perdizes, Consolação, and Vila Mariana. Figure 28 shows that the places with the highest income distribution are like the places with the highest concentration of helipads.

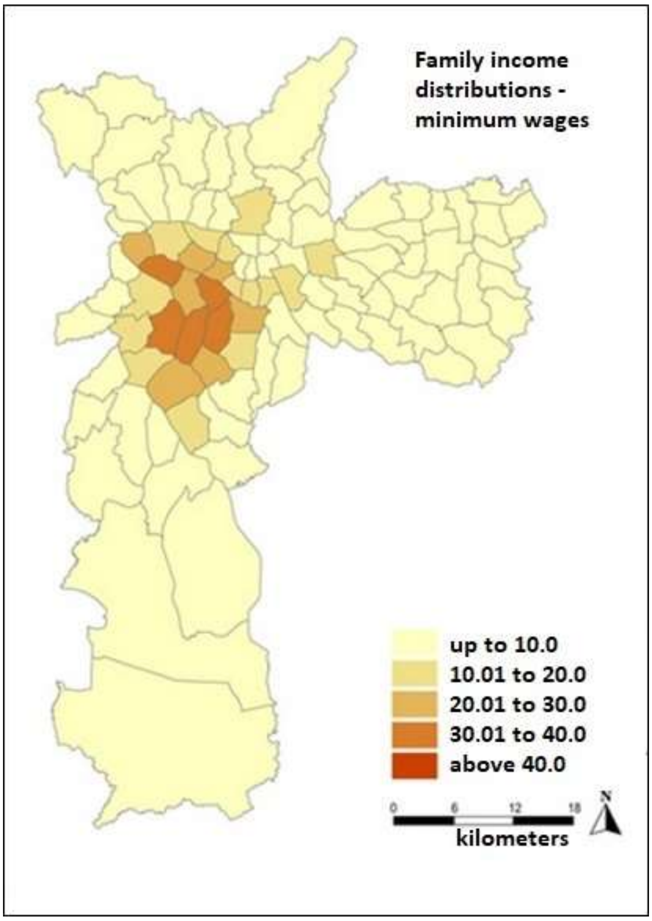

Figure 26: Income Distribution.
Source (KLEIN; GONÇALVES DIAS, 2017).

Figure 27: Regions of São Paulo
Source:(https://www.prefeitura.sp.gov.br/cidade).

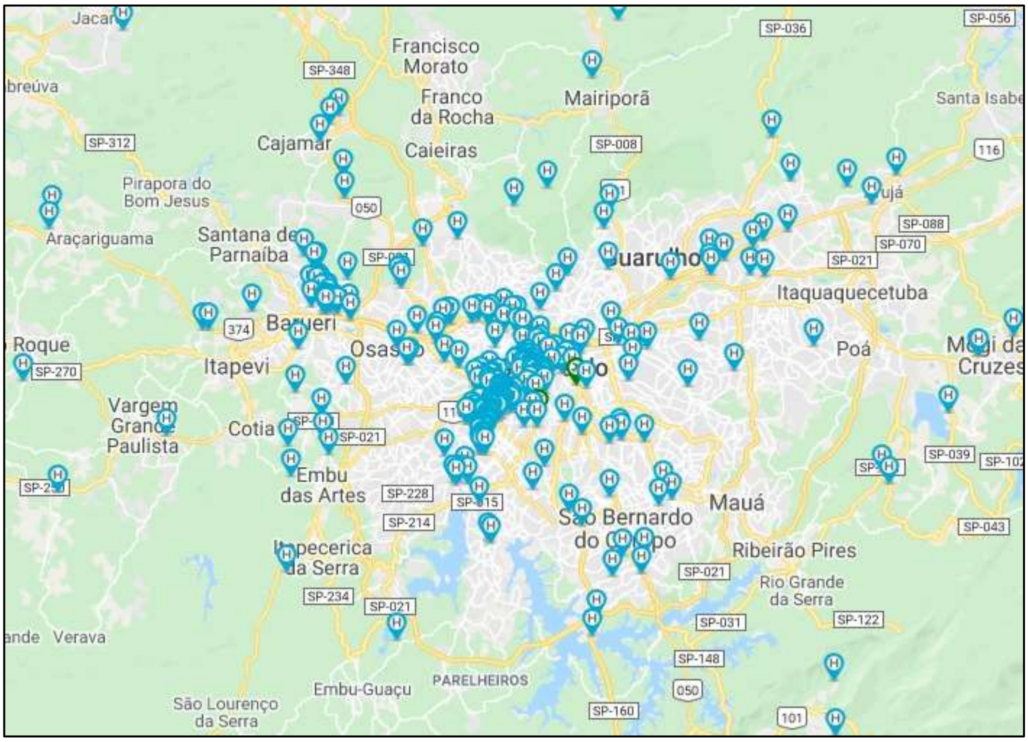

Figure 28: Helipad’s concentration.

Source (https://www.aerodromosweb.com.br/aerodromos).

Figures 29 and 30 show a possible scenario for OCCA based on the number of helipads and, consequently, ODM potential.

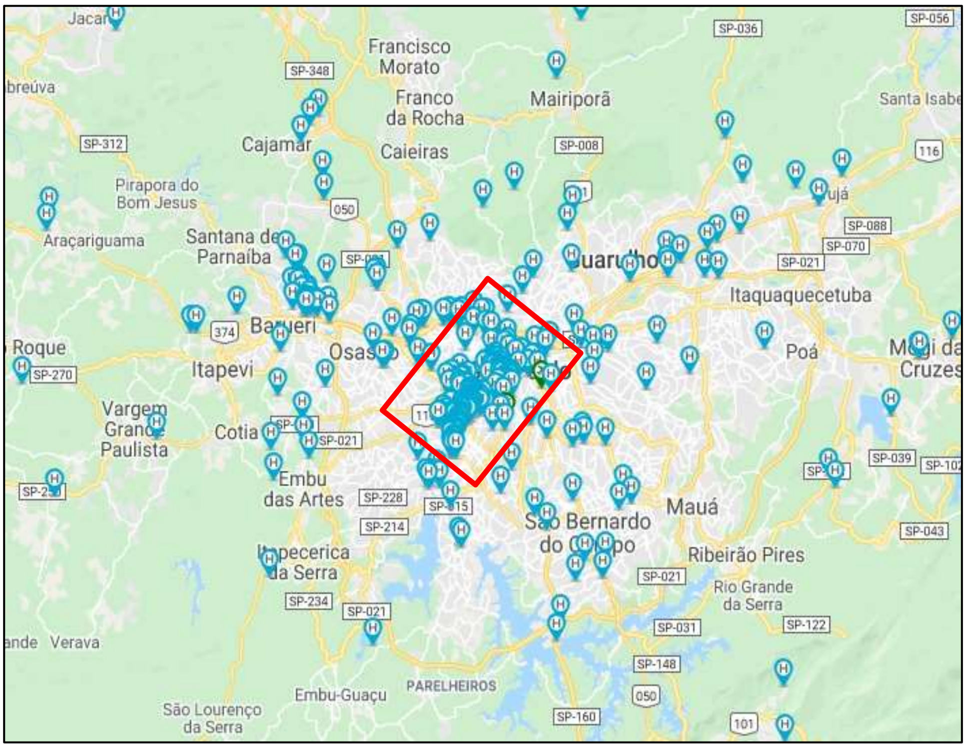

Figure 29: possible OCCA representation.
Source: The author.

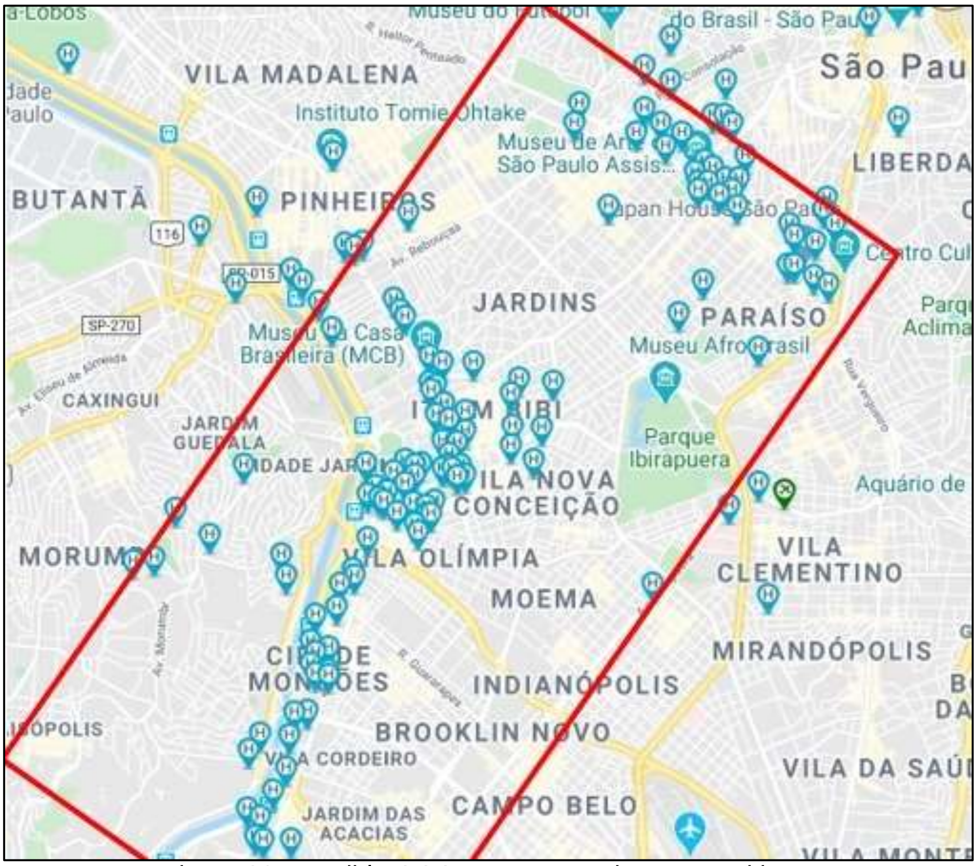

Figure 30: possible OCCA representation zoomed in.
Source: The author.

Its horizontal limits will be defined to meet the demand potential, not conflicting with the protection areas of the airports close to OCCA or any other controlled airspace.

In this research, as presented in (VASCIK; HANSMAN, 2017), we will refer to VTOL takeoff and landing sites as TOLA (Takeoff and Landing Area). Unlike airports, which are few and far between, TOLA can exist in large numbers and close together, just like helipads. Thus, this work proposes dividing the airspace into squares similar to those seen in helicopter control areas but with smaller dimensions.

The proposed dimensions of the grid, considering the performance of eVTOL, is 0.5 NM x 0.5 NM X 200 ft (height)[18]. Thus, what will be of interest for traffic management is the square in which the aircraft makes the approach and take-off regardless of whether one or several TOLAs exist. The approach or take-off will have as reference the central part of the grid, represented by a waypoint. After dimensioning OCCA, the grids will be arranged, following the horizontal and vertical dimensions of the selected area, as shown in figure 31.

[18] The grid definition is the volume given by the parallelepiped formed by 0.5 NM x 0.5 NM x 200 ft (height).

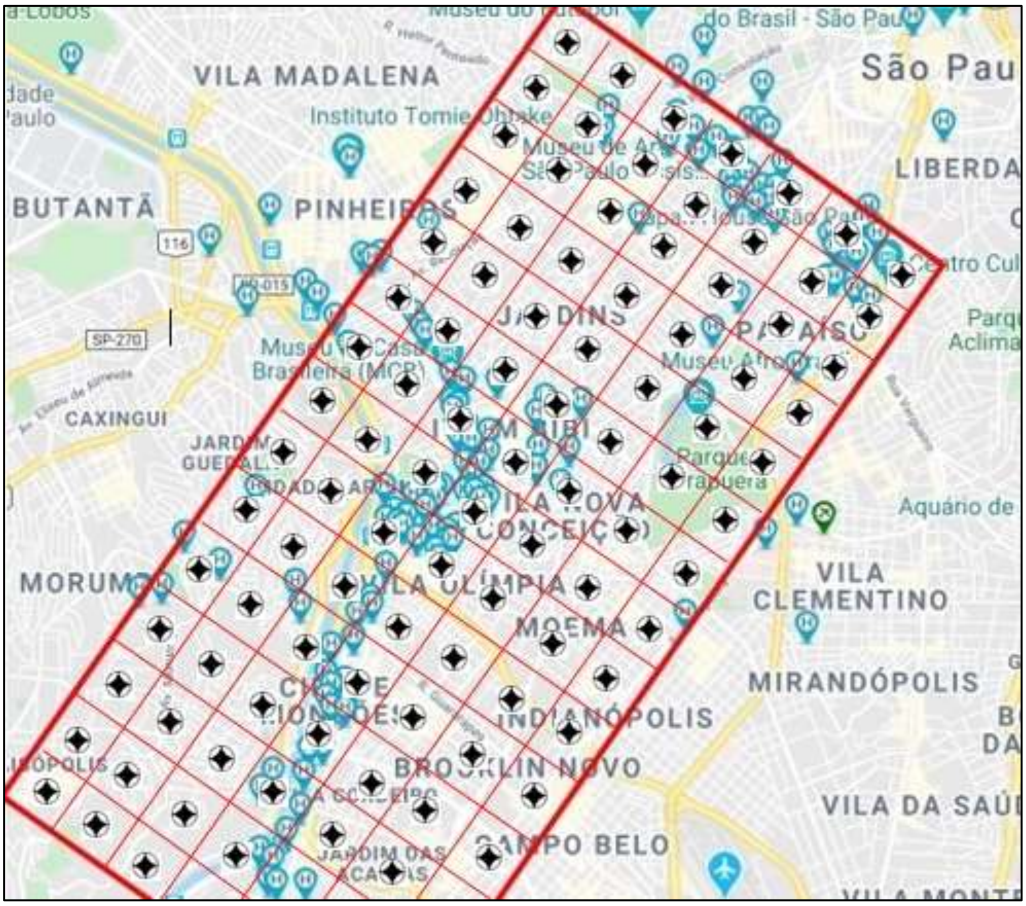

Figure 31: OCCA grids.
Source: The author.

Figure 32 shows the airspace structure with a plan view, including the possible different dimensions and locations of the OCCA.

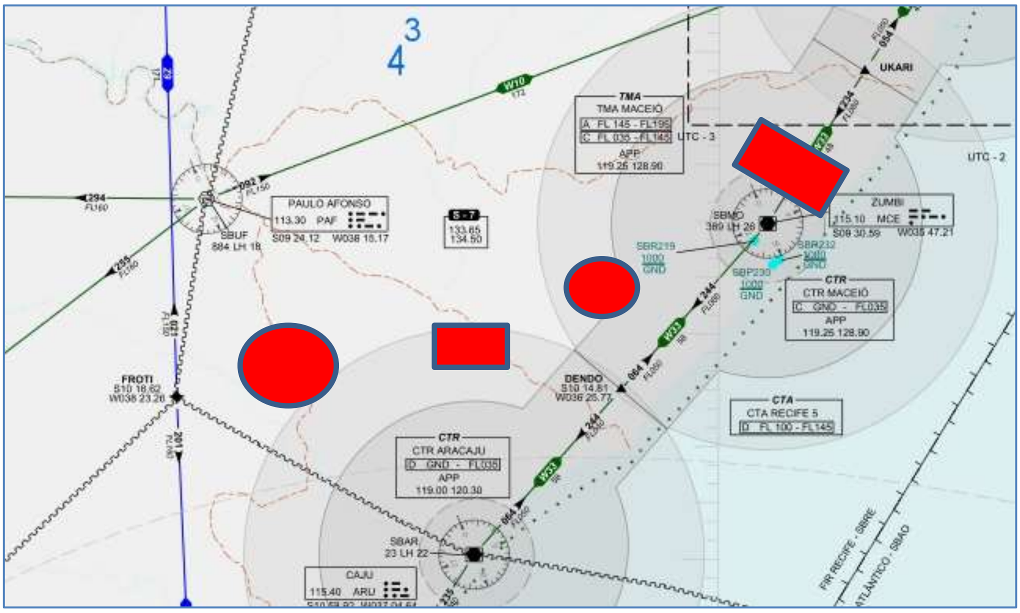

Figure 32: structure of the airspace, with a plan view (different OCCA dimensions and locations)
Adapted from https://www.aisweb.aer.mil.br.

The proposed lower and upper vertical limits for OCCA will be defined according to the height of the obstacles and the existence of controlled airspace. Below lower vertical limit of OCCA has operate "Free Flight", as shown in figure 33. It will be the responsibility of the aircraft operator to separate it from other aircraft and from obstacles. The aircraft operator will receive information from the ATC (automatic tool) about the position of sUAS that may be flying below the OCCA. The OCCA minimum will be 1000 ft AGL (Above Ground Level).

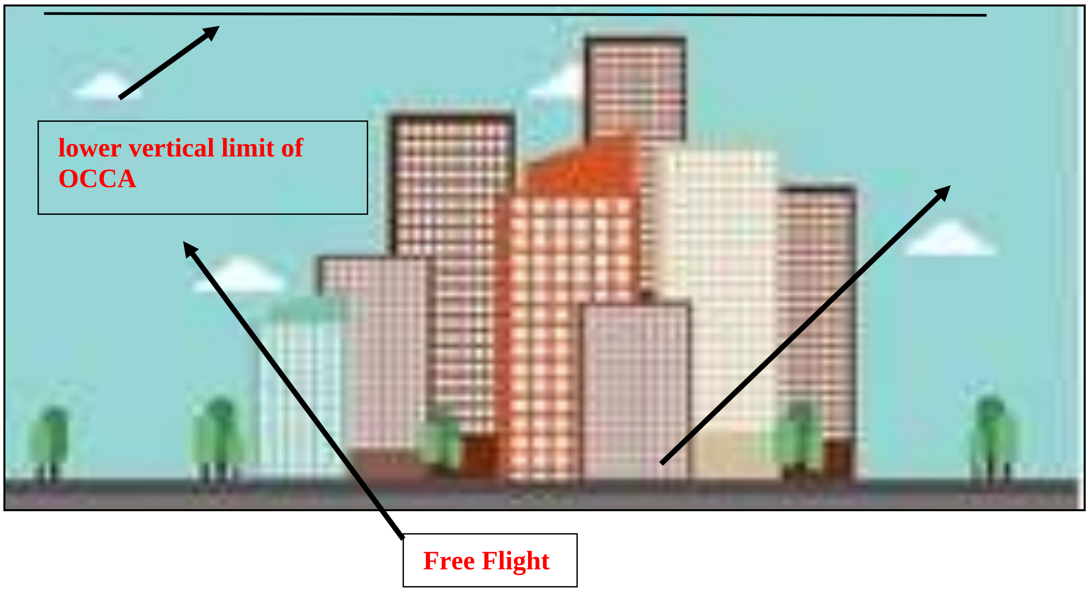

Figure 33: lower vertical limit of OCCA.
Source: The author.

6.2.3. Question 4: Which air traffic rules will be considered in the model?

(BOSSON; LAUDERDALE, 2018) presents an initial implementation of an autonomous Urban Air Mobility in the DFW (Dallas Fort Worth International Airport) metroplex, with 20 existing heliports converted into vertiports (called TOLA in the present work). In the simulations, except for the takeoff and landing phases, UAM eVTOL aircraft characteristics are derived based on the Cessna 172 aircraft performance flying qualities. The reference capabilities are extended to a climb rate of 800 fpm and an airspeed of 170kts during cruise for the UAM aircraft. The separation used between the aircraft was 0.3 NM (Nautic Mile) to 0.1 NM[19]. The air traffic rules

[19] Due to the lack of justifications for the use of these values, the minimum proposed in this work will be significantly more conservative.

and eVTOL performance presented in (NETO et al., 2019b) which will be used in this research, are described in table 16.

Table 16: Air traffic Rules and eVTOL performance.

ASSUMPTION	TOPIC	CONSIDERATION
Airspace Constraints	Flight Rules	IFR-like
	Square	0,5 NM X 0,5 NM
	Capacity	dynamically presented according to the complexity model
	Interdiction of Squares	
Mission scope	People Transportation	On-demand air taxi operations
	Skyports	Considerably large capacity
	Flight Segments	Take-off, Cruise, Landing
eVTOL Vehicle	Cruising Speed	130 kts-170kts
	Speed on Square	080 kt
	Acceleration/Deceleration	1 kts/s
	Climbing/Descending rate	500 ft/ min
	Descent Procedure	Spiral descent into the square
	Rate of Turn	7.2 degrees per second
	Piloting Classification	Piloted, RPAS and Self-Piloted
	Horizontal Separation	1,0 NM
	Vertical Separation	200 ft
	Cruise Condition (according to the proposed cruise level table)	1000 ft to 3000 ft
	Further Specs	Autonomy for flying in urban environments.
		45'in its max dimension
		Weight<=7000 lbs
sUAS	Cruising Speed	040 kts-060kts
	Speed on Square	30 kt
	Acceleration/Deceleration	1 kts/s
	Climbing/Descending rate	200 ft/ min
	Descent Procedure	Spiral descent into the square
	Rate of Turn	7.2 degrees per second
	Piloting Classification	Piloted, RPAS and Self-Piloted
	Horizontal Separation	0,5 NM
	Vertical Separation	200 ft
	Cruise Condition (according to the proposed cruise level table)	Maximum level to 1000 ft AGL
	Further Specs	Autonomy for flying in urban environments.
		45'in its max dimension
		Weight<=7000 lbs

Source: Adapted (NETO et al., 2019b).

The air traffic rules proposed in the UAM environment and used in this research are:

a) Division of OCCA into squares:

As proposed in (DECEA, 2018), using the structure of the UAM airspace in the vicinity of Congonhas airport, OCCA will be divided into 0.5 NM[20] X 0.5 NM squares and 200 ft vertically, with a central waypoint for each square being defined. The eVTOL will have as reference for the approach the central waypoint of the square. At arrival, the aircraft will reach the central waypoint of the grid and descend in a spiral until they cross the minimum level of the area, proceeding to the TOLA. At departure, the aircraft will ascend making a spiral until reaching the authorized level, proceeding to the destination.

b) Upper and lower vertical limit of OCCA

Considering (VASCIK et al., 2018) the upper vertical limit of OCCA will be 3000 ft[21] AGL (Above Ground Level) and the lower vertical limit will be established taking as reference the highest obstacle of OCCA.

c) Table of Cruising Levels (ICAO, 2012)

Depending on the magnetic track between entry Gate and destination waypoint (arrival) or waypoint departure to OCCA exit gate, a cruising level will be defined. Cruising level is a level maintained during a significant portion of a flight (ICAO, 2012). In this research, cruising levels will exist with 200 ft of separation, started at 1000 ft AGL. As shown in figure 34, cruising levels will be defined as follows:

- if the magnetic track is from 360º to 179º cruising levels used will be 1000ft, 1400ft, 1800ft, 2200ft, 2600ft e 3000ft.
- if the magnetic track is from 180º to 359º cruising levels used will be 1200ft, 1600ft, 2000ft, 2400ft, 2800ft e 3200ft[22].

[20] Horizontal distances used will be nautical miles. 1 NM (Nautic Mile)=1,852 Km.
[21] Vertical distances used will be feet. 1 ft= 0,3048m.
[22] This work uses a limit of 3200 ft AGL to allow for the same number of cruise levels in both magnetic track intervals.

.

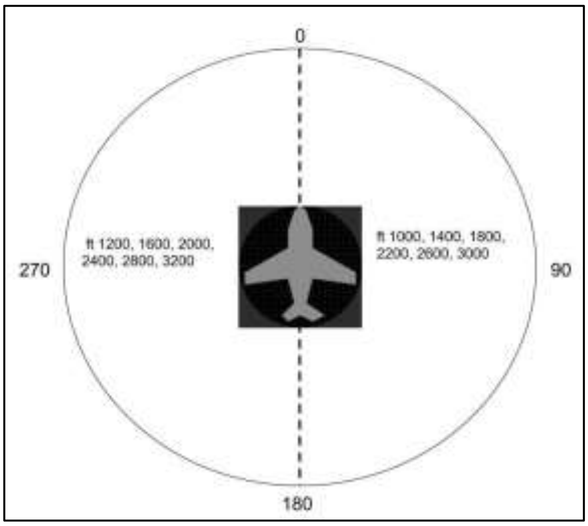

Figure 34: cruising level according to magnetic track.
Source: The author.

d) Gridlock (grid blocked): the grid will be blocked in two cases:

1. Arrival: Δt deltaT before the aircraft's arrival in the destination grid, preventing aircraft from taking off from that grid during this period. Aircraft in flight will be prevented from crossing this grid until the aircraft in approach leaves the respective levels in descent
2. Departure: Δt before the aircraft takes off until it reaches the authorized level. Aircraft in flight will be prevented from crossing the grid base until an aircraft taking off leaves the different levels climbing.

e) Vertical and horizontal separation

The minimum vertical and horizontal separations proposed will be 200 ft and 0.5 NM, respectively. However, several simulation scenarios will apply greater separations between the aircraft for the analysis of the complexity model Aircraft Performance.The aircraft considered in the simulations will be eVTOL, with possibilities of ascending and descending in a spiral, with a rate of climb (vertical speed) ranging from 200 ft / min to 1000 ft / min and horizontal speed ranging from 30 KT to 150 KT. In the simulations performed, different horizontal and vertical speeds were applied.

f) TBO

TBO will enable Airspace Users to operate as close as feasible to their preferred trajectories, thereby satisfying their business and operational needs. TBO allows effective dynamic adjustment of capacity (via airspace characteristics) in order to meet demand, making full use of developed civil/military collaboration (EUROCONTROL, 2019). According to (ICAO, 2016a), TBO enables better traffic localization so that flights can be separated by reduced minima, increasing the offered capacity and allowing for flexible routings and vertical profiles closer to the user-preferred ones.

g) SWIM

Enhanced information exchange capabilities will provide exchange of ATM system information, e.g., airport operational status, weather information, flight data, Flexible Use of Airspace (FUA) information, etc., to a wide range of ATM stakeholders in real time.

6.2.4. Question 5. What is the level of automation of air traffic control?

In this work, the proposed air traffic control is fully automated, with ATCo absent.

According to (MAJUMDAR; POLAK, 2001b) in high air-traffic-density areas the measure of capacity is based on ATCo workload.

For example, if we consider the airspace capacity model used in Brazil (DECEA, 2014), three different variables are presented:

a) T➔ Average aircraft permanence time in the sector (in seconds);
b) Tcom➔ Average ATCo communication time (transmission and reception with the aircraft, in seconds) and
c) TTS➔ Average time spent by ATCo on secondary tasks (in seconds).

Although DECEA defines all the requirements for issuing the ATCo Technical Qualification Certificate in (DECEA, 2020) with the goal of standardizing operations, there is a considerable difference in the operational performance of ATCo due to the professionals' cognitive characteristics.One of the requirements for the application of the DECEA model to calculate the airspace capacity (DECEA, 2014) is to consider that all operational teams have the same operational performance.

According to (MOGFORD, R.; GUTTMAN, J.; MORROW, S.; KOPARDEKAR, 1995), individual differences and controller cognitive strategies affect the controller workload. Thus, designing the UAM environment with considerable air traffic density, enabling safe and efficient UAM operations in the Airspace necessitates a large paradigm shift of the current air traffic control system towards higher levels of autonomy.

NASA has researched the development of algorithms to enable increased levels of integrated automation, using automated conflict detection and resolution, arrival and departure management, and weather avoidance as a basis for autonomous air traffic control (BOSSON; LAUDERDALE, 2018).

The inputs of the algorithm for each flight include the aircraft information, type and motion state, the departure and arrival airports, weather information as well as airspace configuration parameters. Figure 35 summarizes the algorithm functionalities in a functional diagram.

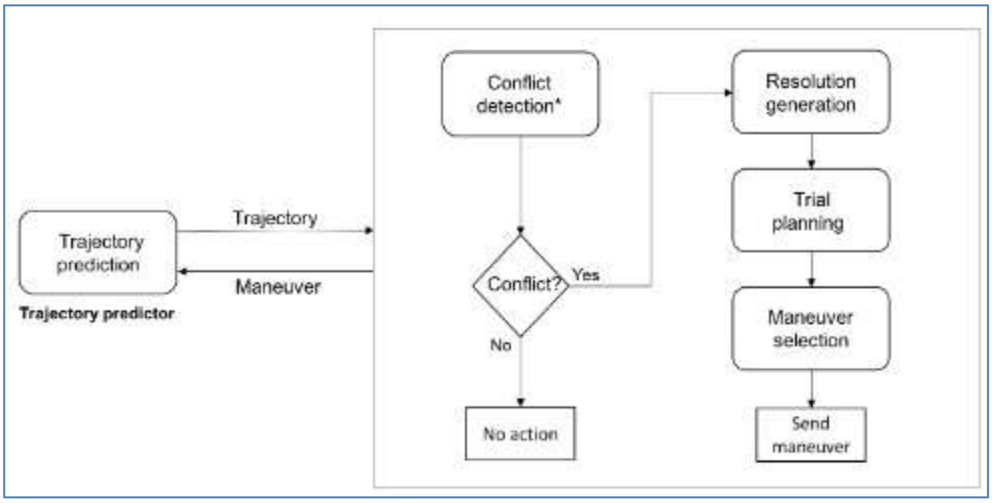

Figure 35: Trajectory predictor functional diagram.
Source: (BOSSON; LAUDERDALE, 2018).

(NETO et al., 2021) proposes a Trajectory-Based UAM Operations Simulator (TUS) considering multiple electrical vertical and take-off landing (eVTOL) vehicles in urban environments. For this, a Discrete Event Simulation (DES) approach is adopted, which considers an input (i.e., the eVTOL vehicles, their origin and destination, and their respective trajectories) and produces an output (which describes if the trajectories are safe and the elapsed operation time). The main contribution of this simulation tool is to provide a simulated environment for testing and measuring the effectiveness (e.g., flight duration) of trajectories planned for eVTOL vehicles.

For this, possible eVTOL performance characteristics were inserted in the model, such as rate of climb and descent, in addition to air traffic rules — all based on the literature.

Figure 36 depicts the entire operation of the eVTOL vehicles in this simulation tools. Firstly, the vehicle follows a vertical take-off procedure up to the take-off fix. Then, the aircraft goes through its cruise trajectory. In this phase, the trajectory may lead the aircraft to change its flight level. After that, the aircraft flies to the landing fix, which is designed to prepare the eVTOL vehicles for the spiral landing. Finally, the aircraft starts the spiral landing procedure to reach the Skyport (TOLA).

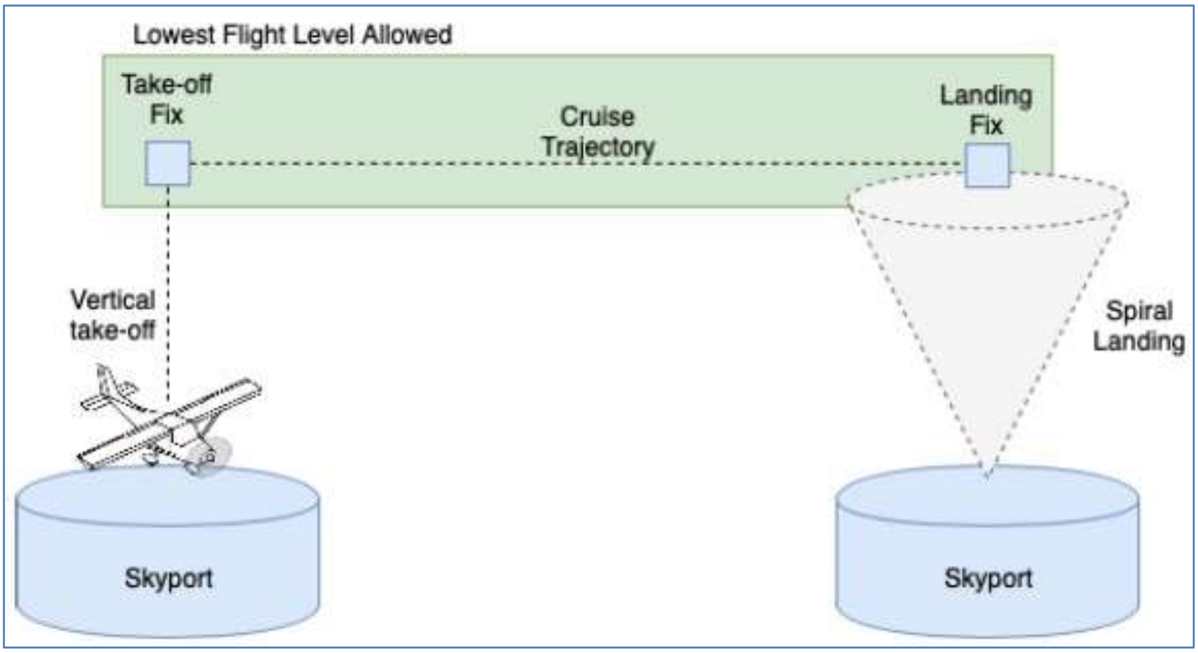

Figure 36: eVTOL Vehicle State.
Source: (NETO et al., 2019a).

The present study's computational tool to perform the air traffic control in the UAM environment is similar to the TUS but with a trajectory optimizer. It is called TUSO (Trajectory-Based UAM Operations Simulator + Optimizer), and its structure is presented in figure 37, based on (BOSSON; LAUDERDALE, 2018) and (NETO et al., 2021).

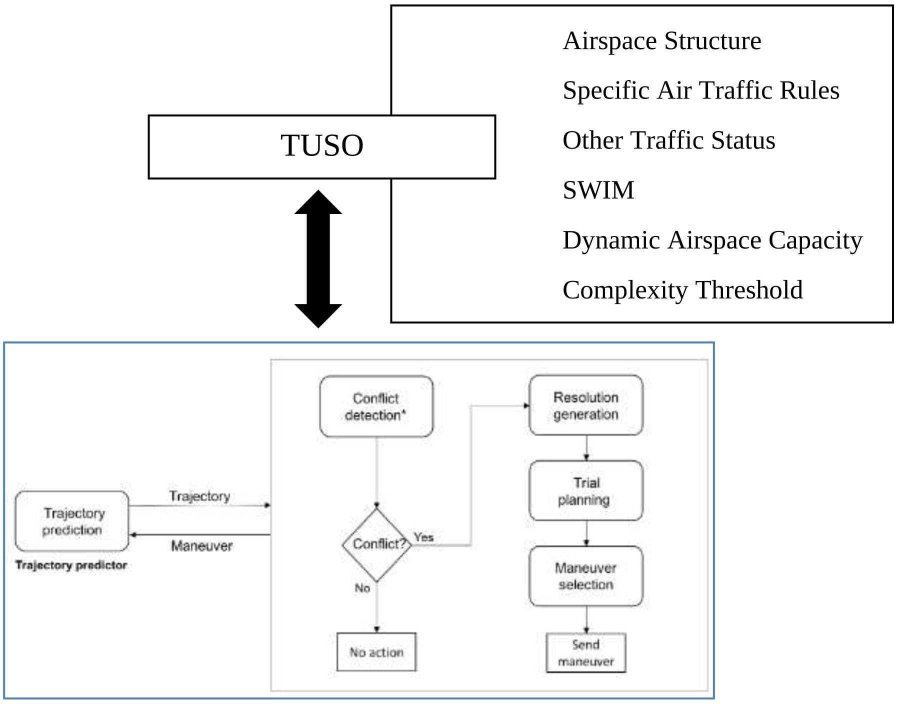

Figure 37: TUSO structure.

Source: The author.

Figure 38 presents the flight steps framework, composed of the intention to fly, processing the request, and instructions.

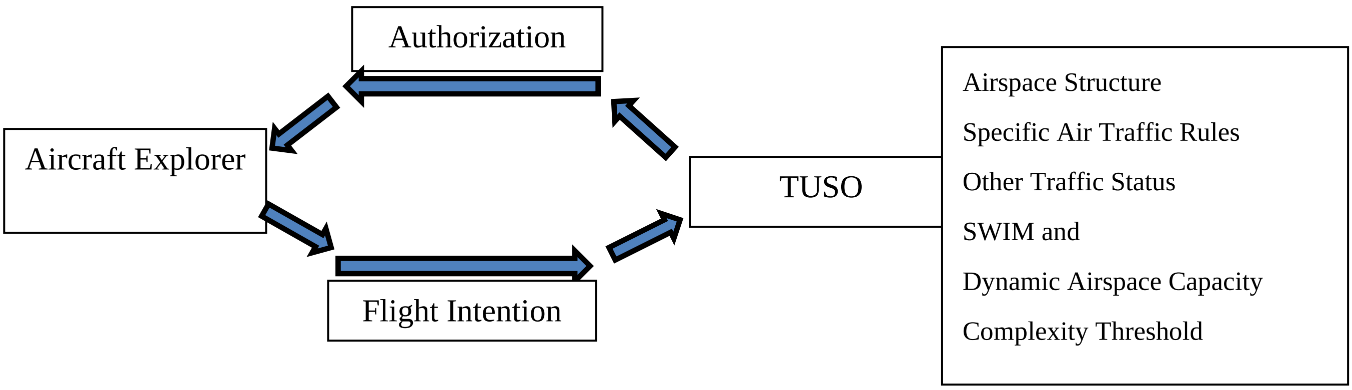

Figure 38: Flight steps framework.

Source: The author.

Each step of the framework is described below:

a) Aircraft Explorer- The explorer of the aircraft will complete the Flight Intention.

b) Flight Intention - it comprises the following steps:

   b.1. Aircraft Identification

   b.2. Desired Flight Level

   b.3. OCCA Entry Gate and destination waypoint (arrival) or waypoint departure to OCCA exit gate.

c) TUSO - considering all available information, it will issue the Authorization.

d) Authorization:

   d.1. authorized flight level

   d.2. trajectory from origin TOLA within OCCA and destination Skyport within OCCA or OCCA Entry Gate or/and OCCA Exit

   d.3. any type of restriction

   d.4. additional information

The objective of this research is not to develop the computational tool to perform the air traffic control activity in a UAM environment, but to contextualize it, presenting its role in the proposed framework.

The purpose of this work is to present an airspace capacity model (presented and developed in the next chapter) and for this we must observe the prerequisites that were presented in this chapter.

7. AIRSPACE CAPACITY MODEL BASED ON AIRSPACE COMPLEXITY CONSIDERING UATM ENVIRONMENT

The capacity model will respond at time T+1, that is, considering that there are N aircraft in the respective airspace at time T, the model will present the capacity conditions for the N+1 aircraft. The capacity model will be developed based on the complexity of the airspace. The dynamic capacity index will be the inverse function of the dynamic complexity index.

As previously presented, the Bayesian Network (BN) will be used to assemble the complexity model.

Developing an effective BN requires a combination of expert knowledge and data. Yet rather than combining both sources of information, in practice, many BN models have been constructed exclusively from data, while others have been built solely based on expert knowledge. Irrespective of the method used, building a BN involves the following two steps (CONSTANTINOU; FENTON; NEIL, 2016):

1) Determining the structure of the network; and
2) Determining the conditional probabilities tables (CPTs) for each node

According to (COMENDADOR et al., 2019) BN models have been built and validated following a process called Engineering of Expert–based Knowledge Engineering of Bayesian Network (EKEBN). This process comprises three main steps:

- Structure building: consisted of the identification of the variables and causal relationships and the states or values that each variable could take.
- Uncertainty quantification: deals with the conditional probabilities that quantify the relationships between variables. Conditional probability tables (CPTs) were obtained via expert's elicitation as well from data and results in existing literature. Model validation: checks the BN resulting from the two previous steps and determines whether it is necessary to revisit any of the previous steps.
- Validation followed a Model Walkthrough approach, which used real case scenarios prepared by domain experts to assess the BN model predictions.

To define the Capacity model, considering (COMENDADOR et al., 2019), (COMENDADOR et al., 2018) and (CONSTANTINOU; FENTON; NEIL, 2016), the following steps will be taken, as shown in figure 39:

1. Identification of relevant variables and the causal relationship based on expert knowledge and the literature.
2. State space of each node: the state space of each node represents the level of uncertainty that affects a particular variable or complexity generator.
3. Definition of conditional probabilities tables (CPTs): Netlogo[23] Simulation
4. Insertion of CPTs in the Bayesian Network
5. Validation of the Capacity Model: Using the concept of Walkthrough approach. The results of different scenarios presented by the Bayesian network will be compared with the expectations of experts for the same scenarios.
6. Insertion of the Capacity Model in TUSO: future research

[23] Netlogo is a multi-agent programmable modeling environment.

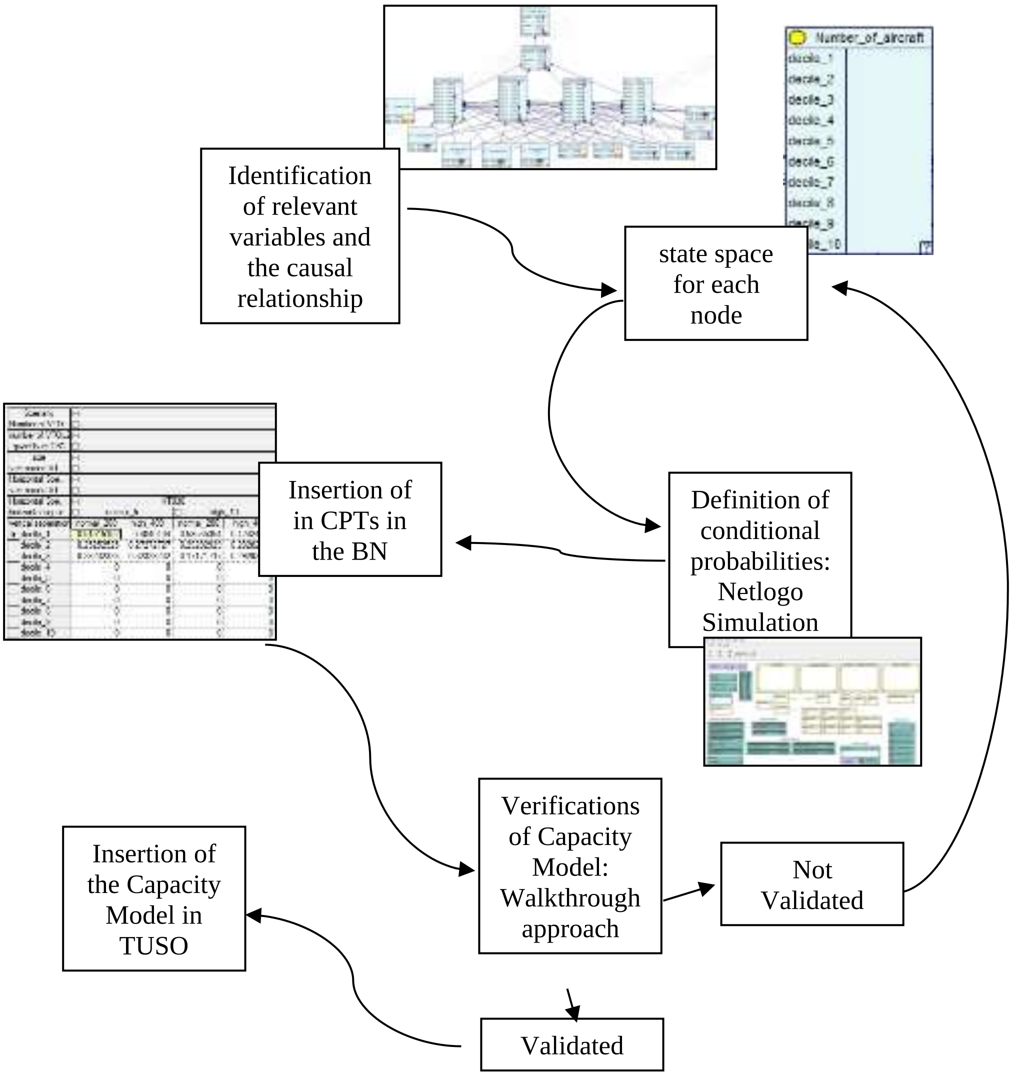

Figure 39: Airspace Complexity and Airspace Capacity Steps

Source: the author

Will be presented in detail all the steps necessary to the development of the airspace capacity model.

7.1. Identification of relevant variables and the causal relationship

As mentioned before, although many technologies have been developed over time, the complexity variables identified in the systems, in general, are the same presented in the literature since the beginning. It is also noteworthy that these same variables are identified as generators of complexity in an urban environment as well.

The first step in the construction of the Bayesian network is to select the variables that will compose the model and then establish the relationship. For this, will be presented the complexity variables that have been studied in the literature.

Dynamic Density (DD) model is a regression equation, development to examine complexity measures. In (KOPARDEKAR et al., 2007) 52 (fifty two) candidate complexity variables were presented for the modeling, and after using Regression Analysis, they were significant, only 17 (seventeen) of them, represented in table 17.

Table 17: Significant Complexity variables

Description			
Aircraft count	Time-to-go to conflict measure 1	Ratio of standard deviation of speed to average speed	Count of number of aircraft within a threshold distance of a sector boundary
Number of aircraft/occupied volume of airspace	The angle of converge between aircraft in a conflict situation	Conflict resolution difficulty based on crossing angle	Squared difference between the heading of each aircraft in a sector and the direction of the major axis of the sector, weighted by the sector aspect ratio
Proximity of conflicting aircraft with respect to their separation minima	Number of climbing aircraft	Number of aircraft with 3-D Euclidean distance between 0-5 nautical miles excluding violations	Number of aircraft with predicted horizontal separation under 8nm
Sector volume	Horizontal proximity measure	Number of aircraft with 3-D Euclidean distance between 5-10 nautical miles excluding violations	Variance of all aircraft headings in a sector
			Squared difference between heading of each aircraft in a sector and direction of major axis

Source: (KOPARDEKAR et al., 2007)

In (MOGFORD, R.; GUTTMAN, J.; MORROW, S.; KOPARDEKAR, 1995), based in literature review are presented several complexity factors, shown in the table 18.

Table 18: Complexity Factors base on literature review

Complexity Factors			
Number of departures	En-route aircraft requiring	Number of airport terminals	Weather conditions
Number of arrivals	Coordination	Traffic volume	Sector geometry
Emergencies	Traffic density	Traffic distribution	Total number of flights handled.
Special Flights	Traffic mixture (arriving/departing vs overflying aircraft)	Staffing	Number of handoffs inbound
Communications with aircraft	Preventing an overtaking conflict	Handling pilot requests	Control adjustments involved in merging and spacing aircraft.
Presence of conflicts	Hand-offs	Traffic structuring Clustering	Climbing and descending aircraft flight paths.
Number of path changes	Point outs	Clustering of aircraft in a small amount of airspace	Sector size
Preventing a crossing conflict.	Coordination with other controllers.	Number of handoffs outbound	Requirements for longitudinal sequencing and spacing
Mixture of aircraft type	Aircraft mix.	Amount of coordination	Adequacy of radio and radar coverage
Frequent coordination with other controllers	Number of intersecting flight paths.	Weather	Radio frequency congestion
Traffic density	Multiple functions	Complex aircraft routings. Restricted	
Amount of climbing or descending traffic.	Number of required procedures	Restricted areas, warning areas, and Military Operating Areas	

Source: (MOGFORD, R.; GUTTMAN, J.; MORROW, S.; KOPARDEKAR, 1995)

(HOPKIN, 1982) state that complexity (defined as a failure in task performance) result from a mismatch between system requirements and human information processing capabilities, considering the complexity factors as shown below:

a) Physical distance between tracks on the radar display;
b) The scale of the radar display;
c) The relative and absolute speeds of aircraft;
d) The aircraft headings and angles of approach;
e) The time until two aircraft conflict;
f) The aircraft altitudes;
g) The aircraft types and maneuverability;
h) The ease of contacting an aircraft; and
i) The known intentions and destinations of an aircraft;

There are other different approach: Analysis of current sectors (CHATTERJI; ZHENG; KOPARDEKAR, 2008), Air Traffic Complexity Indicators (CHRISTIEN et al., 2002b), An efficient Airspace configuration forecast (GIANAZZA; ALLIGNOL; SAPORITO, 2009), Relationship of sector activity and sector complexity (MANNING; PFLEIDERER, 2006),Trajectory uncertainty (KNORR; WALTER, 2011), ATC complexity (ATHÈNES et al., 2002).

Based on the complexity variables presented in the literature, the variables that will be used in the model were proposed, divided into Complexity Generators and Complexity Metric (will be presented below).

Table 19 presents the Literature Complexity Variables and its references, the Complexity Generators and Complexity Metrics.

Table 19: Proposed variables to the complexity model (Complexity Generators)

Literature Complexity Variable	Reference	Complexity Generators (CG)	Complexity Metrics (CM)
Sector volume	KOPARDEKAR et al., 2007;	Size	
Sector Size	MOGFORD, R.; GUTTMAN, J.; MORROW, S.; KOPARDEKAR, 1995		
Current Sector	(CHATTERJI; ZHENG; KOPARDEKAR, 2008	Scenario	
Sector geometry	MOGFORD, R.; GUTTMAN, J.; MORROW, S.; KOPARDEKAR, 1995		
Horizontal proximity measure Number of aircraft with 3-D Euclidean distance between 0-5 nautical miles excluding violations Presence of conflicts Requirements for longitudinal sequencing and spacing	KOPARDEKAR et al., 2007 MOGFORD, R.; GUTTMAN, J.; MORROW, S.; KOPARDEKAR, 1995	Horizontal Separation	Number of Aircraft
aircraft altitudes Requirements for longitudinal sequencing and spacing	HOPKIN, 1982 MOGFORD, R.; GUTTMAN, J.; MORROW, S.; KOPARDEKAR, 1995	Vertical Separation	Below Minimum Separation
Aircraft count Traffic Density	KOPARDEKAR et al., 2007 MOGFORD, R.; GUTTMAN, J.; MORROW, S.; KOPARDEKAR, 1995	Number of VTOL 1	
Aircraft count Traffic Density	KOPARDEKAR et al., 2007 MOGFORD, R.; GUTTMAN, J.; MORROW, S.; KOPARDEKAR, 1995	Number of VTOL 2	Below Stipulated Separation
Aircraft mix	MOGFORD, R.; GUTTMAN, J.; MORROW, S.; KOPARDEKAR, 1995	Horizontal Speed VTOL 1	
Aircraft mix		Horizontal Speed VTOL 2	
Aircraft mix		Vertical Speed VTOL 1	Delay
Aircraft mix		Vertical Speed VTOL 2	
Weather conditions	KOPARDEKAR et al., 2007 MOGFORD, R.; GUTTMAN, J.; MORROW, S.; KOPARDEKAR, 1995	Quantity of CB	

Source: The author.

Figure 40 presents the structure of the complexity model (Bayesian Network), noting that all CGs are connected to all CMs, as well as CMs will be connected to Airspace Complexity. Finally, Airspace Capacity is a reverse function of Airspace Complexity.

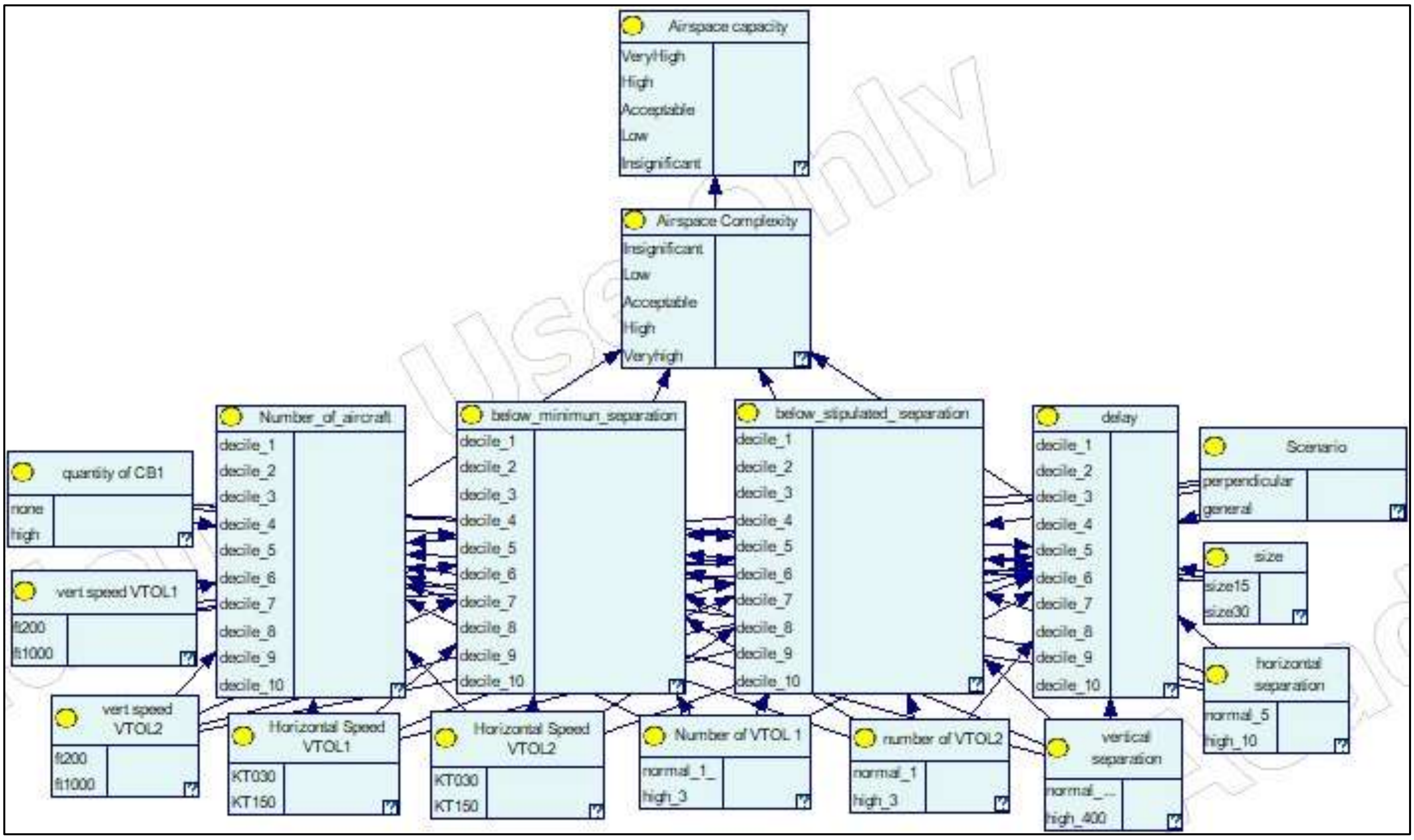

Figure 40: Structure of Complexity Model.
Source: The author.

7.2. State space for each node: Complexity Generators (CG) Complexity Metrics (CM), Airspace Complexity, and Airspace Capacity

Construction of a state space of the described nodes is the definition of the variable states and the full joint probability, defined for all Complexity Generators (CG) nodes and Complexity Metrics (CM) nodes in the network, implying in the discretization of variables.

7.2.1. Complexity Generators (CG) nodes

All CGs were selected based on the literature and an expert, as presented in table 21. Follow the presentations of all parameters:

- Size - Possible horizontal dimensions for OCCA (Outside Conventional Controlled Airspace).
- Scenario – eVTOL trajectories considered within OCCA
- Horizontal Separation – Proposed 0.5 NM and 1.0 NM.In In (BOSSON; LAUDERDALE, 2018) was proposed 0.1 NM to 0.3 NM.
- Vertical Separation – minimums and maximums were proposed, respectively of 200 ft (proposed by BOSSON; LAUDERDALE, 2018) and 400 ft.
- Number of eVTOL 1 and Number of eVTOL2 – two different performance possibilities for aircraft were considered. The number of aircraft of each type entering in the scenario was defined as one or three aircraft per minute.
- Horizontal Speed eVTOL 1 e 2 e Vertical Speed eVTOL 1 e 2 – parameters and maximums were stipulated based on the possible performances of the eVTOL.
- CB (Cumulonimbus) – two situations were considered for CB: its presence in considerable quantity or the absence.

All CGs will have two states, as shown in Table 20 and figure 41.

Table 20: CGs and respective values

Size	Scenario	Horizontal Separation	Vertical Separation	Number of VTOL 1 (per min)	Number of VTOL 2 (per min)	Horizontal Speed VTOL1	Horizontal Speed VTOL2	Vertical speed VTOL1	Vertical speed VTOL2	Quantity of CB
15NM X 15 NM	perpendicular	0,5 NM	200 ft	1	1	30 kt	30 kt	200 ft/min	200 ft/min	0
30NM X 30 NM	General	1 NM	400 ft	3	3	150 kt	150 kt	1000 ft/min	1000 ft/min	100

Source: The author.

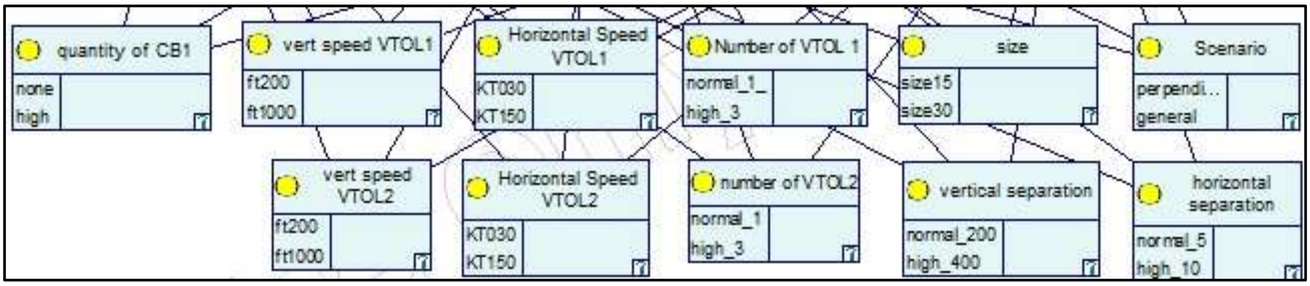

Figure 41: States Space of CGs.

Source: The author.

7.2.2. Complexity Metrics (CM) nodes, Airspace Complexity and Airspace Capacity

All CMs were selected based on the literature and experts: Number of Aircraft, Below Minimum Separation, Below Stipulated Separation and Delay.

It should be noted that all CGs are connected to all CMs, as shown in figure 40. The states Space of the CMs are presented in deciles 1 to 10, as shown in figure 42, depending on the CGs.

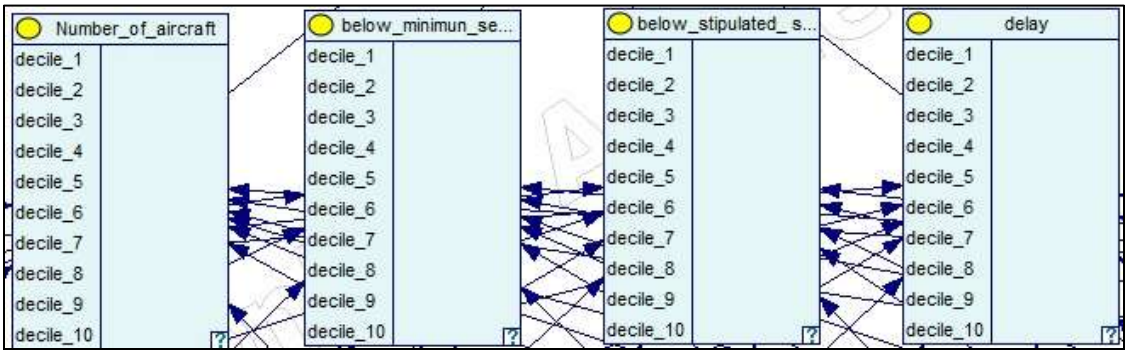

Figure 42: state space of describe nodes to outputs.

Source: The author.

The State Space of Airspace Complexity and Airspace Capacity were presented in five levels: Insignificant, Low, Acceptable, High, and Very high. It should be noted that the State Space of Airspace Capacity is an inverse function of Airspace Complexity, as shown in figure 43.

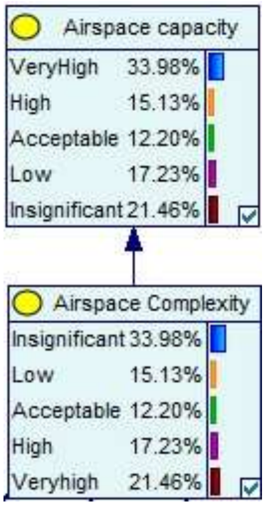

Figure 43: State Space of Airspace Capacity as an inverse function of Airspace Complexity.

Source: The author.

7.3. Definition of Conditional Probabilities

For the definition of conditional probabilities in each of the nodes, it is essential that the relationship between CGs and CMs be understood. For this, a simulation scenario was developed for a UAM environment, considering all the air traffic rules presented in this work, with all parameters of the CGs taken as inputs and the CMs as outputs of the simulation.Multi-Agent System using Netlogo

MAS (Multi-Agent System) is a paradigm for the development of intelligent systems, being a subarea of distributed artificial intelligence, widely used in several areas to solve complex problems in a decentralized manner, with or without coordination between agents. The agent-oriented paradigm is one of the main ones used in artificial intelligence, with the ability for multiple agents to act autonomously in a defined environment. Several applications are presented in the literature, including those that require high reliability, such as aviation (WOOLDRIDGE, 2002).

Netlogo is an agent-based language developed by (TISUE; WILENSKY, 2004) that presents simple structures to facilitate its use. Nevertheless, the language allows for programs with varying levels of complexity.

The literature presents relevant works with agent-based approaches applied to UAM. (COOLEY; WOLF; BOROWCZAK, 2019) use an agent-based approach, forming a group in which several agents coordinate for the execution of a task, as is the case with eVTOLs.

So that agents could be accompanied by carrying out the stipulated tasks, if that were the case, Netlogo 3D version 6.1.1 was used to develop the model. The goal was to create numerous UAM scenarios by varying the various proposed inputs. This allows us to establish the relationship between the varying "input" and the resulting "output." The model development is presented in (FERRARE et al., 2021).

Aircraft generation and landing and takeoff locations occur stochastically within the limits of the proposed scenarios: 30 NM x 30 NM or 15 NM x 15 NM, from 1000 ft to 3200 ft above the landing and takeoff location. Each scenario is divided into 0.5NM x 0.5NM squares horizontally and 200 ft vertically. As for the planning of trajectories, they will be defined according to the landing and take-off locations and the choice of scenario (perpendicular or general).

As previously discussed, the area where the simulation will take place (UAM environment) will be called OCCA and the air traffic rules used in the modeling are:

a) Division of OCCA into squares
b) OCCA upper and lower vertical limit
c) Table of Cruising Levels (ICAO, 2005)
d) Gridlock (grid blocked)
e) Vertical and horizontal separation
f) TBO

Figure 44 presents Netlogo's graphical interface, where the green "buttons" are all the "inputs" that may be affected, making it possible to create numerous UAM scenarios.

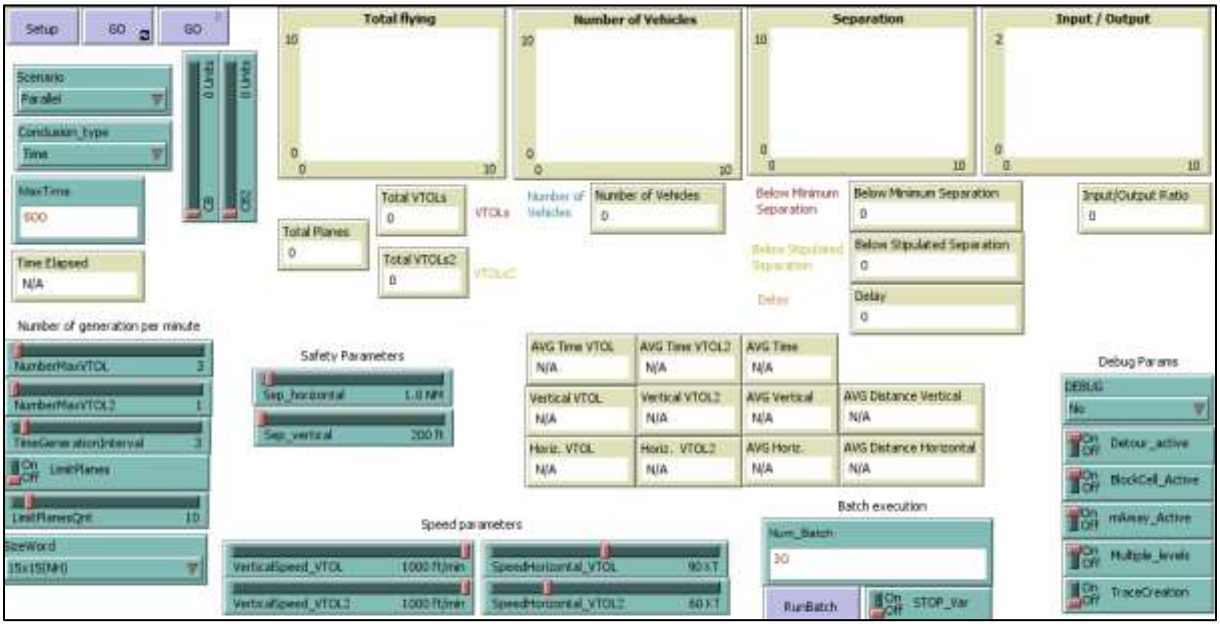

Figure 44: Netlogo graphical interface.

Source: (FERRARE et al., 2021).

The inputs proposed in this model are the CGs and the duration of the simulations was set at 600 minutes, for each simulation. The outputs proposed are CMs, as presented below:

a) Number of aircraft: Take-offs and landings will be considered within the simulation time (600 minutes).
b) Below Minimum Separation: Initially, traffic must remain in different squares (0.5 NM x 0.5 NM and 200 ft). However, depending on the level of complexity generated in the scenario, these minimums may be compromised.
c) Below Stipulated Separation: this occurs when the aircraft do not comply with the minimum horizontal and vertical separation presented in the safety parameters (horizontally 0.5 NM or 1.0 NM and vertically 200 ft or 400 ft and).
d) Delay: is the computation of the number of aircraft that will maintain their position for more than 10 min in order not to enter the restricted airspace.

Figure 45 shows the model in execution, with the agents (aircraft) in 3D. The VTOLs types 1 and 2 are presented by the different colors (yellow and red) in the model.

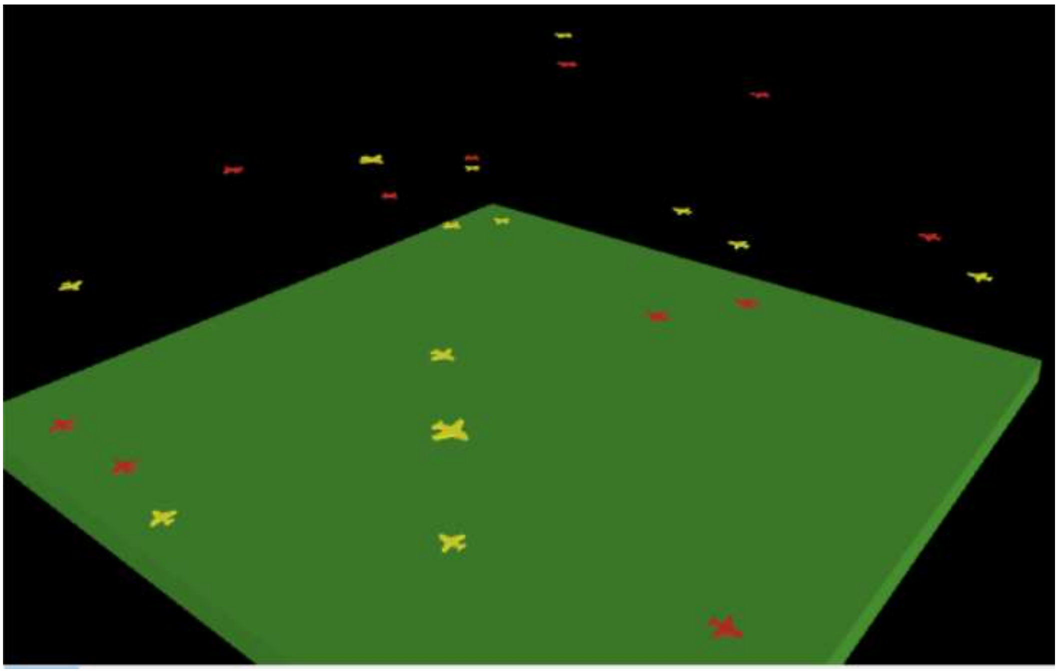

Figure 45: Running model, 3D agents.
Source: (FERRARE et al., 2021).

Considering that the generation of the scenarios is stochastic, it is necessary to perform a considerable number of tests per scenario for the analyses to be correctly performed. For this purpose, the “batch” function allows us to define the number of experiments for the proposed scenario, generating data from multiple simulations and facilitating further analysis.

For model validation of Netlogo application, air traffic experts analyzed each proposed scenario by comparing the results obtained with the expected results. Considering that all landing and takeoff locations are stochastically defined, validation outputs were created on Netlogo to enable the analysis, as shown in figure 46.

The validations factors are:

a) Average Vertical Distance: average vertical distance of all simulation aircraft, between the landing and takeoff location and the cruising level.
b) Average horizontal distance: average horizontal distance of all aircraft in the simulation, between landing and takeoff.
c) Average horizontal flight time: average time spent by all aircraft at the cruise level.
d) Average vertical flight time: average time spent by all aircraft in the ascent and descent procedures.
e) Total average time: average of the total time spent by the aircraft.

The validation procedure consisted of thirty-three versions of the model developed following the Walkthrough approach. The simulation verification was based on the output analysis above and involved successive calibrations. At each calibration, a new version of the scenario was created.

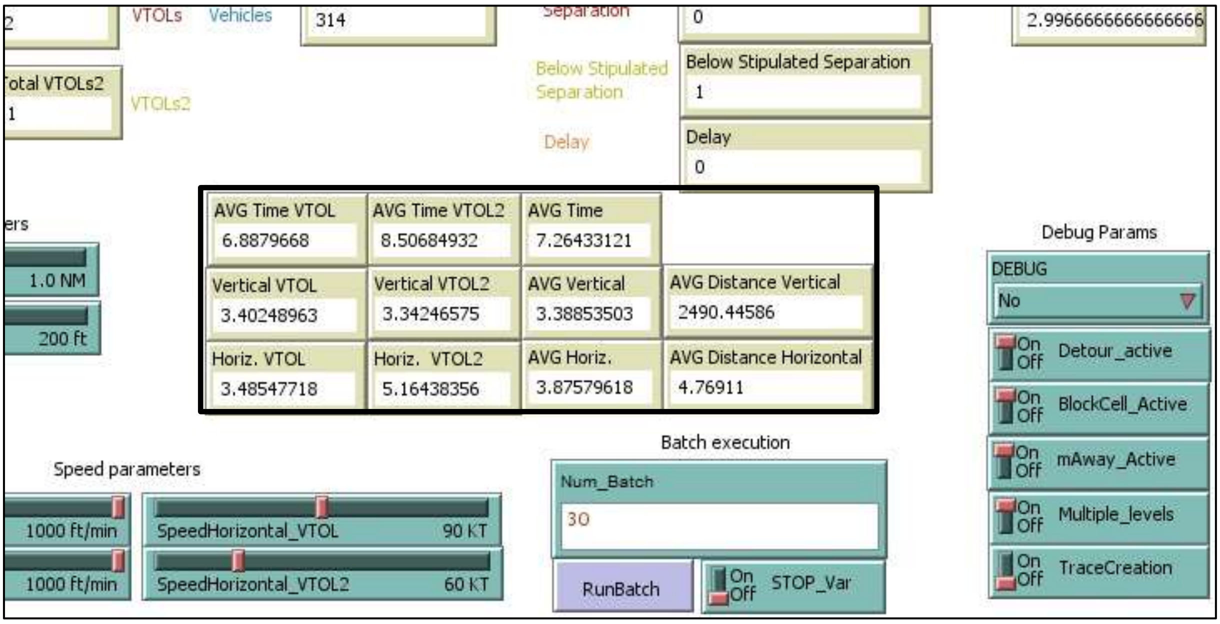

Figure 46: Netlogo Validation Output.

7.3.1. Conditional Probabilities of CGs, CMs, Airspace Complexity and Airspace Capacity

The conditional probabilities of all CGs were presented as 0.5 for each of the parameters, meaning that the complexity model will present, as a result, the average behavior of the system. Figure 47 shows how the conditional probability of CG is indicated.

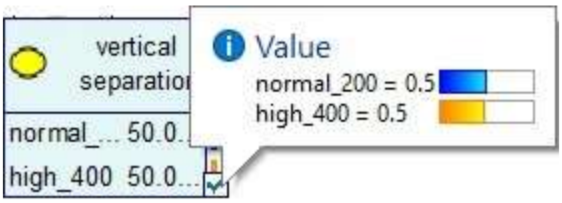

Figure 47: Conditional Probabilities of CGs.
Source: The author.

The challenge is to define the conditional probabilities of the CMs as a function of the CGs, that is, finding the probability of the CMs in each of the deciles of the CMs considering all possible combinations of the CG parameters.

Considering we have eleven inputs (CGs) to be used in the simulation, with two parameters for each of the inputs, we have a total of 2^{11}=2048 different scenarios. For each of the 2048 scenarios, one hundred simulations were performed, and the output (CMs) averages were extracted.

Below are the inputs (CG) and outputs (CM) used:

- Inputs (CG): De- Delay; Sc – Scenario (Perpendicular or General); N1 – Number of VTOL1, N2 - Number of VTOL2; CB – Presence or not of Cumulonimbus; VS1 -Vertical Speed VTOL1; HS1 – Horizontal Speed VTOL1; VS2 - Vertical Speed VTOL2; HS2 – Horizontal Speed VTOL2; HS – Horizontal Separation; VS – Vertical Separation.
- Outputs (CM): Na- Number of Aircraft; MS- Below Minimum Separation; SS - Below Stipulated Separation; and De- Delay.

The final version of the Netlogo model developed is available at: https://drive.google.com/drive/u/2/folders/0AF2q-Aop98gsUk9PVA.

Readers interested in replicating the simulations must first download Netlogo from: https://ccl.northwestern.edu/netlogo/download.shtml.

After selecting the desired scenario (according appendix C), users should click on “Setup” and “GO,” respectively. Then, after sorting the outputs in ascending order, the limits of each decile must be defined, as shown in table 21. Appendix C details the process of defining decile limits. These decile limits will be used for the insertion of CM in the Bayesian Network. Considering that each scenario was simulated 100 times (Appendix D presents the arguments), 2048 x 100 simulations were performed, varying all 11 CG, we found 2048 outputs for all CM (outputs are presented in absolute number of aircraft). Note, for example, that the greater the delay rate, the greater the complexity of the airspace. Thus, we can say that the smallest deciles have the smallest complexities, whereas the largest deciles have the greatest complexities.

Table 21: Output decile limits

Upper limit	Number of Aircraft (Na)	Below Minimum Separation (MS)	Below Stipulated Separation (SS)	Delay (De)
Decile 1	283.5262626	0.161616	0.626263	0.906061
Delice 2	292.9212121	0.282828	2.10101	3.054545
Decile 3	343.8007273	0.486364	11.27879	6.019101
Decile 4	481.7010101	0.757495	38.41818	12.24646
Decile 5	559.3838384	1.111111	95.66162	19.05051
Decile 6	574.7171717	1.515152	191.6667	30.40606
Decile 7	585.1141414	2.121212	345.5879	54.56566
Decile 8	696.2080808	3.10303	646.4323	71.52525
Decile 9	845.8707071	6.020202	1618.847	134.3747
Decile 10	890.2323232	15.31313	13911.93	416.3737

Source: The author.

The next step is to check how all simulations are distributed in deciles, for each of the 2048 scenarios. The process is explained in detail in Appendix C. Consider, for example, scenario 01 presented in Appendix C. Table 22 shows the probability distributions of the outputs of all simulations in the deciles (100 simulations).

Table 22: Distributions of the outputs of all simulations in the deciles – scenario 1.

Probability of each decile	Number of Aircraft (Na)	Below Minimum Separation (MS)	Below Stipulated Separation (SS)	Delay (De)
Decile 1	0.515151515	0.898989899	1	0.181818182
Delice 2	0.252525253	0	0	0.212121212
Decile 3	0.232323232	0	0	0.282828283
Decile 4	0	0	0	0.202020202
Decile 5	0	0	0	0.101010101
Decile 6	0	0	0	0.02020202
Decile 7	0	0.090909091	0	0
Decile 8	0	0	0	0
Decile 9	0	0.01010101	0	0
Decile 10	0	0	0	0

Source: The author.

With the probability distributions in all deciles, all results were entered into the Bayesian Network, considering the 2048 scenarios, as highlighted in tables 23, 24, 25, and 26. The proposed Bayesian Network is presented in Annex E.

Table 23: Distribution of the decile probabilities of the number of aircraft (Na).

Scenario						
Number of VTO...						
number of VTOL2						
quantity of CB1						
size						
vert speed VT...						
Horizontal Spe...						
vert speed VT...	ft200					
Horizontal Spe...	KT030				KT	
horizontal separ...	normal_5		high_10		normal_5	
vertical separati...	normal_200	high_400	normal_200	high_400	normal_200	high_400
decile_1	0.51515152	0.4040404	0.53535354	0.42424242	0.42424242	0.4040404
decile_2	0.25252525	0.27272727	0.29292929	0.28282828	0.3030303	0.32323232
decile_3	0.23232323	0.32323232	0.17171717	0.29292929	0.27272727	0.27272727
decile_4	0	0	0	0	0	0
decile_5	0	0	0	0	0	0
decile_6	0	0	0	0	0	0
decile_7	0	0	0	0	0	0
decile_8	0	0	0	0	0	0
decile_9	0	0	0	0	0	0
decile_10	0	0	0	0	0	0

Source: The author.

Table 24: Distribution of the decile probabilities of Below Minimum Separation (MS).

Scenario						
Number of VTO...						
number of VTOL2						
quantity of CB1						
size						
vert speed VT...						
Horizontal Spe...						
vert speed VT...	ft200					
Horizontal Spe...	KT030				KT	
horizontal separ...	normal_5		high_10		normal_5	
vertical separati...	normal_200	high_400	normal_200	high_400	normal_200	high_400
decile_1	0.8989899	0.81818182	0.90909091	0.86868687	0.7979798	0.87878788
decile_2	0	0	0	0	0	0
decile_3	0	0	0	0	0	0
decile_4	0	0	0	0	0	0
decile_5	0	0	0	0	0	0
decile_6	0	0	0	0	0	0
decile_7	0.090909091	0.13131313	0.050505051	0.12121212	0.17171717	0.11111111
decile_8	0	0	0	0	0	0
decile_9	0.01010101	0.050505051	0.04040404	0.01010101	0.03030303	0.01010101
decile_10	0	0	0	0	0	0

Source: The author.

Table 25: Distribution of the decile probabilities of Below Stipulated Separation (SS).

Scenario						
Number of VTO...						
number of VTOL2						
quantity of CB1						
size						
vert speed VT...						
Horizontal Spe...						
vert speed VT...	ft200					
Horizontal Spe...	KT030				KT	
horizontal separ...	normal_5		high_10		normal_5	
vertical separati...	normal_200	high_400	normal_200	high_400	normal_200	high_400
decile_1	1	0	0	0	1	0.03030303
decile_2	0	0.04040404	0.01010101	0	0	0.15151515
decile_3	0	0.61616162	0.3030303	0.04040404	0	0.64646465
decile_4	0	0.22222222	0.17171717	0.34343434	0	0.04040404
decile_5	0	0.01010101	0.060606061	0.03030303	0	0.04040404
decile_6	0	0.03030303	0.060606061	0.13131313	0	0.01010101
decile_7	0	0.03030303	0.1010101	0.11111111	0	0.02020202
decile_8	0	0.01010101	0.19191919	0.21212121	0	0.050505051
decile_9	0	0.04040404	0.1010101	0.12121212	0	0.01010101
decile_10	0	0	0	0.01010101	0	0

Source: The author.

Table 26: Distribution of the decile probabilities of Delay (De).

Scenario						
Number of VTO...						
number of VTOL2						
quantity of CB1						
size						
vert speed VT...						
Horizontal Spe...						
vert speed VT...	ft200					
Horizontal Spe...	KT030				KT	
horizontal separ...	normal_5		high_10		normal_5	
vertical separati...	normal_200	high_400	normal_200	high_400	normal_200	high_400
decile_1	0.18181818	0.18181818	0.19191919	0.17171717	0.12121212	0.25252525
decile_2	0.21212121	0.27272727	0.25252525	0.27272727	0.21212121	0.25252525
decile_3	0.28282828	0.29292929	0.2020202	0.25252525	0.27272727	0.16161616
decile_4	0.2020202	0.19191919	0.2020202	0.2020202	0.26262626	0.25252525
decile_5	0.1010101	0.050505051	0.13131313	0.090909091	0.11111111	0.080808081
decile_6	0.02020202	0.01010101	0.02020202	0.01010101	0.02020202	0
decile_7	0	0	0	0	0	0
decile_8	0	0	0	0	0	0
decile_9	0	0	0	0	0	0
decile_10	0	0	0	0	0	0

Source: The author.

The values of Airspace Complexity in the Bayesian Network derive from the results found for each CM. As shown in figure 68, the Airspace Complexity State will have the following correspondences in deciles:

i) Insignificant – deciles 1 and 2

ii) Low – deciles 3 and 4

iii) Acceptable – deciles 5 and 6

iv) High – deciles 7 and 8

v) Very High – deciles 9 and 10

Thus, considering that all CMs have the same influence on Airspace Complexity (linear relationship), the Airspace Complexity State Space will consider the probabilities of each CM remaining in the different deciles, taking into account the different combinations, such as the one shown in table 27.

Consider that in one scenario, the CMs were, respectively, in the 3rd, 6th, 7th, and 10th deciles. The proposed division of the complexity index is: deciles 1 and 2 — insignificant; deciles 3 and 4 – low; deciles 5 and 6 — acceptable; deciles 7 and 8 — high; and deciles 9 and 10 — very high. The Airspace Complexity probabilities for this scenario will be 0.25 low, 0.25 acceptable, 0.25 high, and 0.25 very high.

Table 27: Airspace Complexity State Space.

Number_of_air...										
below_minimun...										
below_stipulate...	decile_1									
delay	decile_1	decile_2	decile_3	decile_4	decile_5	decile_6	decile_7	decile_8	decile_9	decile_10
Insignificant	1	1	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Low	0	0	0.25	0.25	0	0	0	0	0	0
Acceptable	0	0	0	0	0.25	0.25	0	0	0	0
High	0	0	0	0	0	0	0.25	0.25	0	0
Veryhigh	0	0	0	0	0	0	0	0	0.25	0.25

Source: The author.

Figure 48 shows an example of the probabilities found for Airspace Complexity, based on the decile probabilities for each CM.

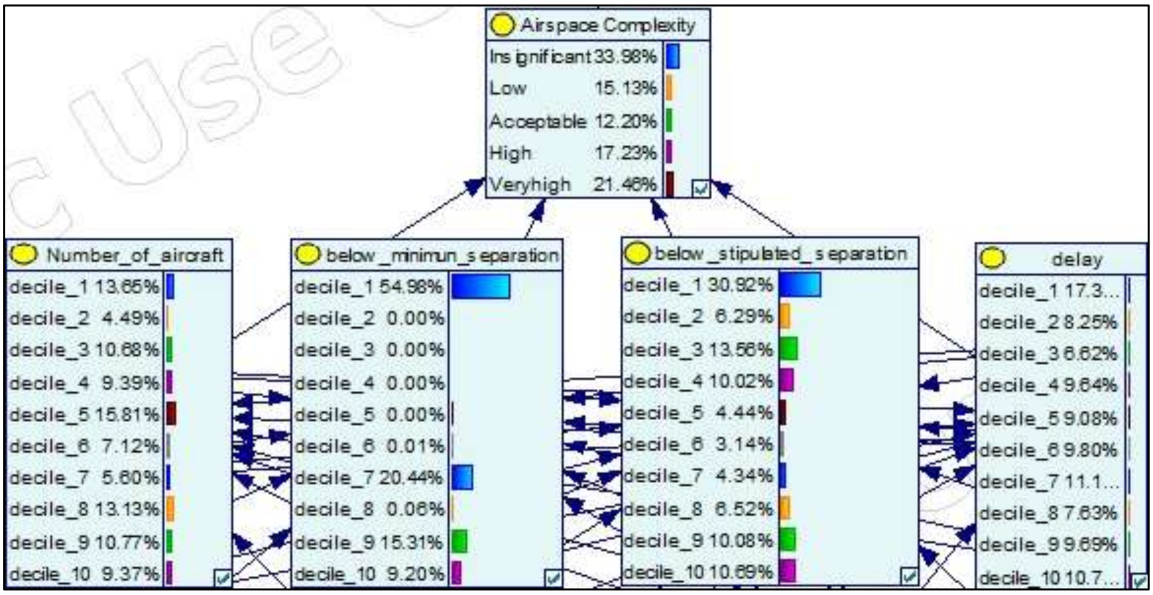

Figure 48: Airspace Complexity probability.
Source: The author.

Finally, the Airspace Capacity conditional probabilities are presented as an inverse function of the Airspace Complexity probabilities. Figure 49 shows that while the probability of airspace complexity being insignificant is 33.98%, the probability of airspace capacity being Very High is also 33.98%.

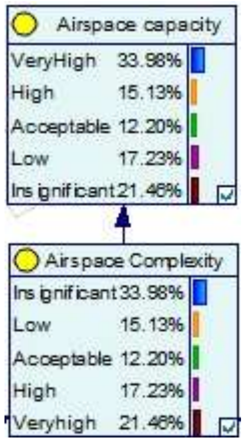

Figure 49: Probability Distribution of Airspace Capacity

7.3.2. Verifications of Capacity Model: Walkthrough approach

Detailed steps are presented in Appendix E.

The Walkthrough approach uses real case scenarios prepared by domain experts to assess the BN model predictions. Given that the airspace capacity is the inverse function of complexity, validating the capacity model entails validating the complexity model. After running the simulations, the results found for the Capacity Index will be compared with the expert's expectation of growth or reduction in airspace capacity.

In order to create an indicator, normalizing the probabilities presented in the states VH, H , A, L and I, we proposed a Capacity Index (CI) representing the Airspace Capacity probabilities found in the Bayesian Network by weighting the probabilities according to equation 21.

Equation 21: Capacity Index

$$Capacity\ Index = 3 * VH + 2 * H + A - 2 * L - 3 * I$$

Where:

- VH➔ Probability of Very High Capacity
- H➔ Probability of High Capacity
- A➔ Probability of Acceptable Capacity

- L➔ Probability of Low Capacity
- I➔ Probability of Insignificant Capacity

The CI exists in the interval [-3, 3], with the indices -3 and 3 representing, respectively, the smallest and largest capacity of the system.

Figures 50 and 51 display, respectively, the Bayesian Networks for the scenario configurations 1 and 2 presented in Appendix C, highlighting the Airspace Capacity probabilities found after running the simulations. Table 28 shows the Capacity Index at T+1, computed according to equation 21.

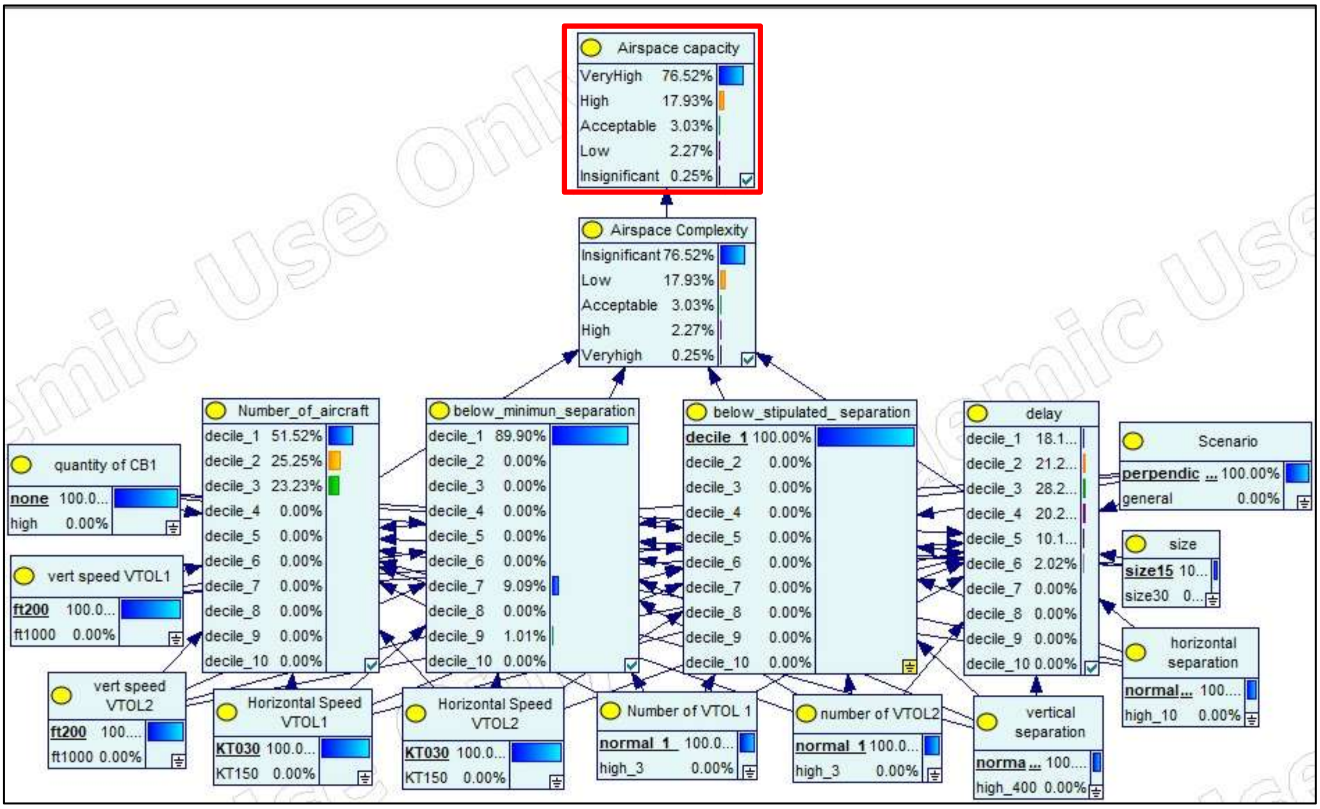

Figure 50: Bayesian Network related to scenario 1.

Source: The author.

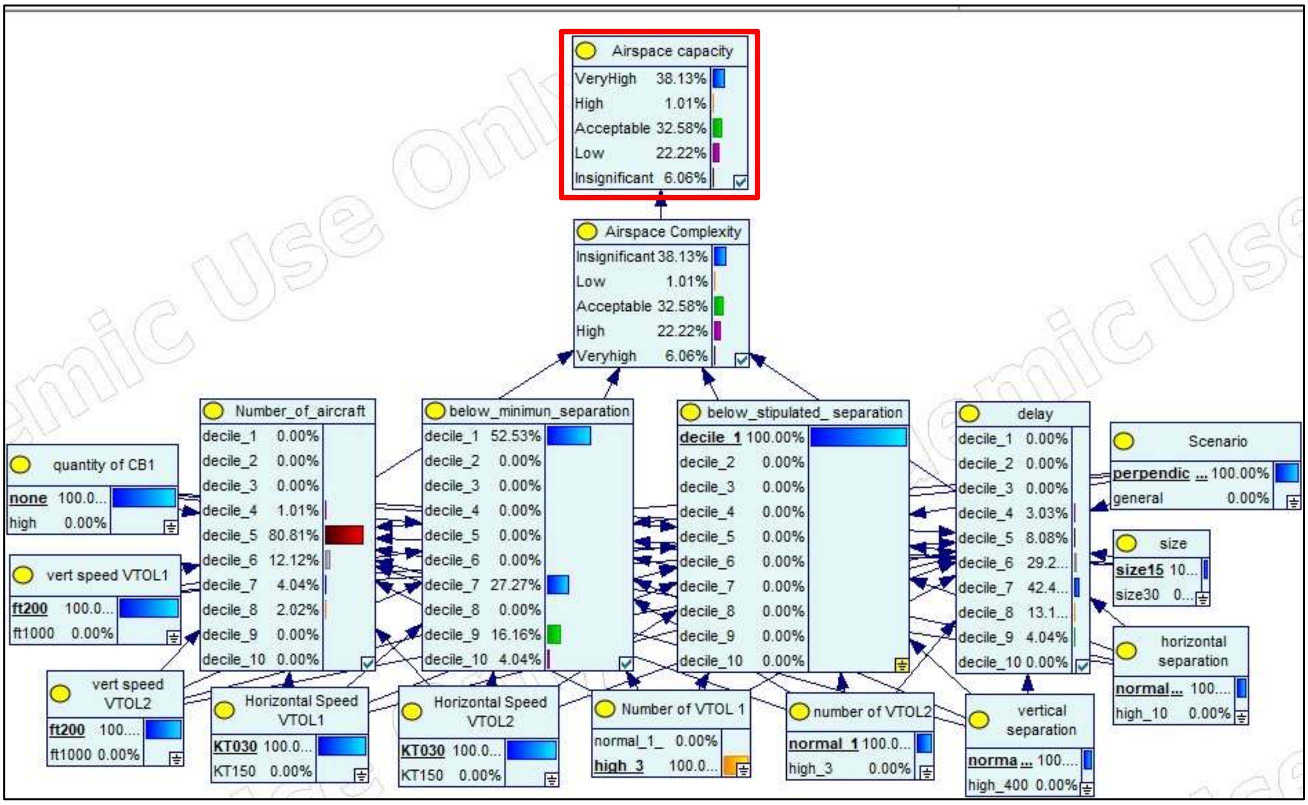

Figure 51: Bayesian Network related to scenario 2.

Source: The author.

Table 28: Capacity Index (CI) of the instant T+1

	Sc	N1	N2	CB	Size	VS 1	HS 1	VS2	HS2	HS	VS	CI
01	Perpendicular	1	1	0	15 X 15	200	30	200	30	0,5	200	2.61316
02	Perpendicular	3	1	0	15 X 15	200	30	200	30	0,5	200	0.8637

Source: The author.

We expect that the capacity at time T+1 will be greater in configuration 1 than in configuration 2, given that the number of aircraft in 2 is higher than that in 1. The CIs in table 29 meet these expectations.

Thus, seeking to validate the model (Appendix E), the Airspace Capacity Walkthrough approach will be carried out exhaustively, considering different scenario configurations presented in Appendix C.

Table 29 presents the CIs associated with scenarios 01 through 08 (Appendix C).

Table 29: CIs related to scenarios from 01 to 08

	Sc	N1	N2	CB	Size	VS 1	HS 1	VS2	HS2	HS	VS	CI
01	Perpendicular	1	1	0	15 X 15	200	30	200	30	0,5	200	2.6316
02	Perpendicular	3	1	0	15 X 15	200	30	200	30	0,5	200	0.8637
03	Perpendicular	1	3	0	15 X 15	200	30	200	30	0,5	200	0.7194
04	Perpendicular	3	3	0	15 X 15	200	30	200	30	0,5	200	-1.1315
05	Perpendicular	1	1	100	15 X 15	200	30	200	30	0,5	200	1.0177
06	Perpendicular	3	1	100	15 X 15	200	30	200	30	0,5	200	-0.1214
07	Perpendicular	1	3	100	15 X 15	200	30	200	30	0,5	200	-0.1164
08	Perpendicular	3	3	100	15 X 15	200	30	200	30	0,5	200	-0.2601

Source: The author.

However, an inconsistency was identified in the modeling during the walkthrough approach. The CG (11 input variables) will define the behavior of the CM (4 output variables), and the results will be divided into deciles. The CM will determine the complexity index and consequently the capacity index, with the highest deciles of the CM indicating the greatest complexities (lowest capacities). Note that the CB and number of VTOL 1 VTOL 2 number are CG (input variables) and the aircraft number is a CM (output variable). The greater the number of VTOL 1 and VTOL 2, the greater the number of aircraft and the greater the complexity index (lower capacity index). Thus, the expectation is that with the increase in the number of CBs, the complexity index will be increased and, consequently, the capacity will be reduced.

Still, increasing the CB number also reduces the number of aircraft in the system. Thus, the CB variable can reduce complexity in certain scenarios since the number of aircraft determines the complexity index. An inconsistency was observed when comparing scenarios 4 and 8 presented in table 25. We would expect the capacity for scenario 8 to be lower than that for scenario 4 since the former has a higher number of aircraft and a larger amount of CB. However, the capacity computed for scenario 4 (-1.1315) is considerably lower than the capacity for scenario 8 (-0.2601).

For this reason, the Bayesian Network was adjusted to exclude the number of aircraft as a CM. Figure 52 shows the adjusted Bayesian network.

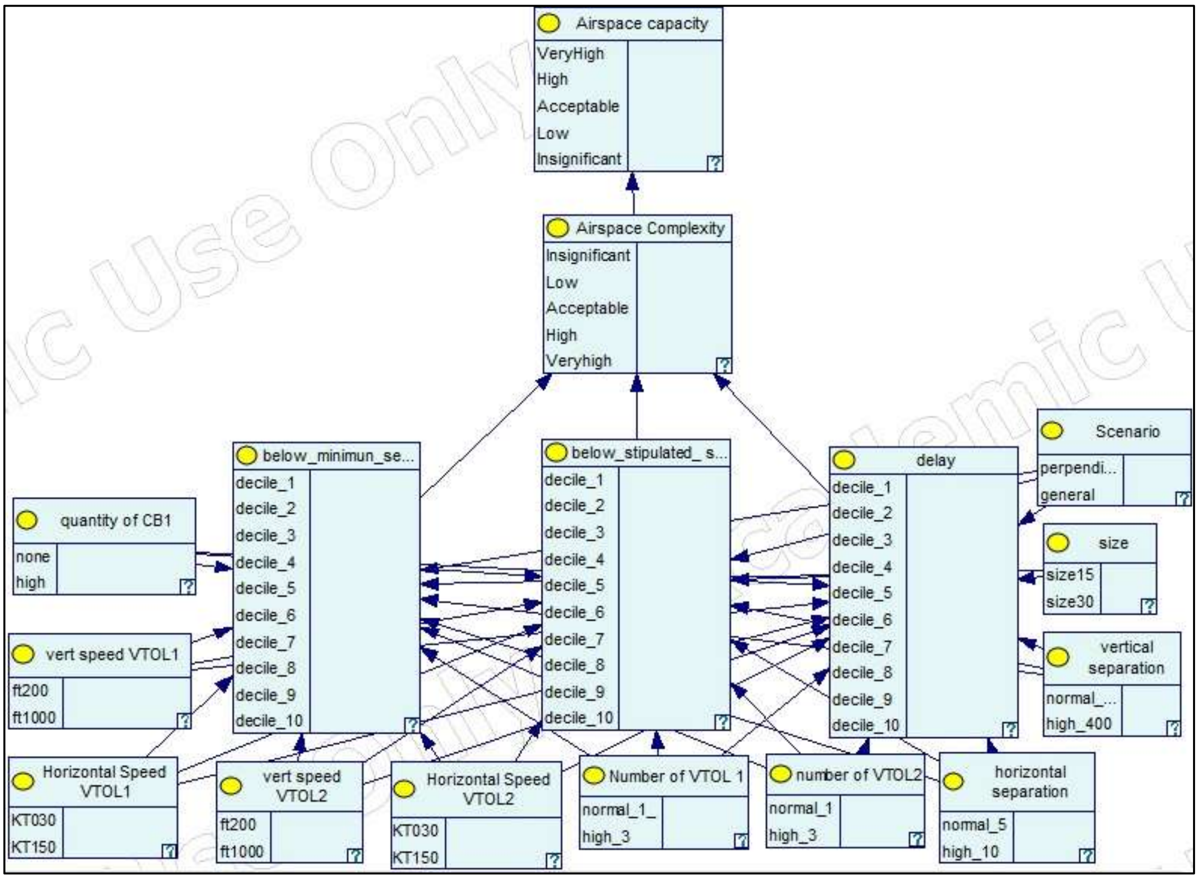

Figure 52: Adjusted Bayesian Network.

Source: The author.

Table 30 presents the CIs of the First Bayesian Network and Second Bayesian Network, which will be called, respectively, Initial Capacity Index (ICI) and Adjusted Capacity Index (ACI).

Table 30: CIs of the 2 Bayesian Networks (initial and adjusted)

	Sc	N1	N2	CB	Size	VS 1	HS 1	VS2	HS2	HS	SV	ICI	ACI
01	perpendicular	1	1	0	15 X 15	200	30	200	30	0,5	200	2.6316	2.5857
02	perpendicular	3	1	0	15 X 15	200	30	200	30	0,5	200	0.8637	0.8754
03	perpendicular	1	3	0	15 X 15	200	30	200	30	0,5	200	0.7194	0.6734
04	perpendicular	3	3	0	15 X 15	200	30	200	30	0,5	200	-1.1315	-0.5318
05	perpendicular	1	1	100	15 X 15	200	30	200	30	0,5	200	1.0177	0.3571
06	perpendicular	3	1	100	15 X 15	200	30	200	30	0,5	200	-0.1214	-0.8416
07	perpendicular	1	3	100	15 X 15	200	30	200	30	0,5	200	-0.1164	-0.8316
08	perpendicular	3	3	100	15 X 15	200	30	200	30	0,5	200	-0.2601	-0.9932

Source:The author.

Note that the models had the same behavior for scenarios without CB. However, under the Second Bayesian Network, the ACI values for scenarios 4 (-0.5318) and 8 (-0.9932) are consistent with our expectations. Next, we will use the adjusted Bayesian Network to investigate different situations and validate the model.

- Situation 1: Variation of the sizes of the scenarios, holding the other CG constant.

The expectation is that the CIs of the scenario with Size 30 X 30 will be greater than the CIs of the scenario with Size 15 X 15. As shown in table 31, the results corresponded to the expectations.

Table 31: Variation of the sizes of the scenarios

	Sc	**N1**	**N2**	**CB**	**Size**	**VS 1**	**HS 1**	**VS2**	**HS2**	**HS**	**VS**	**ACI**
1	perpendicular	1	1	0	15 X 15	200	30	200	30	0,5	200	2.5857
9	perpendicular	1	1	0	30 X 30	200	30	200	30	0,5	200	2.8854
17	perpendicular	1	1	0	15 X 15	1000	30	200	30	0,5	200	2.6061
25	perpendicular	1	1	0	30 X 30	1000	30	200	30	0,5	200	2.9226
33	perpendicular	1	1	0	15 X 15	200	150	200	30	0,5	200	2.3705
41	perpendicular	1	1	0	30 X 30	200	150	200	30	0,5	200	2.9597
49	perpendicular	1	1	0	15 X 15	1000	150	200	30	0,5	200	2.6463
57	perpendicular	1	1	0	30 X 30	1000	150	200	30	0,5	200	2.9597
65	perpendicular	1	1	0	15 X 15	200	30	1000	30	0,5	200	2.606
73	perpendicular	1	1	0	30 X 30	200	30	1000	30	0,5	200	2.9899
81	perpendicular	1	1	0	15 X 15	1000	30	1000	30	0,5	200	2.8484
89	perpendicular	1	1	0	30 X 30	1000	30	1000	30	0,5	200	2.983
97	perpendicular	1	1	0	15 X 15	200	150	1000	30	0,5	200	2.6935
105	perpendicular	1	1	0	30 X 30	200	150	1000	30	0,5	200	2.9595

Source: The author.

The most accentuated difference in CIs is between scenarios with the largest possible number of aircraft (N1=3 and N2=3), as table 32 shows. These results also meet our expectations.

Table 32: Largest possible number of aircraft (N1=3 and N2=3).

	Sc	N1	N2	CB	Size	VS 1	HS 1	VS2	HS2	HS	VS	ACI
4	perpendicular	3	3	0	15 X 15	200	30	200	30	0,5	200	-0.5318
12	perpendicular	3	3	0	30 X 30	200	30	200	30	0,5	200	1.741
20	perpendicular	3	3	0	15 X 15	1000	30	200	30	0,5	200	-0.0065
28	perpendicular	3	3	0	30 X 30	1000	30	200	30	0,5	200	2.2861
36	perpendicular	3	3	0	15 X 15	200	150	200	30	0,5	200	-0.66
44	perpendicular	3	3	0	30 X 30	200	150	200	30	0,5	200	2.1715
52	perpendicular	3	3	0	15 X 15	1000	150	200	30	0,5	200	0.01
60	perpendicular	3	3	0	30 X 30	1000	150	200	30	0,5	200	2.2257
68	perpendicular	3	3	0	15 X 15	200	30	1000	30	0,5	200	-0.0878
76	perpendicular	3	3	0	30 X 30	200	30	1000	30	0,5	200	2.266
84	perpendicular	3	3	0	15 X 15	1000	30	1000	30	0,5	200	1.8113
92	perpendicular	3	3	0	30 X 30	1000	30	1000	30	0,5	200	2.6062
100	perpendicular	3	3	0	15 X 15	200	150	1000	30	0,5	200	-0.1717
108	perpendicular	3	3	0	30 X 30	200	150	1000	30	0,5	200	2.1682

Source: The author.

- Situation 2: Variation of the number of CB, holding the other CG constant.

The expectation is that the CIs of the CB 0 configuration will be greater than the CIs of the CB 100 configuration. As seen in table 33, the results corresponded to our expectations.

Table 33: Variation of the number of CB.

	Sc	N1	N2	CB	Size	VS 1	HS 1	VS2	HS2	HS	VS	ACI
1	perpendicular	1	1	0	15 X 15	200	30	200	30	0,5	200	2.5857
5	perpendicular	1	1	100	15 X 15	200	30	200	30	0,5	200	0.3571
17	perpendicular	1	1	0	15 X 15	1000	30	200	30	0,5	200	2.6061
21	perpendicular	1	1	100	15 X 15	1000	30	200	30	0,5	200	0.1178
33	perpendicular	1	1	0	15 X 15	200	150	200	30	0,5	200	2.3705
37	perpendicular	1	1	100	15 X 15	200	150	200	30	0,5	200	0.3435
49	perpendicular	1	1	0	15 X 15	1000	150	200	30	0,5	200	2.6463
53	perpendicular	1	1	100	15 X 15	1000	150	200	30	0,5	200	0.394
65	perpendicular	1	1	0	15 X 15	200	30	1000	30	0,5	200	2.606
69	perpendicular	1	1	100	15 X 15	200	30	1000	30	0,5	200	0.1348
81	perpendicular	1	1	0	15 X 15	1000	30	1000	30	0,5	200	2.8484
85	perpendicular	1	1	100	15 X 15	1000	30	1000	30	0,5	200	0.2627
97	perpendicular	1	1	0	15 X 15	200	150	1000	30	0,5	200	2.6935
101	perpendicular	1	1	100	15 X 15	200	150	1000	30	0,5	200	2.6667

Source: The author.

In all configurations the CIs presented were consistent with expectations, except for scenarios 97 and 101, where the CIs were practically identical. Thus, verifications and adjustments will be necessary in the modeling.

Figures 53 and 54 represent scenarios 97 and 101, respectively. The CM, particularly the Delay measure, behaved unexpectedly: the Delay remained in the first decile for the configuration with CB 100, when, instead, we would expect that the presence of CB would lead to greater delays — that is, in higher deciles.

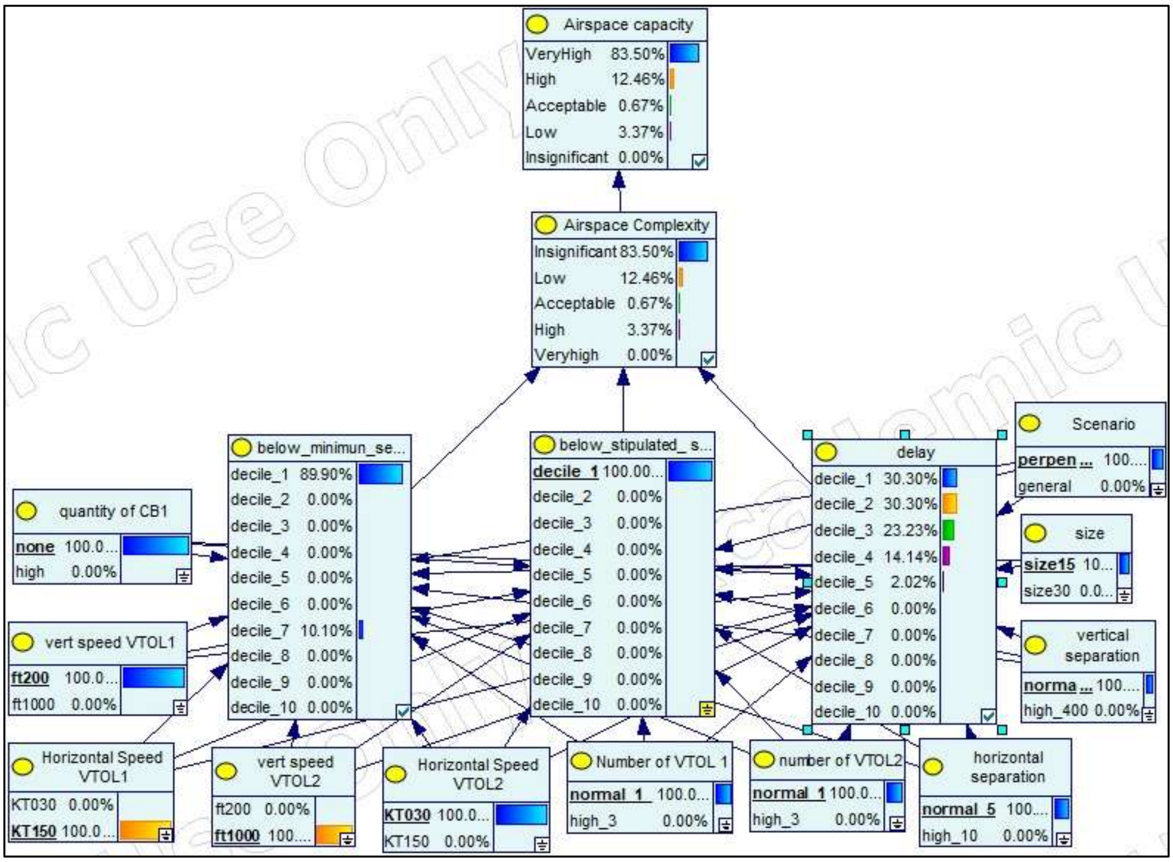

Figure 53: BN of Scenario 97.
Source: The author.

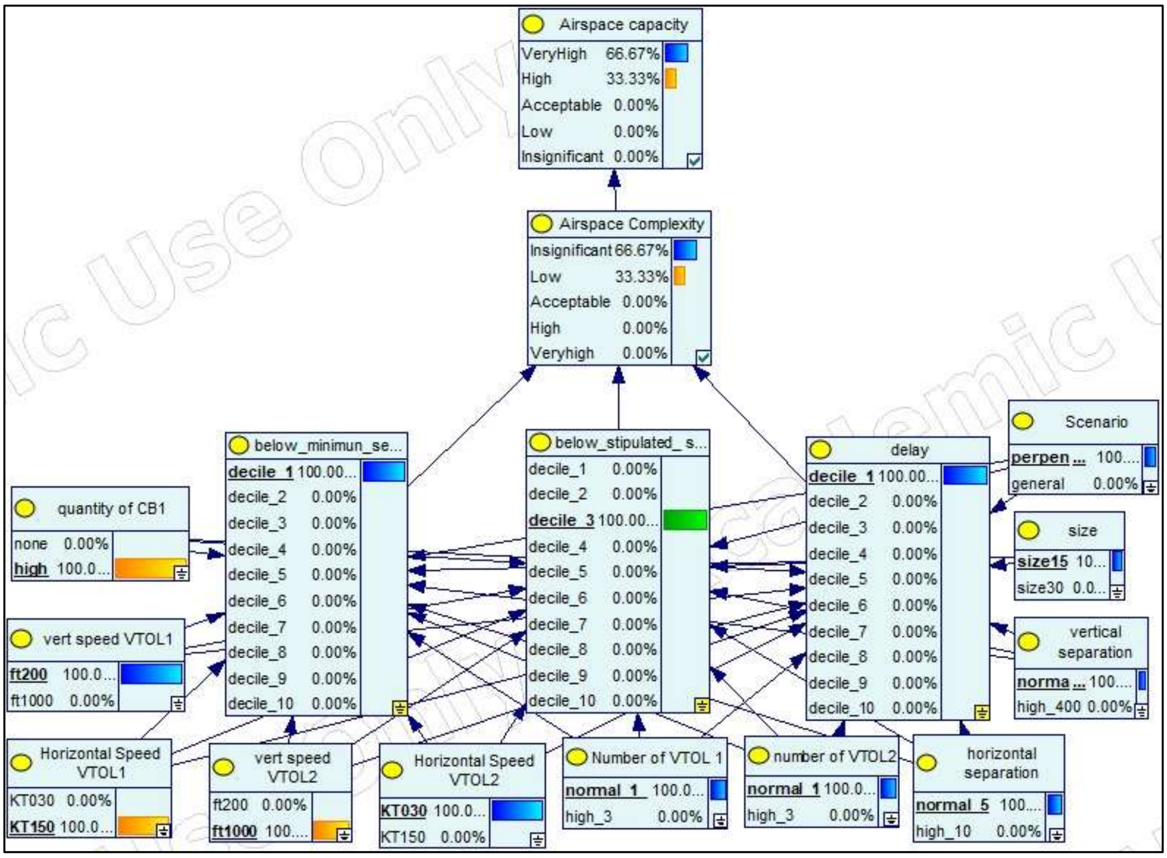

Figure 54: BN of Scenario 101.
Source: The author.

The following steps were taken for verification and adjustment:

1) Verification of conditional probabilities inserted in the Bayesian Network, specifically for the CM, considering scenario 101, followed by comparison with the Netlogo simulation results.
    a. Delay: Table 34 presents the conditional probabilities inserted in the Bayesian Network for scenario 101 and table 35 presents the Netlogo [24] simulations results.

[24]Delay is one of the CM in the Bayesian Network and one of the outputs in the Netlogo simulations — similarly for the Below Minimum Separation and Below Stipulated Separation. In addition, all 11 CGs in the Bayesian Network are inputs in the Netlogo simulations.

Table 34: DE - Conditional probabilities inserted in the Bayesian Network for configuration 101.

Scenario								
Number of VTO...								
number of VTOL2								
quantity of CB1								
size								
vert speed VT...								
Horizontal Spe...	KT150							
vert speed VT...	00				ft10			
Horizontal Spe...	KT150				KT030			
horizontal separ...	normal_5		high_10		normal_5		high_10	
vertical separati...	normal_200	high_400	normal_200	high_400	normal_200	high_400	normal_200	high_400
decile_1	0	0	0	0	1	0	0	0
decile_2	0	0	0	0	0	0	0	0
decile_3	0	0	0	0	0	0	0	0
decile_4	0	0	0	0	0	0	0	0
decile_5	0	0	0	0	0	0	0	0
decile_6	0	0	0	0	0	0.01010101	0	0
decile_7	0.070707071	0.03030303	0.03030303	0.03030303	0	0.22222222	0.13131313	0.060606061
decile_8	0.43434343	0.43434343	0.38383838	0.29292929	0	0.52525252	0.57575758	0.46464647
decile_9	0.4949495	0.53535354	0.58585859	0.67676768	0	0.24242424	0.29292929	0.47474747
decile_10	0	0	0	0	0	0	0	0

Source: The author.

Table 35: DE- Results found in the Netlogo Simulation.

Delay	The amount	% (Probability)
Decile 1	0	0
Decile 2	0	0
Decile 3	0	0
Decile 4	0	0
Decile 5	0	0
Decile 6	0	0
Decile 7	26	0.262626263
Decile 8	53	0.535353535
Decile 9	20	0.202020202
Decile 10	0	0

Souce: The author.

b. Below stipulated Separations: the results in Netologo simulations are identical to the conditional probabilities entered in the Bayesian Network.
c. Below Minimum Separation: Table 36 presents the conditional probabilities entered in the Bayesian Network for the scenario 101 and table 37 presents the results found in the Netlogo simulations.

Table 36: MS - Conditional probabilities entered the Bayesian Network for the scenario 101.

Scenario								
Number of VTO...								
number of VTOL2								
quantity of CB1								
size								
vert speed VT...								
Horizontal Spe...	KT150							
vert speed VT...	00				ft1(			
Horizontal Spe...	KT150				KT030			
horizontal separ...	normal_5		high_10		normal_5		high_10	
vertical separati...	normal_200	high_400	normal_200	high_400	normal_200	high_400	normal_200	high_400
decile_1	0.44444444	0.29292929	0.42424242	0.42424242	1	0.37373737	0.55555556	0.3030303
decile_2	0	0	0	0	0	0	0	0
decile_3	0	0	0	0	0	0	0	0
decile_4	0	0	0	0	0	0	0	0
decile_5	0	0	0	0	0	0	0	0
decile_6	0	0	0	0	0	0	0	0
decile_7	0.37373737	0.36363636	0.41414141	0.28282828	0	0.36363636	0.3030303	0.37373737
decile_8	0	0	0	0	0	0	0	0
decile_9	0.18181818	0.33333333	0.15151515	0.28282828	0	0.24242424	0.14141414	0.28282828
decile_10	0	0.01010101	0.01010101	0.01010101	0	0.02020202	0	0.04040404

Source: The author.

Table 37: Results found in the Netlogo simulations.

Below Stipulate Separation	The amount	% (Probability)
Decile 1	53	0.535353535
Decile 2	0	0
Decile 3	0	0
Decile 4	0	0
Decile 5	0	0
Decile 6	0	0
Decile 7	32	0.323232323
Decile 8	0	0
Decile 9	12	0.121212121
Decile 10	2	0.02020202

Source: The author.

After entering the correct conditional probabilities in the Bayesian network, the new CI for scenario 101, shown in table 38, meets our expectations.

Table 38: new CI found for scenario 101, after the adjustments.

	Sc	N1	N2	CB	Size	VS 1	HS 1	VS2	HS2	HS	VS	ACI
97	perpendicular	1	1	0	15 X 15	200	150	1000	30	0,5	200	2.6935
101	perpendicular	1	1	100	15 X 15	200	150	1000	30	0,5	200	0.1112

Source: The author.

- Situation 3: Variation of the horizontal separation, holding the other CG constant.

The expectation is that the CIs for scenarios with HS 1 are lower than the CIs for scenarios with HS 0.5 since the required separation parameters are higher. As seen in table 39, the results correspond to our expectations.

Table 39: Variation of the horizontal separation, keeping the other CG constant.

	Sc	N1	N2	CB	Size	VS 1	HS 1	VS2	HS2	HS	VS	ACI
1	perpendicular	1	1	0	15 X 15	200	30	200	30	0,5	200	2.5857
257	perpendicular	1	1	0	15 X 15	200	30	200	30	1	200	1.6699
17	perpendicular	1	1	0	15 X 15	1000	30	200	30	0,5	200	2.6061
273	perpendicular	1	1	0	15 X 15	1000	30	200	30	1	200	2.0674
65	perpendicular	1	1	0	15 X 15	200	30	1000	30	0,5	200	2.606
321	perpendicular	1	1	0	15 X 15	200	30	1000	30	1	200	2.0605
81	perpendicular	1	1	0	15 X 15	1000	30	1000	30	0,5	200	2.8484
337	perpendicular	1	1	0	15 X 15	1000	30	1000	30	1	200	2.5926
129	perpendicular	1	1	0	15 X 15	200	30	200	150	0,5	200	2.3873
385	perpendicular	1	1	0	15 X 15	200	30	200	150	1	200	1.68
145	perpendicular	1	1	0	15 X 15	1000	30	200	150	0,5	200	2.6736
401	perpendicular	1	1	0	15 X 15	1000	30	200	150	1	200	1.9966
193	perpendicular	1	1	0	15 X 15	200	30	1000	150	0,5	200	2.6632
449	perpendicular	1	1	0	15 X 15	200	30	1000	150	1	200	1.9696

Source: The author.

- Situation 4: Variation of vertical separation, holding the other CG constant.

The expectation is that the CIs for scenarios with VS 400 are lower than the CIs for scenarios with VS 200 since the required separation parameters are higher. As seen in table 40, the results correspond to our expectations.

Table 40: Variation of vertical separation, keeping the other CG constant.

	Sc	N1	N2	CB	Size	VS 1	HS 1	VS2	HS2	HS	VS	ACI
1	perpendicular	1	1	0	15 X 15	200	30	200	30	0,5	200	2.5857
513	perpendicular	1	1	0	15 X 15	200	30	200	30	0,5	400	2.0237
17	perpendicular	1	1	0	15 X 15	1000	30	200	30	0,5	200	2.6061
529	perpendicular	1	1	0	15 X 15	1000	30	200	30	0,5	400	2.3399
33	perpendicular	1	1	0	15 X 15	200	150	200	30	0,5	200	2.3705
545	perpendicular	1	1	0	15 X 15	200	150	200	30	0,5	400	2.2659
49	perpendicular	1	1	0	15 X 15	1000	150	200	30	0,5	200	2.6463
561	perpendicular	1	1	0	15 X 15	1000	150	200	30	0,5	400	2.4953
65	perpendicular	1	1	0	15 X 15	200	30	1000	30	0,5	200	2.606
577	perpendicular	1	1	0	15 X 15	200	30	1000	30	0,5	400	2.2323
81	perpendicular	1	1	0	15 X 15	1000	30	1000	30	0,5	200	2.8484
593	perpendicular	1	1	0	15 X 15	1000	30	1000	30	0,5	400	2.6634
97	perpendicular	1	1	0	15 X 15	200	150	1000	30	0,5	200	2.6935
609	perpendicular	1	1	0	15 X 15	200	150	1000	30	0,5	400	2.4413

The results found in the Model with the different combinations of CG Horizontal Speed - VTOL 1 (HS1) and VTOL 2 (HS2), Vertical Speed - VTOL 1 (VS1) and 2 (VS2) and Scenario (Sc) - Perpendicular and General, were consistent, the model being considered validated.

Due to CI variations under different scenarios, the results from some scenarios will be discussed in the chapter “Discussion of Results”.

To analyze the relationship between the CGs and the CI, a Linear Regression was performed, as presented in table 41, where CI is the dependent variable and the CGs are the independent variables.

The only variables that are not statistically significant are HS1 (Horizontal Speed VTOL 1) and HS 2 (Horizontal Speed VTOL 2), with $p<0.01$ (99% confidence interval).

Table 41: Linear Regression.

Variable	Difference in Mean Capacity	99% Confidence Interval
Sc (Ref. Geral)	-0.589*** (0.079)	[-0.794, -0.385]
N1 (Ref. 1)	-1.211*** (0.076)	[-1.406, -1.015]
N2 (Ref. 1)	-1.175*** (0.076)	[-1.371, -0.979]
CB (Ref. 0)	-1.957*** (0.068)	[-2.132, -1.782]
Size (Ref. 15 X 15)	1.659*** (0.072)	[1.474, 1.843]
VS1 (Ref. 200)	0.458*** (0.080)	[0.253, 0.664]
HS1 (Ref. 30)	-0.083 (0.080)	[-0.290, 0.124]
VS2 (Ref. 200)	0.458*** (0.080)	[0.253, 0.664]
HS2 (Ref. 30)	-0.085 (0.080)	[-0.292, 0.122]
SH (Ref. 0.5)	-0.690*** (0.079)	[-0.893, -0.486]
SV (Ref. 200)	-0.446*** (0.080)	[-0.652, -0.240]

[1] Standard errors in parentheses
[2] ***p<0.01

Source: The author.

The coefficient estimate represents the difference between the mean CI for observations in the non-reference category and the mean CI for those in the reference category. For example, consider the variable CB. The mean CI for the CB 100 category is 1.957 lower (-1.957) than the mean CI for the CB 0 category.

The confidence interval is computed as the coefficient estimate plus or minus the critical value of the distribution multiplied by the standard error of the coefficient. Consider, for example, the regression coefficient for the variable CB, which is estimated to be -1.957 with a standard error of 0.068.The critical value for a 99% confidence level is approximately 2.58 (table 42). Hence, the lower limit of the confidence interval is -1.957 - 2.58*(0.068) = -2.132, and the upper limit is 1.957 + 2.58*(0.068) = -1.782.

Table 42: Critical value.

Confidence level	Critical (z) value to be used in confidence interval calculation
50%	0.67449
75%	1.15035
90%	1.64485
95%	1.95996
97%	2.17009
99%	2.57583
99.9%	3.29053

The model validation tests are corroborated with the statistical tests. As previously mentioned, the behavior of the variables HS1, HS2, VS1, VS2 and Sc (Perpendicular and General) will be discussed in the chapter “Discussion of Results”, also considered part of the model validation process.

8. DISCUSSION OF RESULTS AND COMPLEXITY THRESHOLD

This chapter discusses the results from combining different inputs in the developed model. Some of these results will only make sense if we keep in mind that we assumed specific air traffic rules in the simulations, which are different from those encountered in ATM.

Later in the chapter, the concept of Complexity Threshold will be constructed from the Capacity Index results yielded by the model. A dashboard will then be used to represent it. The following analyses can also be seen as part of the model validation process.

8.1. Discussion of Results

Using the Capacity Index results from Appendix C and the linear regression shown in table 41, this chapter discusses results that were not presented in the validation chapter — recall that there are 2^{11} possible variable combinations.

Considering the interval range [-3, 3] of the capacity index (CI), will be presented the percentage of the Capacity Index (CIP) in the comparisons of the scenarios. For example, CI 2.5518 corresponds to a CIP of 92,530%, while CI -2.0337 corresponds to a CIP of 16.105%[25].

1st Discussion – Parameter: Perpendicular and General

Table 43 shows the comparison between the perpendicular and general parameters, considering CI, varying the amount of CB and the size of the scenarios. The other variables were constant, considering the lower parameters of N1, N2, VS1, HS1, VH2, HS2, HS and VS.

[25] CIP=(100/6)*(CI+3)

Table 43: comparison between the perpendicular and general parameters

	Sc	N1	N2	CB	Size	VS 1	HS 1	VS2	HS2	HS	VS	CI	CIP	difference
1	perpendicular	1	1	0	15 X 15	200	30	200	30	0,5	200	2.5857	93.095%	0.565%
1025	general	1	1	0	15 X 15	200	30	200	30	0,5	200	2.5518	92.530%	
5	perpendicular	1	1	100	15 X 15	200	30	200	30	0,5	200	0.3571	55.952%	-20.2617%
1029	general	1	1	100	15 X 15	200	30	200	30	0,5	200	1.5728	76.213%	
9	perpendicular	1	1	0	30 X 30	200	30	200	30	0,5	200	2.8854	98.090%	2.245%
1033	general	1	1	0	30 X 30	200	30	200	30	0,5	200	2.7507	95.845%	
13	perpendicular	1	1	100	30 X 30	200	30	200	30	0,5	200	2.3099	88.498%	-1.2250%
1037	general	1	1	100	30 X 30	200	30	200	30	0,5	200	2.3834	89.723%	

Source: The author.

Considering the scenarios with the presence of CB, the only one that showed a significant difference was in the comparison of scenarios 5 and 1029, where the CI of the general parameter is considerably higher than the perpendicular, with a difference of 20.2617%.

Table 44 shows the comparison between the general perpendicular parameters, considering the CIP, varying the amount of CB and the size of the scenarios. The other variables were constant, considering the lower parameters of N1, N2, VS1, HS1, VH2 and HS2 and upper parameters for HS and VS.

Table 44: Comparison between the general perpendicular parameters.

	Sc	N1	N2	CB	Size	VS 1	HS 1	VS2	HS2	HS	VS	CI	CIP	difference
769	perpendicular	1	1	0	15 X 15	200	30	200	30	1	400	1.5218	75.363%	-11.5017%
1793	general	1	1	0	15 X 15	200	30	200	30	1	400	2.2119	86.865%	
773	perpendicular	1	1	100	15 X 15	200	30	200	30	1	400	-2.0337	16.105%	-48.257%
1797	general	1	1	100	15 X 15	200	30	200	30	1	400	0.8617	64.362%	
777	perpendicular	1	1	0	30 X 30	200	30	200	30	1	400	2.4917	91.528%	0.23%
1801	general	1	1	0	30 X 30	200	30	200	30	1	400	2.4779	91.298%	
781	perpendicular	1	1	100	30 X 30	200	30	200	30	1	400	1.3837	73.062%	-12.963%
1805	general	1	1	100	30 X 30	200	30	200	30	1	400	2.1615	86.025%	

Source: The author.

The general scenario has a CI with significant difference for the perpendicular parameter, in all scenarios, except for the comparison of scenarios 777 and 1801. The biggest difference found is in the scenario with a size of 15 X 15 and with the presence of CB.

Conclusion of the 1st discussion: In all comparisons, observing tables 45 and 46 and Annex A, the general parameter has a highest CI with significant difference increasing considerably with the presence of CB and size 15 X 15. When the horizontal and vertical separation minimums are increased, the index differences between the general and perpendicular parameters increase further. The perpendicular parameter has a CI significantly higher than the general scenario only in combinations without the presence of CB and with the reduction of the separation minima.

2nd Discussion – VS1 and VS2 (200 ft/min or 1000 ft/min)

For this analysis, will be used only the general parameter.

Table 45 presents scenarios with the least amount of VTOL and the lowest horizontal speeds (HS1 and HS2).

Table 45: scenarios with the least amount of VTOL and the lowest horizontal speeds (HS1 and HS2).

	Sc	N1	N2	CB	Size	VS 1	HS 1	VS2	HS2	HS	VS	CI	CIP	difference
1025	general	1	1	0	15 X 15	200	30	200	30	0,5	200	2.5518	92.530%	1025/1105 -6.177%
1041	general	1	1	0	15 X 15	1000	30	200	30	0,5	200	2.7814	96.357%	
1089	general	1	1	0	15 X 15	200	30	1000	30	0,5	200	2.6396	93.993%	
1105	general	1	1	0	15 X 15	1000	30	1000	30	0,5	200	2.9224	98.707%	
1029	general	1	1	100	15 X 15	200	30	200	30	0,5	200	1.5728	76.213%	1029-1109 -4.93%
1045	general	1	1	100	15 X 15	1000	30	200	30	0,5	200	1.7779	79.632%	
1093	general	1	1	100	15 X 15	200	30	1000	30	0,5	200	1.6262	77.103%	
1109	General	1	1	100	15 X 15	1000	30	1000	30	0,5	200	1.8686	81.143%	

Source: The author.

It is observed that the difference between the VS1 and VS2 scenarios of 200 ft/min and 1000ft/min, without CB and with CB, respectively, is – 6.177% and – 4.93%.

Table 46 uses the same parameters as table 47, considering the highest horizontal speeds (HS1 and HS2).

Table 46: Same parameters as table 45, considering the highest horizontal speeds (HS1 and HS2).

	Sc	N1	N2	CB	Size	VS 1	HS 1	VS2	HS2	HS	VS	CI	CIP	difference
1185	General	1	1	0	15 X 15	200	150	200	150	0,5	200	2.2124	86.873%	1185/1265 -9.535%
1201	General	1	1	0	15 X 15	1000	150	200	150	0,5	200	2.512	91.867%	
1249	General	1	1	0	15 X 15	200	150	1000	150	0,5	200	2.4816	91.360%	
1265	general	1	1	0	15 X 15	1000	150	1000	150	0,5	200	2.7845	96.408%	
1189	general	1	1	100	15 X 15	200	150	200	150	0,5	200	1	66.667%	1189-1269 -9.822%
1205	general	1	1	100	15 X 15	1000	150	200	150	0,5	200	1.2698	71.163%	
1253	general	1	1	100	15 X 15	200	150	1000	150	0,5	200	1.1012	68.353%	
1269	general	1	1	100	15 X 15	1000	150	1000	150	0,5	200	1.5893	76.488%	

Source: The author.

It is observed that the difference between the VS1 and VS2 scenarios of 200 ft/min and 1000ft/min, without CB and with CB, respectively, is –9.535% and –9.822%.

Table 47 presents the same considerations as Table 42, considering now the increase in VTOL (N1 and N2= 3).

Table 47: Same parameters as Table 46, considering now the increase in VTOL (N1 and N2= 3).

	Sc	N1	N2	CB	Size	VS 1	HS 1	VS2	HS2	HS	VS	CI	CIP	difference
1028	general	3	3	0	15 X 15	200	30	200	30	0,5	200	-0.4879	41.868%	1028/1108 -37.192%
1044	general	3	3	0	15 X 15	1000	30	200	30	0,5	200	0.3366	55.610%	
1092	general	3	3	0	15 X 15	200	30	1000	30	0,5	200	0.3568	55.947%	
1108	general	3	3	0	15 X 15	1000	30	1000	30	0,5	200	1.791	79.850%	
1032	general	3	3	100	15 X 15	200	30	200	30	0,5	200	-0.8416	35.973%	1032-1112 -6.447%
1048	general	3	3	100	15 X 15	1000	30	200	30	0,5	200	-0.7048	38.253%	
1096	general	3	3	100	15 X 15	200	30	1000	30	0,5	200	-0.7138	38.103%	
1112	general	3	3	100	15 X 15	1000	30	1000	30	0,5	200	-0.4548	42.420%	

Source: The author.

When we vary VS1 and VS2, we observe that the difference in CI is considerable without the presence of CB.

Table 48 presents the same conditions as table 49, considering now the increase in VTOL (N1 and N2= 3).

Table 48: Same parameters as table 47, considering now the increase in VTOL (N1 and N2= 3).

	Sc	N1	N2	CB	Size	VS 1	HS 1	VS2	HS2	HS	VS	CI	CIP	difference
1188	general	3	3	0	15 X 15	200	150	200	150	0,5	200	-0.6802	38.663%	1188/1268 -34.450%
1204	general	3	3	0	15 X 15	1000	150	200	150	0,5	200	-0.2798	45.337%	
1252	general	3	3	0	15 X 15	200	150	1000	150	0,5	200	-0.2796	45.340%	
1268	general	3	3	0	15 X 15	1000	150	1000	150	0,5	200	1.3868	73.113%	
1192	general	3	3	100	15 X 15	200	150	200	150	0,5	200	-0.9663	33.895%	1192-1272 -3.815%
1208	general	3	3	100	15 X 15	1000	150	200	150	0,5	200	-0.9224	34.627%	
1256	general	3	3	100	15 X 15	200	150	1000	150	0,5	200	-0.9428	34.287%	
1272	general	3	3	100	15 X 15	1000	150	1000	150	0,5	200	-0.7374	37.710%	

Source: The author.

When we vary VS1 and VS2, we observe that the difference in CI is considerable without the presence of CB.

Conclusion of the 2nd discussion: In all comparisons, observing tables 47, 48, 49, 50 and Annex A, the largest VS1 and VS2 have the highest CI, considerably increasing the percentage difference for the lowest scenarios and with the highest amount of VTOL (N1 and N2=3).

3rd Discussion – HS1 and HS2 (30 KT or 150 KT)

We must consider that the linear regression shown in table 42, shows the only non-significant variables are HS1 and HS2. For this analysis, will be used only the general parameter.

Table 49 presents a scenario considering the lower limits for VS1 and VS2 and with the smallest amounts of VTOL.

Table 49: Scenario considering the lower limits for VS1 and VS2 and with the smallest amounts of VTOL.

	Sc	N1	N2	CB	Size	VS 1	HS 1	VS2	HS2	HS	VS	CI	CIP	difference
1025	general	1	1	0	15 X 15	200	30	200	30	0,5	200	2.5518	92.530%	1025/1185 5.657%
1057	general	1	1	0	15 X 15	200	150	200	30	0,5	200	2.3838	89.730%	
1153	general	1	1	0	15 X 15	200	30	200	150	0,5	200	2.3839	89.732%	
1185	general	1	1	0	15 X 15	200	150	200	150	0,5	200	2.2124	86.873%	
1029	general	1	1	100	15 X 15	200	30	200	30	0,5	200	1.5728	76.213%	1029/1189 9.547%
1061	general	1	1	100	15 X 15	200	150	200	30	0,5	200	1.1788	69.647%	
1157	general	1	1	100	15 X 15	200	30	200	150	0,5	200	1.1251	68.752%	
1189	general	1	1	100	15 X 15	200	150	200	150	0,5	200	1	66.667%	

Source: The author.

Comparing scenarios between the smallest and largest HS1 and HS2, without the presence of CB, we find a significant percentage difference and when we consider the insertion of CB, the reduction in the CI for HS1 and HS2 of 150 kt still becomes more relevant.

Table 50 presents scenarios considering the upper limits for VS1 and VS2 and the smallest amounts of VTOL.

Table 50: scenarios considering the upper limits for VS1 and VS2 and the smallest amounts of VTOL.

	Sc	N1	N2	CB	Size	VS 1	HS 1	VS2	HS2	HS	VS	CI	CIP	difference
1105	general	1	1	0	15 X 15	1000	30	1000	30	0,5	200	2.9224	98.707%	1105/1133 2.298%
1137	general	1	1	0	15 X 15	1000	150	1000	30	0,5	200	2.9025	98.375%	
1233	general	1	1	0	15 X 15	1000	30	1000	150	0,5	200	2.9327	98.878%	
1265	general	1	1	0	15 X 15	1000	150	1000	150	0,5	200	2.7845	96.408%	
1109	general	1	1	100	15 X 15	1000	30	1000	30	0,5	200	1.8686	81.143%	1109/1269 4.655%
1141	general	1	1	100	15 X 15	1000	150	1000	30	0,5	200	1.6872	78.120%	
1237	general	1	1	100	15 X 15	1000	30	1000	150	0,5	200	1.4651	74.418%	
1269	general	1	1	100	15 X 15	1000	150	1000	150	0,5	200	1.5893	76.488%	

Source: The author.

The results presented in table 50 follow the same trends as those presented in table 49. However, due to the use of VS1 and VS2 of 1000 ft/min, the percentage differences, although significant, were reduced.

Table 51 presents the scenario considering the increase in VTOL (N1 and N2=3) with the smallest VS1 and VS2.

Table 51: Combinations considering the increase in VTOL (N1 and N2=3) with the smallest VS1 and VS2.

	Sc	N1	N2	CB	Size	VS 1	HS 1	VS2	HS2	HS	VS	CI	CIP	difference
1028	general	3	3	0	15 X 15	200	30	200	30	0,5	200	-0.4879	41.868%	1028/1188 3.205%
1060	general	3	3	0	15 X 15	200	150	200	30	0,5	200	-0.6649	38.918%	
1156	general	3	3	0	15 X 15	200	30	200	150	0,5	200	-0.6701	38.832%	
1188	general	3	3	0	15 X 15	200	150	200	150	0,5	200	-0.6802	38.663%	
1032	general	3	3	100	15 X 15	200	30	200	30	0,5	200	-0.8416	35.973%	1032/1193 2.078%
1064	general	3	3	100	15 X 15	200	150	200	30	0,5	200	-0.9562	34.063%	
1160	general	3	3	100	15 X 15	200	30	200	150	0,5	200	-0.9455	34.242%	
1192	general	3	3	100	15 X 15	200	150	200	150	0,5	200	-0.9663	33.895%	

Source: The author.

Considering the increase in traffic, the percentage differences, although existing and significant, are reduced. However, it is noteworthy that the high amount of traffic is already considerably reducing the airspace capacity.

Table 52 shows the scenarios considering the increase in VTOL (N1 and N2=3) with the highest VS1 and VS2.

Table 52: Scenarios considering the increase in VTOL (N1 and N2=3) with the highest VS1 and VS2.

	Sc	N1	N2	CB	Size	VS 1	HS 1	VS2	HS2	HS	VS	CI	CIP	difference
1108	general	3	3	0	15 X 15	1000	30	1000	30	0,5	200	1.791	79.850%	1128/1268 6.737%
1140	general	3	3	0	15 X 15	1000	150	1000	30	0,5	200	1.7543	79.238%	
1236	general	3	3	0	15 X 15	1000	30	1000	150	0,5	200	1.67	77.833%	
1268	general	3	3	0	15 X 15	1000	150	1000	150	0,5	200	1.3868	73.113%	
1112	general	3	3	100	15 X 15	1000	30	1000	30	0,5	200	-0.4548	42.420%	1112-1272 4.710%
1144	general	3	3	100	15 X 15	1000	150	1000	30	0,5	200	-0.7574	37.377%	
1240	general	3	3	100	15 X 15	1000	30	1000	150	0,5	200	-0.677	38.717%	
1272	general	3	3	100	15 X 15	1000	150	1000	150	0,5	200	-0.7374	37.710%	

Source: The author.

Scenarios with an increase in the amount of VTOL and using the highest VS1 and VS2, the percentage differences are greater when compared to the scenarios from table 53 (smallest VS1 and VS2).

Although discussions on the impact of VS1 and VS2 variations have been discussed above, it should be noted that when comparing scenarios 1028 (VS1 and VS2 of 200 ft/min) and 1108 (VS1 and VS2 of 1000 ft/min) the percentage difference in the capacity index is 37.98%.

Conclusion of the 3rd discussion: In all comparisons, observing tables 51, 52, 53, 54 and Annex A, the combinations with the highest HS1 and HS2 have the lowest CI when compared to the combinations with the lowest HS1 and HS2.

As previously mentioned, the linear regression performed showed that the HS1 HS2 variables are not significant, remembering that the dependent variable corresponds to the CI.

4th Discussion –Lower Capacity Indexes

As expected, and according to the linear regression results presented in table 42, the model presented the lowest CI for scenarios with the perpendicular parameter, lower size, high amount of VTOL, presence of CB and with increased horizontal separations (HS) and vertical (VS), as shown in table 53.

Table 53: Scenarios with the perpendicular parameter, lower size, high amount of VTOL, presence of CB and with increased horizontal separations (HS) and vertical (VS).

	Sc	N1	N2	CB	Size	VS 1	HS 1	VS2	HS2	HS	VS	CI	CIP
312	perpendicular	3	3	100	15 X 15	1000	150	200	30	1	200	-3	0%
328	perpendicular	3	3	100	15 X 15	200	30	1000	30	1	200	-3	0%
424	perpendicular	3	3	100	15 X 15	200	150	200	150	1	200	-3	0%
440	perpendicular	3	3	100	15 X 15	1000	150	200	150	1	200	-3	0%
536	perpendicular	3	3	100	15 X 15	1000	30	200	30	0,5	400	-3	0%
680	perpendicular	3	3	100	15 X 15	200	150	200	150	0,5	400	-3	0%
712	perpendicular	3	3	100	15 X 15	200	30	1000	150	0,5	400	-3	0%
840	perpendicular	3	3	100	15 X 15	200	30	1000	30	1	400	-3	0%

Souce: The autor.

8.2. Complexity Threshold

According to (BING, 2014) the management of air traffic complexity involves identifying a complex air traffic condition and taking effective actions such as operation programs for scaling down the complexity to an acceptable range or level.

The complexity model developed has the objective of presenting the dynamic capacity of the airspace according to the dynamic complexity index, considering the complexity variables that make up the model. Thus, we will define the dynamic airspace capacity as the maximum number of aircraft flying simultaneously that will represent, according to the defined variables, a certain index of complexity. If this index is lower than the stipulated complexity limit, the entry of aircraft will be authorized, as shown in figure 55.

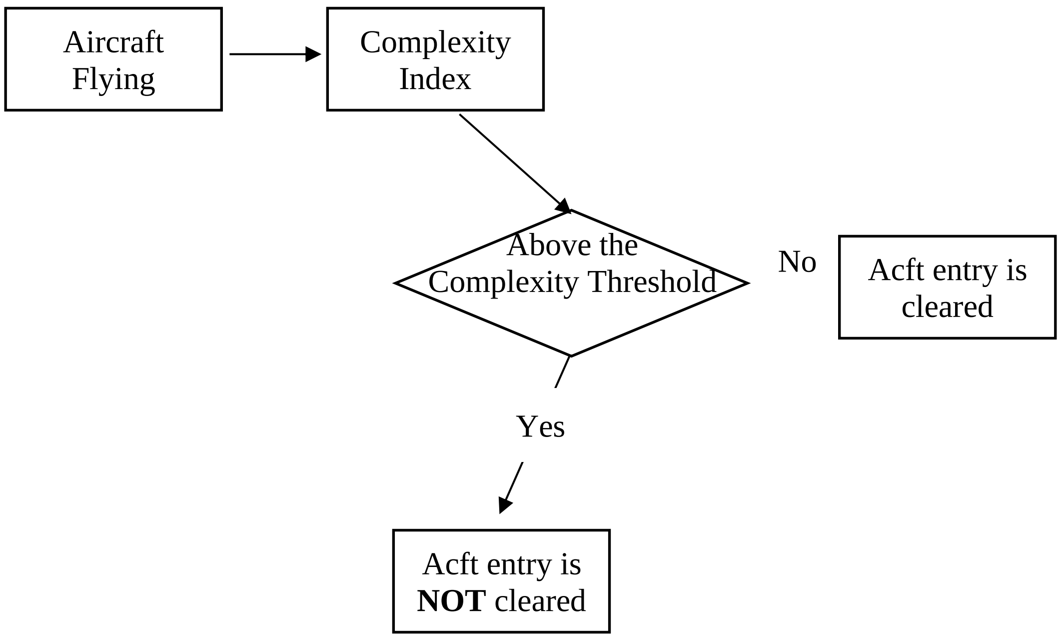

Figure 55: Framework of Complexity Threshold.

Source: The author.

The Complexity Threshold will be defined as Capacity Index 0 (zero)[26], considering an uncertainty of 10% which will correspond to a variation of +- 0.3 in the Capacity Index.

Thus, scenarios that are in the interval of [-0.3, +0.3] of the capacity index will be exactly in the Complexity Threshold and those with capacity indexes greater than +0.3 and less than -0.3 will be, respectively, below and above the Complexity Threshold. There are 143 scenarios in this interval (Complexity Threshold), corresponding to 6.98% of the total.

Figure 56 presents graphically the scenarios in this interval.

[26] The capability index 0 refers precisely to the "acceptable" state.

Figure 56: Complexity Threshold.
Source: The author.

Figure 57 shows the combinations that have the capacity index above + 0.3, that is, below the Complexity Threshold. 1230 scenarios were identified under these conditions, corresponding to 60.06% of the total.

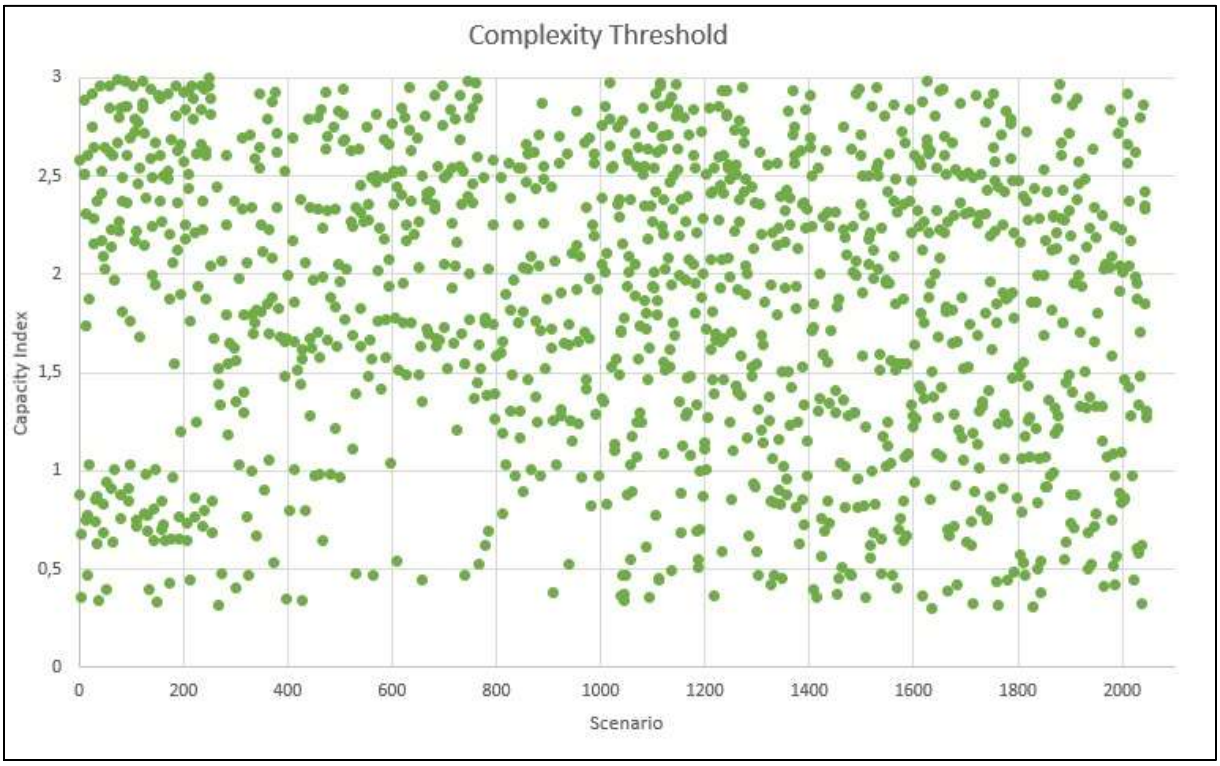

Figure 57: Below the Complexity Threshold.
Source: The author.

Figure 58 presents the scenarios that have the capacity index below -0.3, that is, above the Complexity Threshold. 675 scenarios were identified under these conditions, corresponding to 32.96% of the total.

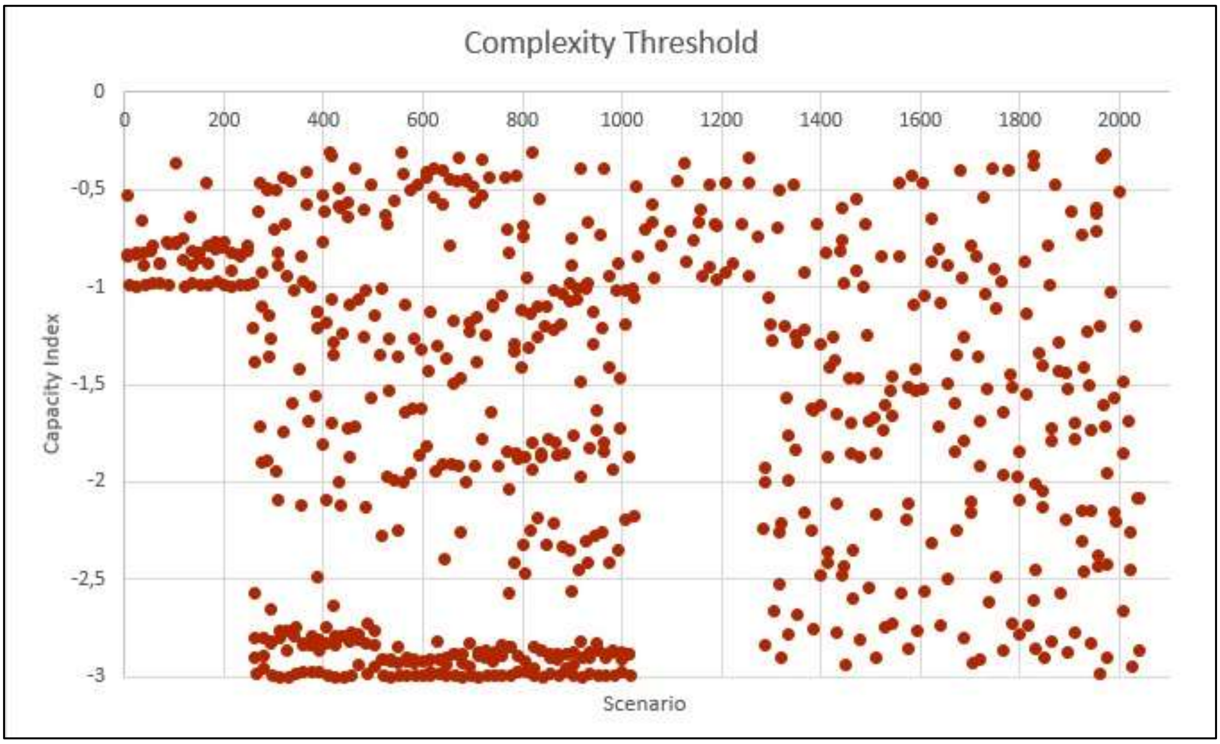

Figure 58: Above the Complexity Threshold.

Source: The author.

Figure 58 shows that the Capacity Index is never lower than -1 between scenario 1 and scenario 250, approximately. We can see that the HS is 0.5 NM for the first 256 scenarios; it is 1.0 NM after that, which drastically reduces the capacity.

It can also be observed that from scenario 257 to approximately scenario 1050, the capacity indexes are at the lower limits. We identified that from combination 257 to combination 1024, were used superior parameters of the HS (1.0 NM) or superior parameters of the VS (400 ft). From the 1025 combination, the general parameter starts to be used, starting with the lower parameters of the HS and VS.

Figure 59 presents the Complexity Threshold for the 2048 scenarios.

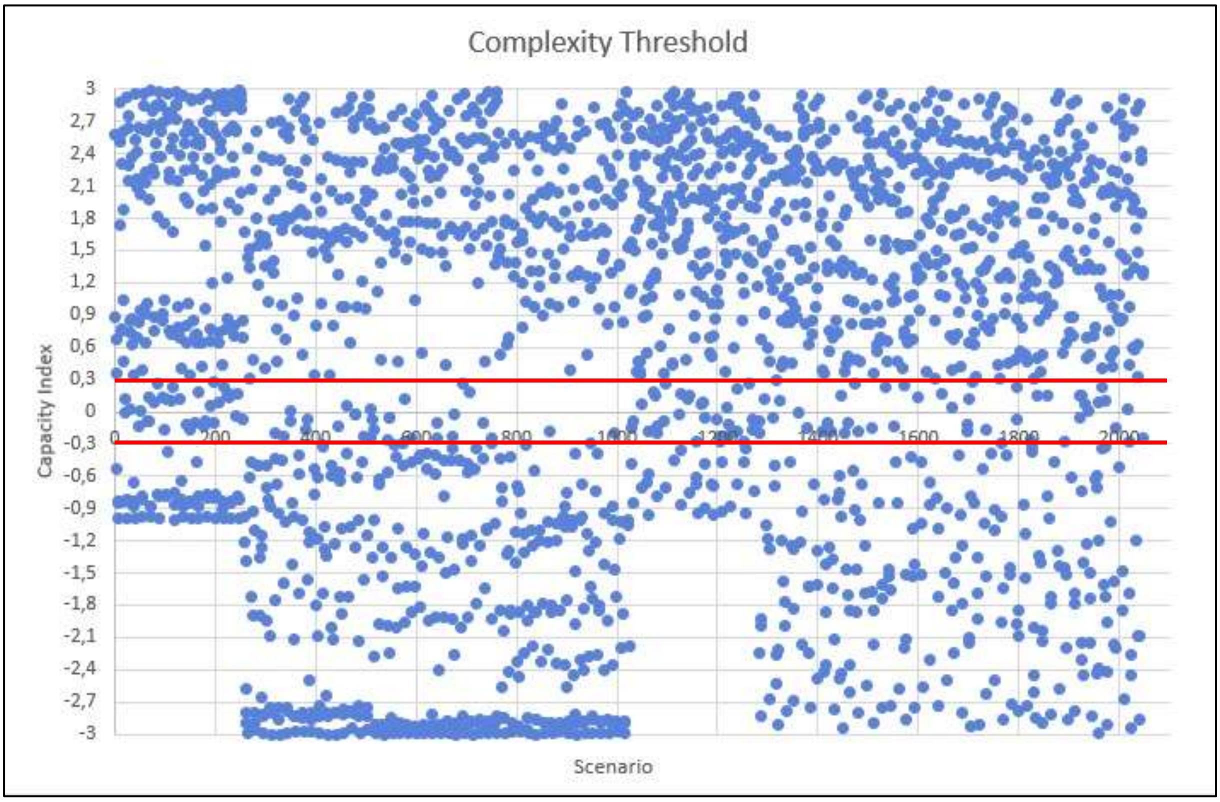

Figure 59: Complexity Threshold and 2048 scenarios.

Source: The author.

9. ANALYTICAL COMPLEXITY MODEL

The proposal to present an analytical model of complexity aims to understand the relationship between all variables, that is, the Strength of Influence in the relationships between CG and CM of the system. Thus, it will be possible to identify the priority of treatment of the system input variables (CG) in order to reduce the complexity and consequently increase the airspace capacity, identifying the strength of influence of each of the CM in the relations with the Complexity Index and identify which CM has the greatest impact on the Complexity Index.

To measure this strength of influence, we will start with the Kull Kullback-Leibler distance concept developed in (KULLBACK; LEIBLER, 1951) and presented in (KOITER, 2006);(WANG et al., 2018).

The Kullback-Leibler distance, or Kullback-Leibler (KL) divergence, comes from the field of information theory and is given as shown in equation 22.

Equation 22: Kullback-Leibler (KL) divergence

$$K(P,Q) = \sum_{i=1}^{n} pi.log2(\frac{pi}{qi})$$

Equation 23 presents how equation 26 can also be written.

Equation 23: Kullback-Leibler (KL) divergence - rewrite

$$K(P,Q) = -\sum_{i=1}^{n} pi.log2(qi) + \sum_{i=1}^{n} pi.log2(pi) = H(P,Q) - H(P)$$

Where H(P,Q) is the cross-entropy of P and Q, which expresses the overall difference between two distributions, and H(P) is the entropy of P, which is a measure of how much information P carries. The value of this measure ranges from 0 to ∞.

But there are three problems with the Kullback-Leibler distance. First, it is not symmetric, second, its values go to infinity, and third, if a qi = 0 there is a division by zero. We will deal with these problems with the help of the J-divergence measure.

To make the Kullback-Leibler distance symmetric, we can instead choose to use the J-divergence[27], which can be given as the average of the two possible values of the Kullback-Leibler distance (equation 24):

Equation 24: J-Divergence

$$J(P,Q) = \frac{K(P,Q)+K(Q,P)}{2}$$

This solves the symmetry issue, but it still has values that go to infinity. To make the J-divergence range from 0 to 1 we can normalize it as follows in equation 25.

Equation 25: J-divergence normalized

$$Jnorm(P,Q) = \frac{J(P,Q)}{\sqrt{J(P,Q)^2 + \alpha}}$$

where α ≥ 0 is a parameter controlling the “smoothness” of the normalization. It will be considered $\alpha = 10$.

To also solve the third and final problem, the possible division by zero, we can change the definition into, equation 26.

Equation 26: J-Divergence with possible division by zero

$$Jnorm(P,Q) = \begin{cases} 1 \; \exists i\ (1, \ldots, n), qi = 0 \\ \frac{J(P,Q)}{\sqrt{J(P,Q)^2 + \alpha}}, \text{ else} \end{cases}$$

The J-Divergence is the index of the strength of influence of each CG – Complexity Generator in the different CM – Complexity Metric. Thus, the higher the index, the greater the influence of the variable on the increase in Complexity and consequent reduction in Capacity.

[27] Jensen- Shannon Divergence

After the construction and validation of the Bayesian Network using the GeNIe Modeler, it is possible to calculate the J-Divergence strength of influence, considering the relationship between all variables.

Figures 60, 61 and 62 show, respectively, the strength of influence between CG and CM Below Minimum Separation (BM), Below Stipulated Separation (BS) and Delay (DE).

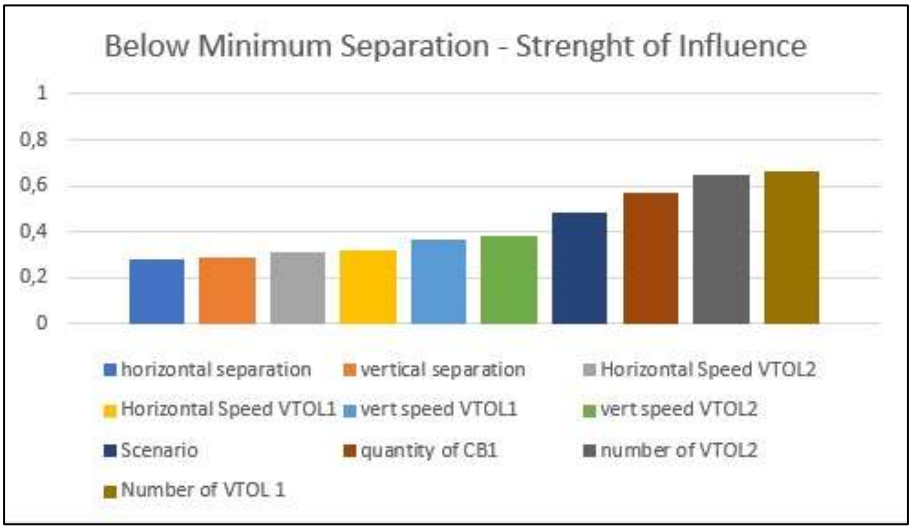

Figure 60: Strength of influence between CG and CM Below Minimum Separation (BM).
Source: The author.

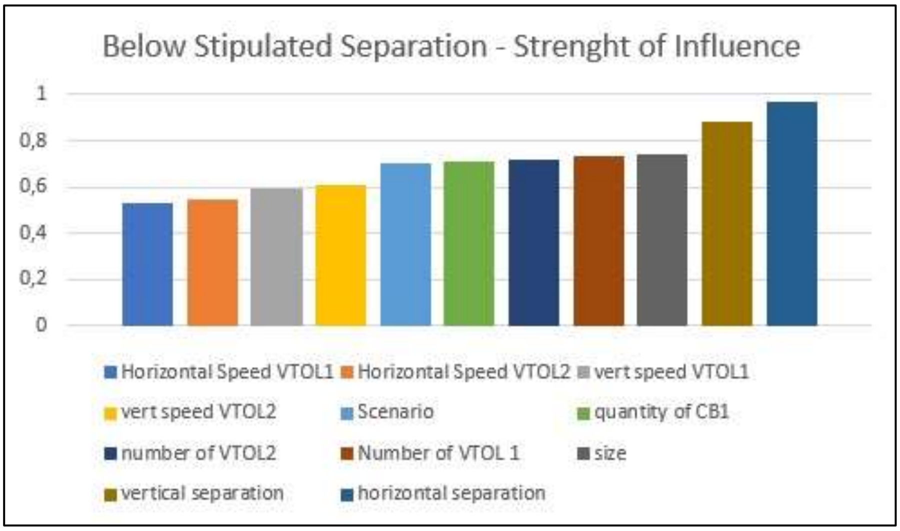

Figure 61: Strength of influence between CG and CM Below Stipulated Separation (BS).
Source: The author.

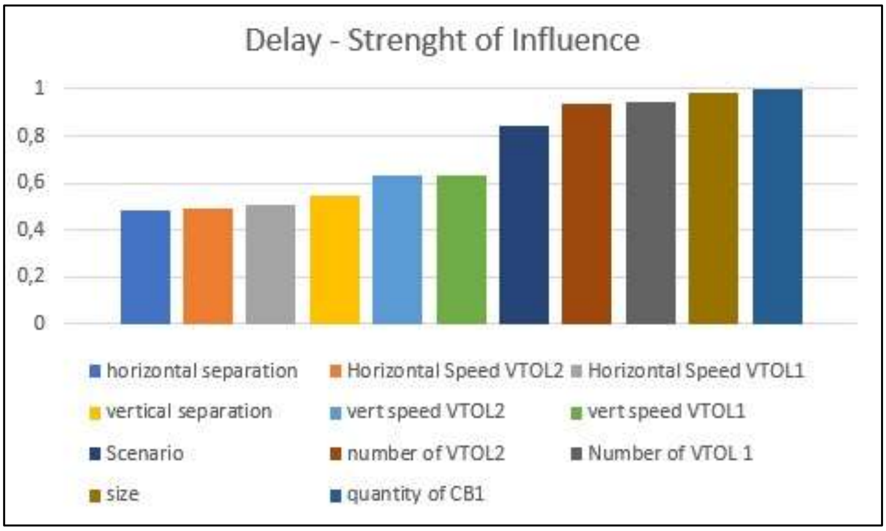

Figure 62: Strength of influence between CG and CM Delay (De).
Source: The author.

The relationship between input variables (CG) and outputs (CM) is not homogeneous, that is, the strength of influence will vary depending on the context.

When we look at figures 60, 61 and 62, we understand which variables cause the greatest impact on the CM (strenght of influence) indexes, remembering that the complexity index will be presented based on the behavior of the CM (BM, BS, and DE).

Consider, for example, Figure 62 (delay). We understand that in a scenario with CB the delay indexes are highly impacted, followed by the size of the scenario and the number of VTOL 1 and 2. Thus, if we want to immediately reduce the Delay indices, we should act primarily on these variables.

However, it is noteworthy that the CM have different strengths of influence in different CG. Thus, it should be understood that the reduction of a certain input variable (CG) will mean a significant reduction in the indexes of a given output (CM), but it may represent an insignificant reduction for another CM. Figure 63 and table 54 show the strength of influence of each of the CGs in the different CM.

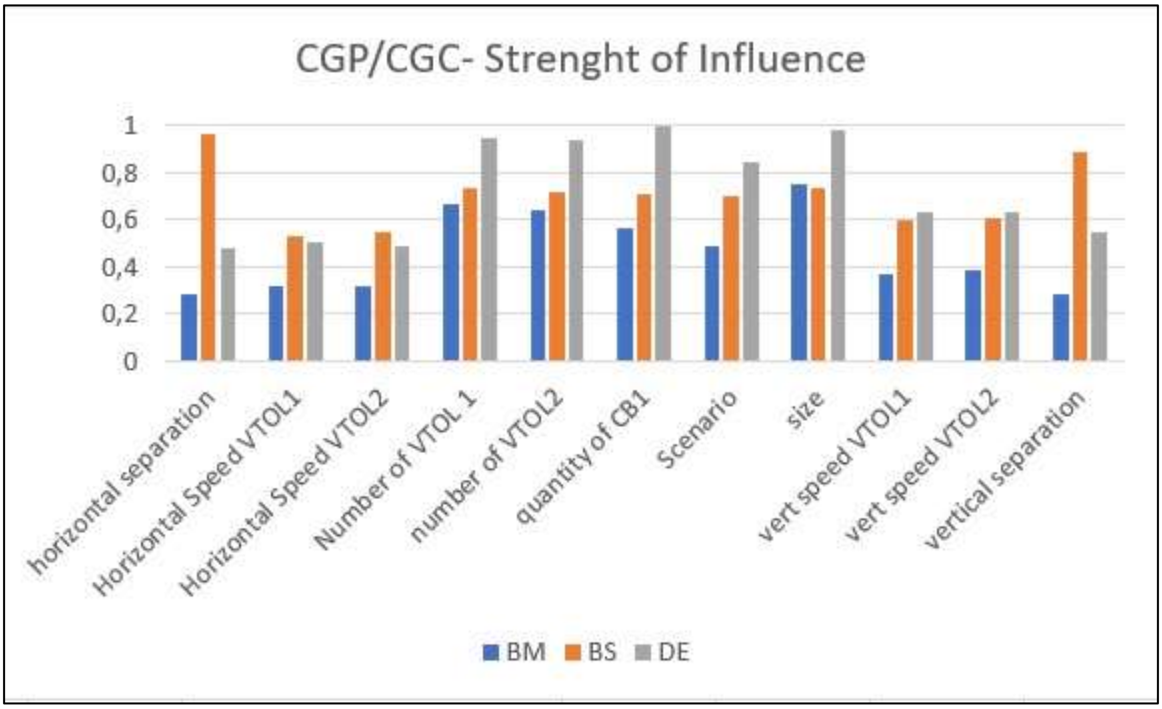

Figure 63: Strenght of influence of each of the CGs in the different CM.

Source: The author.

Table 54 shows the J-Divergence Index (strenght of influence) of all CG (11) and CM (3), the normalized J-Divergence, the sum of the strength of influence of all CM for each CG (as for example in row 1) as well as the sum of the strength of influence of all the CG in each CM (as for example in column 1).

Table 54: Strenght of influence of each of the CGs in the different CM.

	BM	**BS**	**DE**	**Total**	**Normalized**
Horizontal Separation (HS)	0.283176	0.965934	0.481519	**1.730629**	0.083236
Horizontal Speed VTOL1 (HS1)	0.320562	0.531513	0.507089	**1.359164**	0.06537
Horizontal Speed VTOL2 (HS2)	0.315097	0.543451	0.488539	**1.347087**	0.064789
Number of VTOL 1 (N1)	0.663549	0.730721	0.94351	**2.33778**	0.112437
Number of VTOL2 (N2)	0.644002	0.720602	0.937201	**2.301805**	0.110707
Quantity of CB (CB)	0.568483	0.707833	0.998047	**2.274363**	0.109387
Scenario (Sc)	0.485929	0.702787	0.844535	**2.033251**	0.09779
Size (S)	0.747682	0.737971	0.982081	**2.467734**	0.118687
Vert Speed VTOL1 (VS1)	0.368028	0.59572	0.633947	**1.597695**	0.076842
Vert Speed VTOL2 (VS2)	0.38544	0.606842	0.62853	**1.620812**	0.077954
Vertical Separation (VS)	0.286854	0.885543	0.549202	**1.721599**	0.082801
Total	**5.068802**	**7.728917**	**7.9942**	**20.79192**	1
Normalized	**0.243787**	**0.371727**	**0.384486**	1	

Source: The author.

Equation 27 presents the Analytical Model of Complexity, where the 1st term of the equation presents the sum of all the Strength of Influence of all the CGs for each CM and the 2nd term presents the sum of each CG for all the CM .

Equation 27: Analytical Model of Complexity

$$CA = [(\sum_{\substack{i=11\\k=1\\i=1}}^{k=3} J(norm)_{ik}]; [(\sum_{\substack{k=3\\j=1\\k=1}}^{i=11} J(norm)_{ki}]$$

Where:

- CA is the Analytical Complexity Index
- J_{norm} is the Normalized J-Divergence
- i is the representation of each CG, considering the 11 existing
- k is the representation of each CM, considering the 3 existing

Expanding equation 27 we find (equation 28).

Equation 28: Expanding equation 27

CA= $[0.243787_{(\Sigma CGP,\text{BM})} + 0.371727_{(\Sigma CGP,\text{BS})} + 0.384486_{(\Sigma CGP,\text{DE})}]_{\text{1st term}}$; $[0.083236_{(\text{HS}, \Sigma CGC)} + 0.06537_{(\text{HS1}, \Sigma CGC)} + 0.064789_{(\text{HS2}, \Sigma CGC)} + 0.112437_{(\text{N1}, \Sigma CGC)} + 0.110707_{(\text{N2}, \Sigma CGC)} + 0.109387_{(\text{CB}, \Sigma CGC)} + 0.09779_{(\text{SC}, \Sigma CGC)} + 0.118687_{(\text{S}, \Sigma CGC)} + 0.076842_{(\text{VS1}, \Sigma CGC)} + 0.077954_{(\text{VS2}, \Sigma CGC)} + 0.082801_{(\text{VS}, \Sigma CGC)}]_{\text{2nd term}}$

By identifying the strength of influence among all the variables, we will know at any time what is the best strategy for reducing complexity and consequently increasing airspace capacity, that is, what is the sequence of actions depending on the weight of influence of each variable.

10. FINAL CONSIDERATIONS AND FUTURE WORKS

10.1. Final Considerations

When conceptualizing complexity, we often find it difficult to differentiate it from the concept of complicated. But to understand complexity, we must relate it to the complicated and the chaotic. Situations where you are far from an agreement and close to certainty, or far from certainty and close to an agreement, are considered regions where you work on complicated issues. Complexity arises between the complicated and the chaotic.

The study of complexity has become vital to many activities, which has led to numerous definitions and strategies to measure it as well as different complexity measurement units. For example, when measuring the complexity of a system, we must know it in-depth before constructing or choosing a model that can describe it satisfactorily. Next, we must understand the meaning of the estimated complexity indices and determine the application of these results.

We examined the concept of complexity in different areas and how its definition varies from context to context. For example, under a structural complexity approach, a system's complexity is a consequence of the complexity of its connections, and the complexity of a connection is, in turn, measured using the concepts of information theory. In this case, the model used is the Shannon Entropy.

In air traffic, the study of complexity began in the 1960s, and different approaches have been presented since then. Here, complexity is associated with the airspace structure or the difficulty of an ATCo to perform a certain activity due to several variables. Thus, the belief among researchers that complexity affects the ATCo workload is unanimous. However, there are many challenges involved in establishing and measuring how this occurs.

Aeronautical authorities must use modeling strategies to define the maximum aircraft capacity of some airspace, typically by considering the amount of traffic allowed to fly simultaneously. This capacity is usually associated with ATCo's workload. The literature presents two ways to measure this workload: 1) Direct measurement techniques - focus on workload indicators from the ATCo; 2) Indirect techniques that estimate ATCo workload based on other indicators (e.g., complexity metrics).

The complexity models used often present non-dynamic results, that is, they are measured at a given time and disregard the current conditions of that airspace, such as weather conditions or if there is any other condition that forces the aircraft to hold in flight. It is noteworthy that some mathematically sophisticated models present real-time responses using only variables related to the aircraft, such as aircraft headings or distance between them.

The literature presents the definition of dynamic complexity as a function of three fundamental components: inherent uncertainty in system responses; inherent uncertainty in the pair-wise dependency relationships among system responses; and dependency structure among those system responses. Thus, it is essential to establish the relationships between all variables in the process and understand how these relationships impact complexity.

Referring specifically to air traffic, we have to recognize it as a system and, in order to measure complexity, it will be necessary to understand the interdependence between all system variables. A system is defined as a combination of interacting elements organized to achieve one or more stated purposes or as an integrated set of elements, subsystems, or assemblies that accomplish a defined objective. In this work, which aims to develop the airspace complexity model, interactions will be established between different systems, such as air traffic control and meteorology, air traffic control and aircraft, and aircraft and meteorology, among others.

As these variables are dynamically presented (for example, aircraft trajectory, weather conditions or airport capacities), the relationship between the variables will impact complexity in different ways, depending on how they are presented at time T.

In this work, the capacity model will respond at time T+1, that is, considering that there are N aircraft in the respective airspace at time T, the model will present the capacity conditions for the N+1 aircraft. The capacity model was developed based on the complexity of the airspace and dynamic capacity index is the inverse function of the dynamic complexity index.

We sought to establish and understand the relationship between different variables of different systems and offer the possibility for future researchers to insert new variables in the modeling or revise those already presented. For this to be feasible, the chosen tool to build the model was the Bayesian Network (BN). For the selection of the variables that made up the model, experts selected, based on the literature, variables and established the relationships between them. To understand how these variables were related and what impact the modification in any of them would cause on the others and consequently on the result, the results of a computational simulation tool were used, considering the concept of multi-agent.

Although the purpose of this work was to present the Airspace Capacity Model in UAM Environment Based, we intend that the model can be applied in different environments. For this, the following questions should be answered first :

1) Will it be a UTM, UATM or ATM environment?
2) What are the aircraft performances? Will they be considered manned or unmanned?
3) What is the airspace structure where the model will be implemented: will it be segregated or not, what are its dimensions and route structure?
4) Which air traffic rules will be considered in the model?
5) What is the level of automation of air traffic control?

In response to the above questions and to make the development of the capacity model feasible, the following were developed:

- Criteria for the creation of controlled airspaces considering UAM environments.
- eVTOL approach and take-off procedures; and
- Specific air traffic rules to be used in a UAM environment and without the presence of ATCo.

Development of the model consists in the construction of the Bayesian Network and for this several steps were proposed, starting with the identification of relevant variables and ending with the model validation process, as shown below:

1) Identification of relevant variables and the causal relationship.
2) State space for each node.
3) Definition of conditional probabilities: Netlogo Simulation.
4) Insertion of Conditional Probabilities in the BN.
5) Verification of Capacity Model: Walkthrough Approach.

6) Validation.
7) Insertion of the Capacity Model in TUSO (proposed as future work).

10.2. Future Works

- Keeping all other conditions unchanged, insert new variables in the model, such as capacity limitation in TOLAs (Takeoff and Landing Area) and compare with current results.
- Propose changes in the air traffic rules presented for the UAM environment, performing a sensitivity analysis on the model: air traffic rules are decisive in the application of any capacity model. The air traffic rules presented (minimum separation, approach and departure procedures, etc.) were essential inputs in Netlogo, as they directly impact the relationship between CG (Complexity Generators) and CM (Complexity Metrics). When changing air traffic rules, such as separation minima or approach procedures, it is expected that the outputs will be modified.
- Present to DECEA the air traffic rules proposed in this work to be applied in a UAM environment, as well as the criteria for the construction of control areas in a UAM environment (OCCA).
- Analyze other computational simulation tools for the development of the UAM environment, comparing them with the results obtained in Netlogo: this proposal will aim to improve the model developed in Netlogo, as well as to present other computational tools that can be used for the development of the model.
- Analyze other existing tools for the construction of the Bayesian Network.
- Automate the processing of data extracted from the simulation of the UAM environment, (Netlogo or another tool that will be proposed in the future) and propose methods for automating the insertion of data into the Bayesian network.
- Advance the development of TUSO, considering the insertion of the capacity model, aiming at the real-time presentation of the dynamic capacity.
- Considering the prerequisites presented and the stages of model development, analyze the possibility of inserting the model presented in different environments, such as ATM.

REFERÊNCIAS

ANTCLIFF, K. R.; MOORE, M. D.; GOODRICH, K. H. Silicon valley as an early adopter for on-demand civil VTOL operations. **16th AIAA Aviation Technology, Integration, and Operations Conference**, p. 1–17, 2016.

ATHÈNES, S.; AVERTY, P.; PUECHMOREL, S.; DELAHAYE, D.; COLLET, C. ATC complexity and controller workload: Trying to bridge the gap. **Proceedings of the International Conference on HCI in Aeronautics**, n. 56, p. 56–60, 2002. Disponível em: <http://www.aaai.org/Papers/HCI/2002/HCI02-009.pdf>.

AYHAN, S.; SAMET, H. Aircraft Trajectory Prediction Made Easy with Predictive Analytics. **Proceedings of the 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining - KDD '16**, p. 21–30, 2016. Disponível em: <http://dx.doi.org/10.1145/2939672.2939694%5Cnhttp://dl.acm.org/citation.cfm?doid=2939672.2939694>.

BAUM, D. .; NETO, E. C. P.; RADY, J. A. .; CUGNASCA, P. .; JUNIOR, J. B. C. A Mindset-Based Evolution of Unmanned Aircraft System (UAS) Acceptance into the National Airspace System (NAS). v. 55, n. 11, 2018.

BAUM, D. M.; NETO, E. C. P.; ALMEIDA, J. R.; CAMARGO, J. B.; CUGNASCA, P. S. A Mindset-Based Evolution of Unmanned Aircraft System (UAS) Acceptance into the National Airspace System (NAS). **IEEE Access**, v. 8, p. 1–1, 2019.

BIJJAHALLI, S.; SABATINI, R.; GARDI, A. GNSS performance modelling and augmentation for urban air mobility. **Sensors (Switzerland)**, v. 19, n. 19, 2019.

BING, D. Aircrafts Monitoring and Early Warning Based on Air Traffic Complexity Measure Analysis. p. 1563–1569, 2014.

BOOZ; ALLEN; HAMILTON. Final Report Urban Air Mobility (UAM) Market Study. n. November, p. 160, 2018. Disponível em: <https://ntrs.nasa.gov/api/citations/20190001472/downloads/20190001472.pdf>.

BOSSON, C. S.; LAUDERDALE, T. A. Simulation evaluations of an autonomous urban air mobility network management and separation service. **2018 Aviation Technology, Integration, and Operations Conference**, p. 1–14, 2018.

BRADFORD, S.; KOPARDEKAR, P. H. UAM - Concept of Operations - V1.0. **FAA**, 2020.

BULUSU, V.; POLISHCHUK, V. A threshold based airspace capacity estimation method for UAS traffic management. **11th Annual IEEE International Systems Conference, SysCon 2017 - Proceedings**, 2017.

BULUSU, V.; SENGUPTA, R.; LIU, Z. Unmanned Aviation: To Be Free or Not To Be Free? **7th International Conference on Research in Air Transportation**, 2016.

CHATTERJI, G. B.; ZHENG, Y.; KOPARDEKAR, P. Analysis of current sectors based on traffic and geometry. **AIAA Guidance, Navigation and Control**

Conference and Exhibit, n. December, 2008.

CHRISTIEN, R.; BENKOUAR, A.; CHABOUD, T.; LOUBIERES, P. Air traffic complexity indicators & ATC sectors classification. **AIAA/IEEE Digital Avionics Systems Conference - Proceedings**, v. 1, n. June, p. 1–8, 2002a.

CHRISTIEN, R.; BENKOUAR, A.; CHABOUD, T.; LOUBIERES, P. Air traffic complexity indicators & ATC sectors classification. **Proceedings. The 21st Digital Avionics Systems Conference**, v. 1, n. June, p. 1–7, 2002b.

COMENDADOR, V. F. G.; VALDÉS, R. M. A.; DIAZ, M. V.; PARLA, E. P.; ZHENG, D. Bayesian network modelling of ATC complexity metrics for future SESAR demand and capacity balance solutions. **Entropy**, v. 21, n. 4, 2019.

COMENDADOR, V. F. G.; VALDÉS, R. M. A.; ROSENDO, J.; CIDONCHA, M. S.; PARLA, E. P.; ZHENGA, D. Impact of trajectories ’ uncertainty in existing complexity methodologies. **SESAR**, n. July 2018, 2018.

CONSTANTINOU, A. C.; FENTON, N.; NEIL, M. **Integrating expert knowledge with data in Bayesian networks: Preserving data-driven expectations when the expert variables remain unobservedExpert Systems with Applications**, 2016. .

CORRÊA, M. A. Modelo de Veículos Aéreo não tripulados Baseado em Sistemas Multi-Agentes. **102 p. Tese (Doutorado) –Departamento de Computação e Sistemas Digitais. Escola Politécnica da Universidade de São Paulo, 2008.**, 2008.

COURT, C. Small RPAS Operations Near Regional Airports Operational Description , Impacts , and Issues. 2015.

DECEA. MCA 100-17: Capacidade de Setor ATC. p. 1–26, 2014. Disponível em: <http://publicacoes.decea.gov.br/?i=publicacao&id=4065>.

DECEA. Regras do Ar/ ICA 100-12. 2016a.

DECEA. Serviços de Tráfego aéreo/ICA 100-37. 2016b.

DECEA. CARTA DE CORREDORES VISUAIS ROTAS ESPECIAIS DE HELICÓPTEROS NA CTR-SP (Área de Controle Helicóptero). 2018.

DECEA. SWIM no ATM Nacional. 2019.

DECEA. Certificado de Habilitação Técnica de Controlador de Tráfego Aéreo - ICA 100-18. 2020.

DECEA. Concepção Operacional Atm Nacional. 2021.

DELAHAYE, D.; PUECHMOREL, S. Air traffic complexity: towards intrinsic metrics. **3rd USA/Europe Air Traffic Management R&D Seminar**, n. June, p. 1–11, 2000. Disponível em: <http://tinyurl.com/affmbc6>.

DELAHAYE, D.; PUECHMOREL, S. Air traffic complexity based on dynamical systems To cite this version : HAL Id : hal-00938405 Air Traffic Complexity based on Dynamical Systems. 2014.

DOMPIERI, M. Análise de complexidade aplicada à antecipação de crises no mercado de bens minerais. 2014.

ELEVATE, U. eVTOL Vehicle Requirements and Missions. 2018.

EMBRAER. Flight Plan 2030: An Air Traffic Management Concept for Urban Air Mobility. p. 48, 2019. Disponível em: <www.embraerx.com>.

EMBRAER; ATECH; HARRIS. Flight plan 2030. 2019.

EUROCONTROL. EUROCONTROL MANUAL FOR AIRSPACE PLANNING - Volume 2. v. 2, 2005.

EUROCONTROL. European ATM Master Plan 2015. p. 140, 2015.

EUROCONTROL. UAS ATM Flight Rules. 2018.

EUROCONTROL. SESAR Concept of Operations Step 1. n. May, p. 146, 2019. Disponível em: <http://www.sesarju.eu/sites/default/files/documents/highlight/SESAR_ConOps_Document_Step_1.pdf>.

FERRARE, F. D.; BAUM, D. M.; RADY, J. A. J.; CAMARGO, J. B.; CUGNASCA, P. S. Urban Air Mobility (UAM): A Model Proposal Based on Agents Using Netlogo. v. 2035, p. 1–242, 2021.

FERREIRA, R. B.; BAUM, D. M.; NETO, E. C. P.; MARTINS, M. R.; ALMEIDA, J. R.; CUGNASCA, P. S.; CAMARGO, J. B. A Risk Analysis of Unmanned Aircraft Systems (UAS) Integration into non-Segregate Airspace. In: 2018 International Conference on Unmanned Aircraft Systems, ICUAS 2018, **Anais**...2018.

GENIE. GeNIe Modeler User Manual. **BayesFusion**, p. 339–347, 2020.

GIANAZZA, D.; ALLIGNOL, C.; SAPORITO, N. An efficient airspace configuration forecast. **Proceedings of the 8th USA/Europe Air Traffic Management Research and Development Seminar, ATM 2009**, n. June 2002, p. 384–393, 2009.

GOODHEART, B. Identification of causal paths and prediction of runway incursion risk by means of Bayesian belief networks. **Transportation Research Record**, n. 2400, p. 9–20, 2014.

GREENFELD, I. Concept of Operations for Urban Air Mobility Command and Control Communications. n. April, 2019.

HOBBS, A.; LYALL, B. Human Factors Guidelines for Unmanned Aircraft Systems. **Ergonomics in Design**, v. 24, n. 3, p. 23–28, 2016.

HOLDEN, J.; GOEL, N. Fast-Forwarding to a Future of On-Demand Urban Air Transportation. p. 1–98, 2016. Disponível em: <https://www.uber.com/elevate.pdf>.

HOPKIN, V. D. (Royal A. F. I. of A. M. **Human factor in air traffic control**. [s.l: s.n.]

ICAO. Doc 4444 - Procedures for Air Navigation Services. n. June, 2001a.

ICAO. Air Traffic Services, Annex 11, Amendments. n. July, 2001b.

ICAO. **Annex 2 - rules of the air - tenth edition**. [s.l: s.n.]

ICAO. **Unmanned aircraft systems - (uas)**. [s.l: s.n.]

ICAO. **Annex 2 - rules of the air**. [s.l: s.n.]

ICAO. Convention on International Civil Aviation. **Journal of Chemical Information and Modeling**, v. 53, n. 9, p. 1689–1699, 2013.

ICAO. **MANUAL on remotely piloted aircraft systems (rpas). 2015**. [s.l: s.n.]

ICAO. Manual on System Wide Information Management (SWIM) Concept. v. Doc 10039, n. Doc 10039, p. 88, 2015b. Disponível em: <http://bit.ly/1QMrDZp>.

ICAO. 2016–2030 Global Air Navigation Plan. **International Civil Aviation Organization Published in Montréal, Canada**, 2016a.

ICAO. **Air traffic management - doc 444**. [s.l: s.n.]

INCOSE. systems engineering handbook. 2015.

ISO/IEC/IEEE. Systems and software engineering - System life cycle processes. v. 17, 2015.

JANG, D. S.; IPPOLITO, C.; SANKARARAMAN, S.; STEPANYAN, V. Concepts of airspace structures and system analysis for UAS traffic flows for urban areas. **AIAA Information Systems-AIAA Infotech at Aerospace, 2017**, n. January, p. 1–15, 2017.

JIANG, T.; GELLER, J.; NI, D.; COLLURA, J. Unmanned Aircraft System traffic management: Concept of operation and system architecture. **International Journal of Transportation Science and Technology**, v. 5, n. 3, p. 123–135, 2016. Disponível em: <http://linkinghub.elsevier.com/retrieve/pii/S2046043016300260>.

KAYA, Y. B.; INALHAN, G. A Dynamic Bayesian Belief Network Approach for Modelling the ATM Network Delays. **Icrat 2014**, p. 1–8, 2014.

KLEIN, F. B.; GONÇALVES DIAS, S. L. F. A deposição irregular de resíduos da construção civil no município de São Paulo: um estudo a partir dos instrumentos de políticas públicas ambientais. **Desenvolvimento e Meio Ambiente**, v. 40, n. April, 2017.

KNORR, D.; WALTER, L. Trajectory uncertainty and the impact on sector complexity and workload. **SIDs 2011 - Proceedings of the SESAR Innovation Days**, n. December, p. 1–8, 2011.

KOITER, J. R. Visualizing inference in Bayesian networks. **Man-machine**

interaction group, v. Master of, 2006. Disponível em: <http://www.kbs.twi.tudelft.nl/Publications/MSc/2006-JRKoiter-Msc.html>.

KOPARDEKAR, P. DYNAMIC DENSITY: THE MEASURE OF AIR TRAFFIC CONTROL SECTOR COMPLEXITY FOR THE EN ROUTE ENVIRONMENT. n. April, 2001.

KOPARDEKAR, P. Unmanned Aerial System (UAS) Traffic Management (UTM): Enabling Low-Altitude Airspace and UAS Operations. n. April, 2014.

KOPARDEKAR, P. H.; MAGYARITS, S. Measurement and prediction of dynamic density. **Proceedings of the 5th USA/Europe Air Traffic Management R & D Seminar**, n. Dd, p. 1–10, 2003. Disponível em: <http://tinyurl.com/a364woc>.

KOPARDEKAR, P.; PREVOT, T.; RIOS, J.; ROBINSON III, J. E.; JOHNSON, M.; JUNG, J. UAS Traffic Management (UTM) Concept of Operations to Safely Enable Low Altitude Flight Operations. **16th AIAA Aviation Technology, Integration, and Operations Conference**, n. June, p. 1–16, 2016. Disponível em: <http://arc.aiaa.org/doi/10.2514/6.2016-3292>.

KOPARDEKAR, P.; SCHWARTZ, A. Airspace complexity measurement: An air traffic control simulation analysis. **7th USA/Europe ATM …**, v. 16, n. 1, p. 1–9, 2007. Disponível em: <http://www.atmseminarus.org/seminarContent/seminar7/presentations/pr_052_AAPM.pdf>.

KOPARDEKAR, P.; SCHWARTZ, A.; MAGYARITS, S.; RHODES, J. Airspace complexity measurement: An air traffic control simulation analysis. **Proceedings of the 7th USA/Europe Air Traffic Management Research and Development Seminar, ATM 2007**, v. 16, n. 1, p. 145–153, 2007.

KULLBACK, S.; LEIBLER, R. A. On Information and Sufficiency. **The Annals of Mathematical Statistics**, v. 22, n. 1, p. 79–86, mar. 1951. Disponível em: <http://projecteuclid.org/euclid.aoms/1177729694>.

LADYMAN, J.; LAMBERT, J.; WIESNER, K. What is a Complex System ? 2012.

LAUDEMAN, I. V.; SHELDEN, S. G.; BRANSTROM, R.; BRASIL, C. L. Dynamic Density: An Air Traffic Management Metric. n. April, 1998.

LEMES, M. J. R. Complexidade, acoplamento e criticalidade (C2A) como indicadores de risco em projetos de sistemas. p. 278, 2012.

LLOYD, S. Measures of Complexity a non--exhaustive list. 2001.

MAJUMDAR, A.; OCHIENG, W. Y. **Factors affecting air traffic controller workload: multivariate analysis based on simulation modeling of controller workload**. [s.l: s.n.]

MAJUMDAR, A.; POLAK, J. Estimating Capacity of Europe ' s Airspace Using a Simulation Model of Air Traffic Controller Workload. n. 01, 2001a.

MAJUMDAR, A.; POLAK, J. Estimating capacity of Europe’s airspace using a simulation model of air traffic controller workload. **Transportation Research Record: Journal of the Transportation Research Board**, n. 1744, p. 30–43, 2001b.

MANNING, C. A.; PFLEIDERER, E. M. Relationship of sector activity and sector complexity to air traffic controller taskload. n. DOT/FAA/AM-06/29, p. 1–14, 2006. Disponível em: <http://tinyurl.com/a3nytj6>.

MARCZYK, J. **A new theory of risk and rating**. [s.l.] Editrice, 2011.

MARCZYK, J. **PRACTICAL complexity management**. [s.l: s.n.]

MARCZYK, J. Quantitative Complexity Theory Applications in Medicine White Paper. 2015.

MASALONIS, A. J.; CALLAHAM, M. B.; WANKE, C. R. Dynamic density and complexity metrics for realtime traffic flow management. **Proceedings of the 5th USA/Europe Air Traffic Management R & D Seminar**, n. January 2003, p. 1–10, 2003. Disponível em: <http://www.mitre.org/work/tech_papers/tech_papers_03/masalonis_tfm/masalonis_tfm.pdf>.

MECKIFF, C.; CHONE, R.; NICOLAON, J. The tactical load smoother for multi-sector planning. **2nd USA/EUROPE AIR TRAFFIC MANAGEMENT R&D SEMINAR**, n. December, p. 1–12, 1998.

MITCHELL, M. **Complexity: a guide tour**. [s.l: s.n.]

MOGFORD, R.; GUTTMAN, J.; MORROW, S.; KOPARDEKAR, P. The Complexity Construct in Air Traffic Control: A Review and Synthesis of the Literature. v. 4, n. 1, p. 64–75, 1995.

MUELLER, E.; KOPARDEKAR, P.; GOODRICH, K. Enabling airspace integration for high-density on-demand mobility operations. **17th AIAA Aviation Technology, Integration, and Operations Conference, 2017**, n. June, p. 1–24, 2017.

MURAKAMI, D.; NAG, S.; LIFSON, M.; KOPARDEKAR, P. Space traffic management with a nasa uas traffic management (Utm) inspired architecture. **AIAA Scitech 2019 Forum**, n. January, 2019.

NASA. Uam-Market-Study-Executive-Summary-Pr.Pdf. n. November, 2018. Disponível em: <https://www.nasa.gov/sites/default/files/atoms/files/uam-market-study-executive-summary-pr.pdf>.

NEAPOLITAN, R. E. Learning Bayesian Network. **Prentice Hall Series in Artificial Inteligence**, v. 53, n. 9, p. 1689–1699, 2013.

NETO, E.; BAUM, D. M.; DE ALMEIDA, J. R.; CAMARGO, J. B.; CUGNASCA, P. S. Trajectory-based urban air mobility (UAM) operations simulator (TUS). **arXiv**, v. 55, n. 11, p. 1–50, 2019a.

NETO, E. C. P.; BAUM, D. M.; JUNIOR, J. R. de A.; JUNIOR, J. B. C.; CUGNASCA, P. S. A Trajectory Evaluation Platform for Urban Air Mobility (UAM). **EEE Intelligent Transportation Systems Transactions**, 2021.

NETO, E. P.; BAUM, D. M.; HERNANDEZ-SIM, C. E.; JR, J. R. A.; JR, B. C.; CUGNASCA, P. S. An Airspace Capacity-Based Safety Assessment Model Considering UAS Integration . 2017a.

NETO, E. P.; BAUM, D. M.; HERNANDEZ-SIMOES, C. E.; ALMEIDA, J. R.; CAMARGO, J. B.; CUGNASCA, P. S. An airspace capacity-based safety assessment model considering UAS integration. In: 2017 International Conference on Unmanned Aircraft Systems, ICUAS 2017, **Anais**...2017b.

NETO, E. P. C.; BAUM, D. M.; JUNIOR, J. R. de A.; CUGNASCA, J. B. C. J. P. S. TRAJECTORY-BASED URBAN AIR MOBILITY (UAM) OPERATIONS SIMULATOR (TUS). **Quality**, 2019b.

NEUBAUER, K.; FLEET, D.; GROSOLI, F.; VERSTYNEN, H. **Unmanned aircraft systems (uas) at airports: a primer. 2015**. [s.l: s.n.]

NIELSEN, C. B.; LARSEN, P. G.; FITZGERALD, J.; WOODCOCK, J.; PELESKA, J. Systems of Systems Engineering: Basic Concepts, Model-Based Techniques, and Research Directions. **ACM Computing Surveys**, v. 48, n. 2, p. 1–41, 2015. Disponível em: <http://dl.acm.org/citation.cfm?doid=2830539.2794381>.

OCHIENG, W.; MAJUMDAR, A. **The factors affecting air traffic controller workload : a multivariate analysis based upon simulation modelling of controller workload .** [s.l: s.n.]

PANG, B.; DAI, W.; RA, T.; LOW, K. H. A Concept of Airspace Configuration and Operational Rules for UAS in Current Airspace. In: 2020 AIAA/IEEE 39th Digital Avionics Systems Conference (DASC), **Anais**...IEEE, 11 out. 2020. Disponível em: <https://ieeexplore.ieee.org/document/9256627/>.

PATTERSON, M. D.; ANTCLIFF, K. R.; KOHLMAN, L. W. A proposed approach to studying urban air mobility missions including an initial exploration of mission requirements. **Annual Forum Proceedings - AHS International**, v. 2018- May, 2018.

PEARL, J.; RUSSEL, S. Bayesian networks. **In M.A. Arbib (Ed.), Handbook of Brain Theory and Neural Networks, Cambridge, MA: MIT Press, 157--160, 2003**, v. 53, n. 12, p. 80–90, 2003.

PEPPER, J. W.; MILLS, K. R.; WOJCIK, L. a. Predictability and Uncertainty in Air Traffic Flow Management. **Weather**, n. June, p. 23–27, 2003.

PERROW, C. **Normal Accidents- Living with high-risk technoligies**, 1984. .

PORSCHE. The future of vertical flight. **7th Asian/Australian Rotorcraft Forum, ARF 2018**, 2018.

POSTORINO, M. N.; SARNÉ, G. M. L. Reinventing mobility paradigms: Flying car scenarios and challenges for urban mobility. **Sustainability (Switzerland)**, v. 12, n. 9, p. 1–16, 2020.

R. AUSTIN. **Unmanned aircraft systems. 2011**. [s.l: s.n.]

RADISIC, T.; NOVAK, D.; JURICIC, B. Reduction of air traffic complexity using trajectory-based operations and validation of novel complexity indicators. **IEEE Transactions on Intelligent Transportation Systems**, v. 18, n. 11, p. 3038–3048, 2017.

RAJU, P.; RIOS, J.; JORDAN, A. UTM - A complementary set of services to ATM. **ICNS 2018 - Integrated Communications, Navigation, Surveillance Conference**, p. 2F21-2F27, 2018.

RANIERI, A. Assessing ATM performance interdependencies through Bayesian Networks Preliminary applications and results. n. May 2014, 2015.

REICHE, C.; BRODY, F.; MCGILLEN, C. Final Report An Assessment of the Potential Weather Barriers of Urban Air Mobility (UAM). 2018.

RODGERS, M.; MOGFORD, R. **The Relationship of Sector Characteristics to Operational Errors - 9814.pdf**, 1998. .

SCHRANK, D.; EISELE, B.; LOMAX, T. Urban Mobility Report. **Texas A&M Transportation Institute**, n. February, p. 4–7, 2019.

SHANNON, C.; WEAVER, W. THE MATHEMATICAL THEORY. 1964.

SIEGFRIED, R. Modeling and Simulation of Complex Systems. **Simulation and Modeling of Systems of Systems**, 2013. Disponível em: <http://link.springer.com/10.1007/978-3-658-07529-3>.

SINGAPORE; THAILAND; AMERICA, U. S. of. SWIM IN ASEAN DEMONSTRATION. **55 th CONFERENCE OF DIRECTORS GENERAL OF CIVIL AVIATION AIR NAVIGATION**, 2018.

SINHA, K. Structural Complexity and its Implications for Design of Cyber- Physical Systems. **Handbook of Optical Constants of Solids**, p. 1000-, 2014. Disponível em: <http://www.sciencedirect.com/science/article/pii/B9780125444156501436>.

SRIDHAR, B.; SHETH, K. S.; GRABBE, S. Airspace Complexity and its Application in Air Traffic Management. **System**, n. December, p. 1–9, 1998.

SUÁREZ, N;LÓPEZ,, P; PUNTERO, E;RODRIGUEZ, S. Quantifying Air Traffic Controller Mental Workload. **Fourth SESAR Innovation Days**, n. November, p. 1–6, 2014.

THIPPHAVONG, D. P.; APAZA, R. D.; BARMORE, B. E.; BATTISTE, V.; BELCASTRO, C. M.; BURIAN, B. K.; DAO, Q. V.; FEARY, M. S.; GO, S.; GOODRICH, K. H.; HOMOLA, J. R.; IDRIS, H. R.; KOPARDEKAR, P. H.; LACHTER, J. B.; NEOGI, N. A.; NG, H. K.; OSEGUERA-LOHR, R. M.; PATTERSON, M. D.; VERMA, S. A. Urban air mobility airspace integration concepts and considerations.

2018 Aviation Technology, Integration, and Operations Conference, 2018.

TISUE, S.; WILENSKY, U. Netlogo: Design and Implementatio of a Multi-Agent Modeling Environment. **Center for Connected Learning and Computer-Based Modeling Northwestern University**, v. 1, n. 2, p. 564–577, 2004. Disponível em: <http://www.jstor.org/stable/2117868%5Cnhttp://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=256564>.

TOBARUELA, G.; SCHUSTER, W.; MAJUMDAR, A.; OCHIENG, W. Y.; MARTINEZ, L.; HENDRICKX, P. A method to estimate air traffic controller mental workload based on traffic clearances. **Journal of Air Transport Management**, v. 39, p. 59–71, 2014.

UBER. Fast-Forwarding to a Future of On-Demand Urban Air Transportation. 2016. Disponível em: <https://www.uber.com/elevate.pdf>.

UBER. eVTOL Vehicle Requirements and Missions. 2018.

VALDÉS, R. M. A.; COMENDADOR, V. F. G.; SANZ, A. R.; AYRA, E. S.; CASTÁN, J. A. P.; SANZ, L. P. Bayesian Networks for Decision-Making and Causal Analysis under Uncertainty in Aviation. **Intech**, v. 32, p. 137–144, 2018. Disponível em: <http://www.intechopen.com/books/trends-in-telecommunications-technologies/gps-total-electron-content-tec- prediction-at-ionosphere-layer-over-the-equatorial-region%0AInTec>.

VASCIK, P.; BALAKRISHNAN, H.; HANSMAN, J.; CASTELLDEFLS, U. P. C. Assessment of Air Traffic Control for Urban Air Mobility and Unmanned Systems International Conference on Research in Air Transportation Emerging Low Altitude Airspace Operators. n. June, 2018.

VASCIK, P. D.; HANSMAN, R. J. Constraint Identification in On-Demand Mobility for. **MIT International Center for Air Transportation (ICAT)**, n. June, 2017.

VASCIK, P. D.; HANSMAN, R. J. Scaling constraints for urban air mobility operations: Air traffic control, ground infrastructure, and noise. **2018 Aviation Technology, Integration, and Operations Conference**, n. June, 2018.

WANG, H.; GAO, J. Bayesian network assessment method for civil aviation safety based on flight delays. **Mathematical Problems in Engineering**, v. 2013, 2013.

WANG, H.; GONG, D.; WEN, R. Air traffic controllers workload forecasting method based on neural network. v. 161, p. 2460–2463, 2015.

WANG, L.; LI, X.; MIAO, Y.; WU, S. An Assessment Method of Unmanned Aerial Vehicle Mission Planning Quality Based on Bayesian Network. **Proceedings - 2018 11th International Congress on Image and Signal Processing, BioMedical Engineering and Informatics, CISP-BMEI 2018**, n. 1, p. 1–5, 2019.

WANG, Y.; LIU, Y.; SUN, Z.; TANG, P. A Bayesian-entropy network for information fusion and reliability assessment of national airspace systems. **Proceedings of the Annual Conference of the Prognostics and Health Management Society, PHM**, p. 1–8, 2018.

WECK, KAUSHIK SINHA, O. L. de. Empirical Validation of Structural Complexity Metric and Complexity Management for Engineering Systems. **Systems Engineering**, v. 14, n. 3, p. 305–326, 2016. Disponível em: <http://ezproxy.lib.ucf.edu/login?url=http://search.proquest.com/docview/926281441?accountid=10003%5Cnhttp://sfx.fcla.edu/ucf?url_ver=Z39.88-2004&rft_val_fmt=info:ofi/fmt:kev:mtx:journal&genre=article&sid=ProQ:ProQ:civilengineering&atitle=Model+Based+Syste>.

WILEY, J.; GELL-MANN, M. WHAT IS COMPLEXITY ? v. 1, n. 1, 1995.

WU, Z.; ZHANG, Y. **Integrated Network Design and Demand Forecast for On-Demand Urban Air MobilityEngineering**, 2021. .

APPENDIX A: AIR TRAFFIC CONCEPTS, AIR TRAFFIC RULES AND AIRSPACE STRUCTURE AND KEY CONCEPTS

1. Introduction

According to (ICAO, 2016b) Air traffic Service (ATS) is defined as generic term meaning variously, flight information service, alerting service, air traffic advisory service, air traffic control service (area control service, approach control service or aerodrome control service).

The objectives of the air traffic services shall be to (ICAO, 2001b):

a) prevent collisions between aircraft;
b) prevent collisions between aircraft on the maneuvering area and obstructions on that area;
c) provide advice and information useful for the safe and efficient conduct of flights;
d) notify appropriate organizations regarding aircraft in need of search and rescue aid, and assist such organizations as required.

The need for the provision of air traffic services shall be determined by consideration of the following (ICAO, 2001b):

a) Types of air traffic involved.
b) Density of air traffic.
c) Meteorological conditions; and
d) such other factors as may be relevant.

Due to the number of elements involved, it has not been possible to develop specific data to determine the need for air traffic services in a given area or at a given location (ICAO, 2001b). For example:

a) A mixture of different types of air traffic with aircraft of varying speeds (conventional jet, etc.) might necessitate the provision of air traffic services.

b) Meteorological conditions might have considerable effect in areas where there is a constant flow of air traffic (e.g., scheduled traffic), whereas similar or worse meteorological conditions might be relatively unimportant in an area where air traffic would be discontinued in such conditions (e.g., local VFR flights); and

c) open stretches of water, mountainous, uninhabited, or desert areas might necessitate the provision of air traffic services even though the frequency of operations is extremely low.

Considering the definition for Air Traffic Services, basically the airspace is divided, regarding the designation and the type of service that will be provided, in Controlled Airspace (ATC) and Flight Information Regions (FIR).

Controlled Airspace is divided into ATZ[28] (Aerodrome Traffic Zone), CTR (Control Zone), TMA (Terminal Control Area) and AWY (Airway).

Except for AWY that have defined lateral and vertical dimensions, the other controlled air spaces have variable dimensions, defined in aeronautical publications. Figure 64 shows the structure of the airspace from the side.

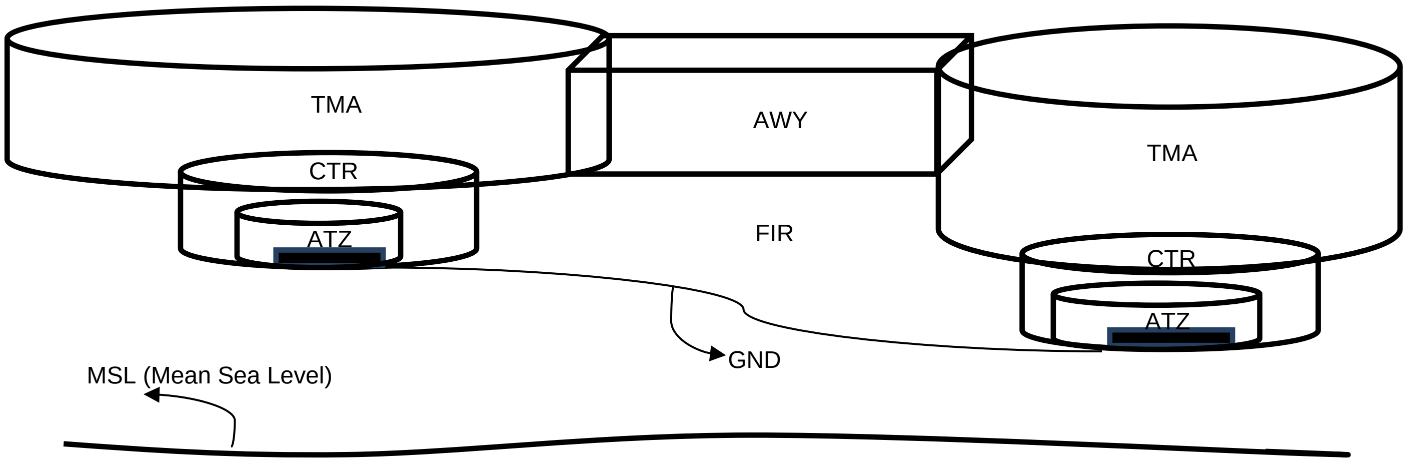

Figure 64: structure of the airspace from the side.
Source: (ICAO, 2001a) adapted.

Air traffic Control Service is provided at ATZ, CTR, TMA and AWY for the purpose of:

a) prevent collisions between aircraft and on the maneuvering area between aircraft and obstructions; and
b) expediting and maintaining orderly flow of air traffic.

[28] Where there is TWR (Aerodrome Control Tower).

Outside the controlled airspaces shown in Figure 1, the only service provided by ATS units to aircraft is the flight information service (FIS)[29]. Figure 65 presents an enroute chart, containing airspace structure (plan view), with the lateral and vertical limits of the CTR and TMA and the representation of the AWYs. Outside these airspaces we find the FIR.

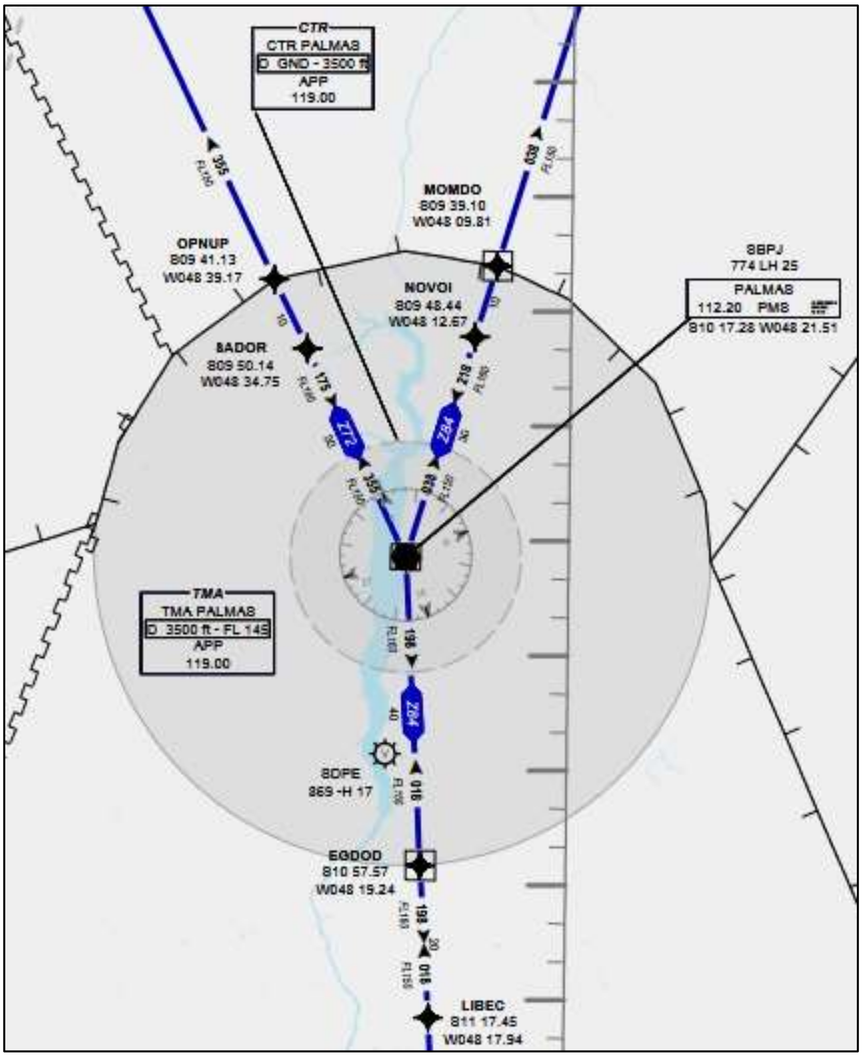

Figure 65: Enroute Chart that presents controlled airspace, and FIR.
Source: www.aisweb.decea.mil.br.

[29] Flight information service is provided in any airspace, if the aircraft is in bilateral contact with the ATS.

2. São Paulo Helicopter Control: An UAM Case

The large concentration of helipads near the airport of São Paulo (Congonhas), specifically under the final approach of runway 17 (RWY) (figure 66), has made the movement of helicopters in this region to be considerable intense.

As helicopters approaching or taking off from the helipads did not have the obligation to request authorization for any control unit, until the creation of a helicopter control area, there were several conflicts between helicopters approaching/departuring from the helipads and aircraft approaching to Congonhas airport, specifically for RWY 17. The only recommendation for helicopters was to perform air-to-air coordination with other helicopters at a specific VHF frequency.

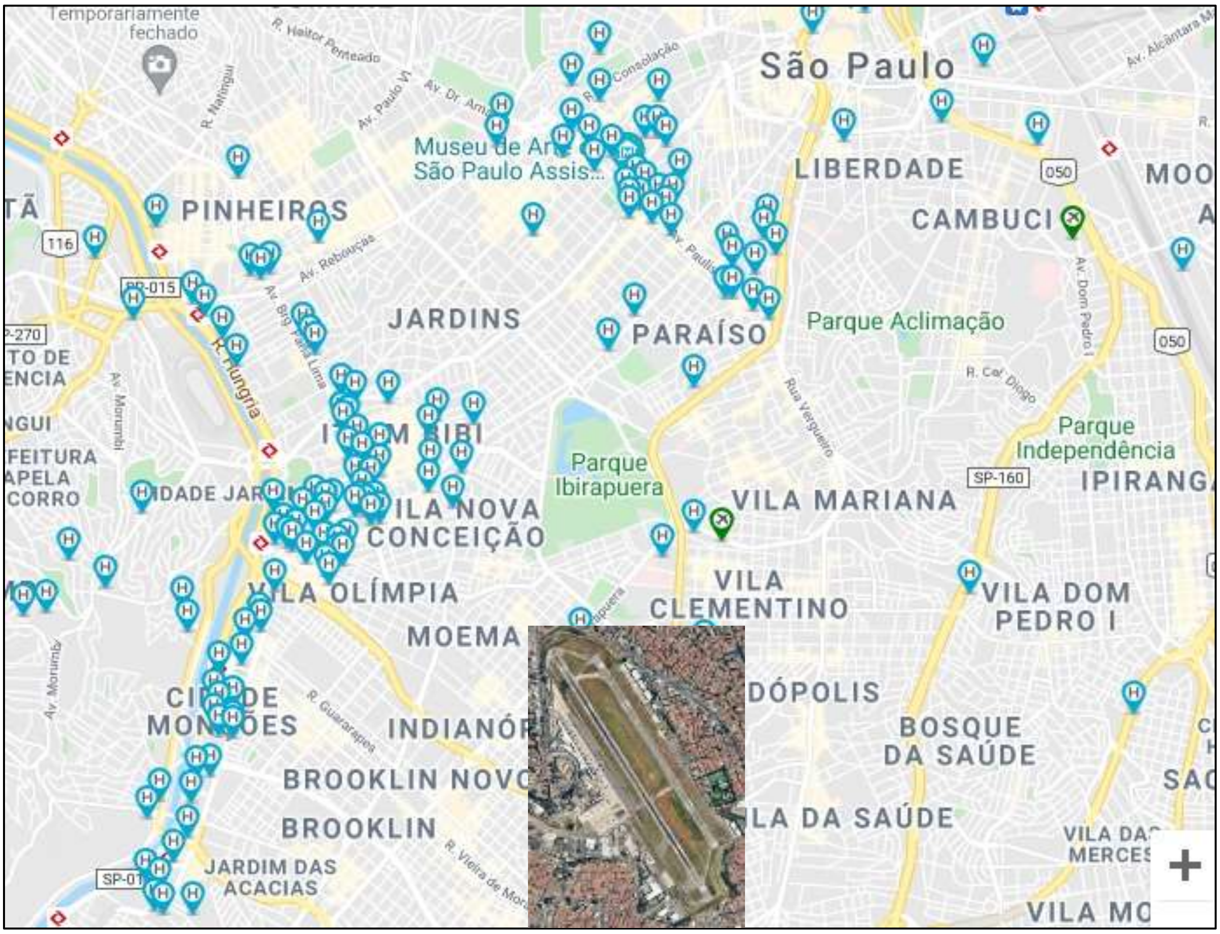

Figure 66 – Helipad Concentration near Airport Congonhas.
Source: https://www.aerodromosweb.com.br/aerodromos and Google Earth.

The solution found was the creation of a control area, starting from the airport runway, with a width of 5NM and a length of 6NM, divided into squares. This area was called the Helicopter Control Area and, simultaneously with the creation of this area, a

Control Unit called the Helicopter Control was created. This control position, although physically located within TWR SP, uses Radar to perform the air traffic control service. The simultaneous capacity stipulated for this area is 6 helicopters flying simultaneously. Figure 67 shows the helicopter control area. This case is presented in (VASCIK; HANSMAN, 2017), as a successful implementation of UAM in São Paulo with helicopters.

Figure 67 – São Paulo Helicopter Control Case.
Source: (DECEA, 2018).

3. Air Traffic Rules

a) Visual Flight Rules (VFR)

Independent of flight rules, except when necessary for take-off or landing, or except by permission from the appropriate authority, aircraft shall not be flown over the congested areas of cities, towns or settlements or over an open-air assembly of persons, unless at such a height as will permit, in the event of an emergency arising, a landing to be made without undue hazard to persons or property on the surface (ICAO, 2012). A VFR flight shall not be flown (ICAO, 2012):

a) over the congested areas of cities, towns or settlements or over an open-air assembly of persons at a height less than 300 m (1 000 ft) above the highest obstacle within a radius of 600 m from the aircraft (Figure 5 – Part 1).

b) elsewhere than as specified above, at a height less than 150 m (500 ft) above the ground or water.

Visual flight rules require the pilot to maintain constant visual contact with the ground so that references are maintained, identifying locations, in addition to maintaining horizontal, vertical separation of clouds, maximum speed and maximum flight level, as shown in the figure 68 (Part 2).

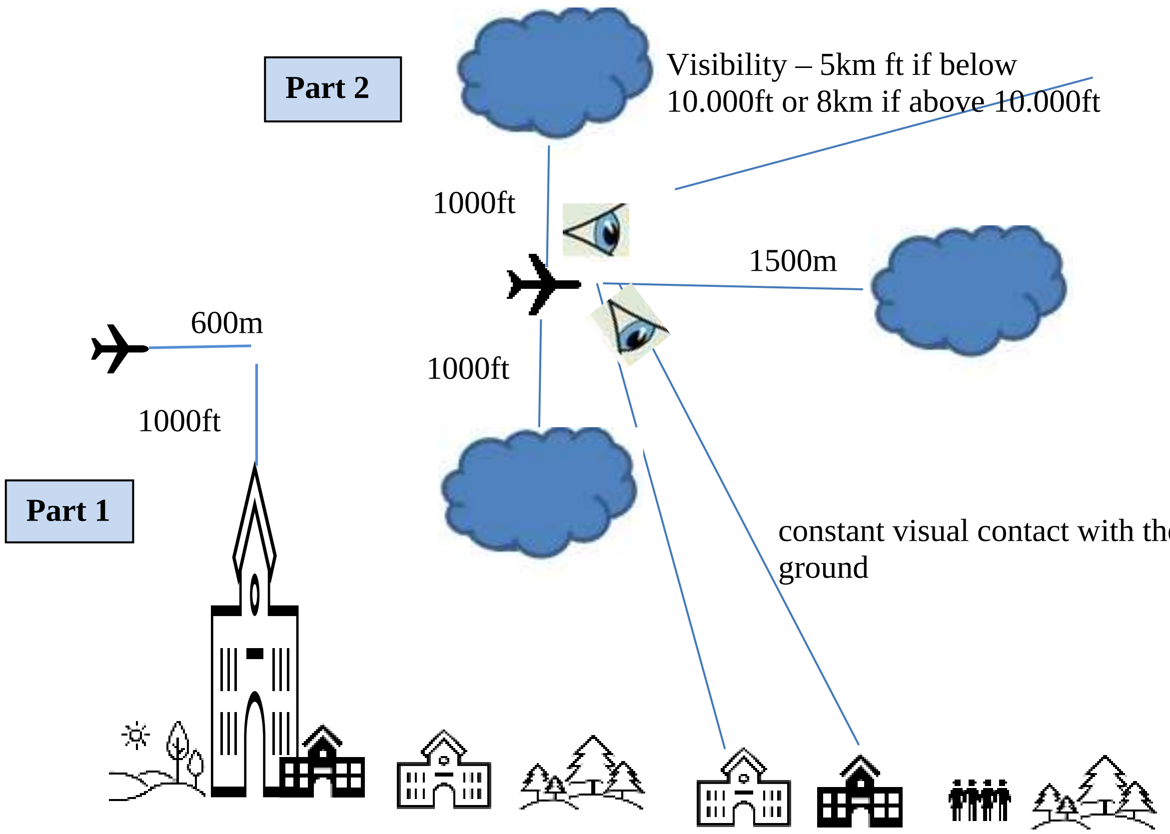

Figure 68 – Visibility and distance from clouds to VFR flight.
Source: (DECEA, 2016a) adapted.

Thus, as shown in Figure 58, for a flight to be conducted according to the Visual Flight Rules (VFR), the pilot must maintain horizontal and vertical distance from clouds and obstacles, maintain minimum visibility and maintain visual contact with the ground or water.

In addition, the VFR flight shall be conducted at a cruising level appropriate to the track as specified in the tables of cruising levels, presented in table 55 In (ICAO, 2012), a flight level (FL) is defined as a surface of constant atmospheric pressure which is related to a specific pressure datum, 1013,2 hectopascals (hPa), and is separated from other such surfaces by specific pressure intervals. It must be observed that the greatest VFR FL is 145 (14.500 ft).

Table 55- cruising levels to VFR fligt.

Track			
From 180 degrees to 359 degrees		From 000 degrees to 179 degrees	
FL	Feet	FL	Feet
045	4,500	035	3,500
065	6,500	055	5,500
085	8,500	075	7,500
105	10,500	095	9,500
125	12,500	115	11,500
145	14,500	135	13,500

Fonte: (ICAO, 2012).

Considering, for example, a flight that intends to continue VFR. In addition to the requirements presented in figure 68, an FL must be chosen according to the magnetic track you want to fly. Imagine the aircraft in figure 5 flying at magnetic track 090º; it could fly FL 035, FL 055, FL 075, FL095, FL115, or FL135. Now imagine the aircraft flying at magnetic track 270º; it could fly FL 045, FL065, FL085, FL105, FL125, or FL145.

As shown in figure 68, on a VFR flight, the pilot must maintain visual contact with the ground during the entire flight, identifying notable landmarks. One of the aeronautical charts used for flight planning is the WAC (World Aeronautical Chart), presented on a scale of 1: 1,000,000, as shown in figure 69. This is one of the charts that present the visual references for the VFR, such as rivers, cities, etc.

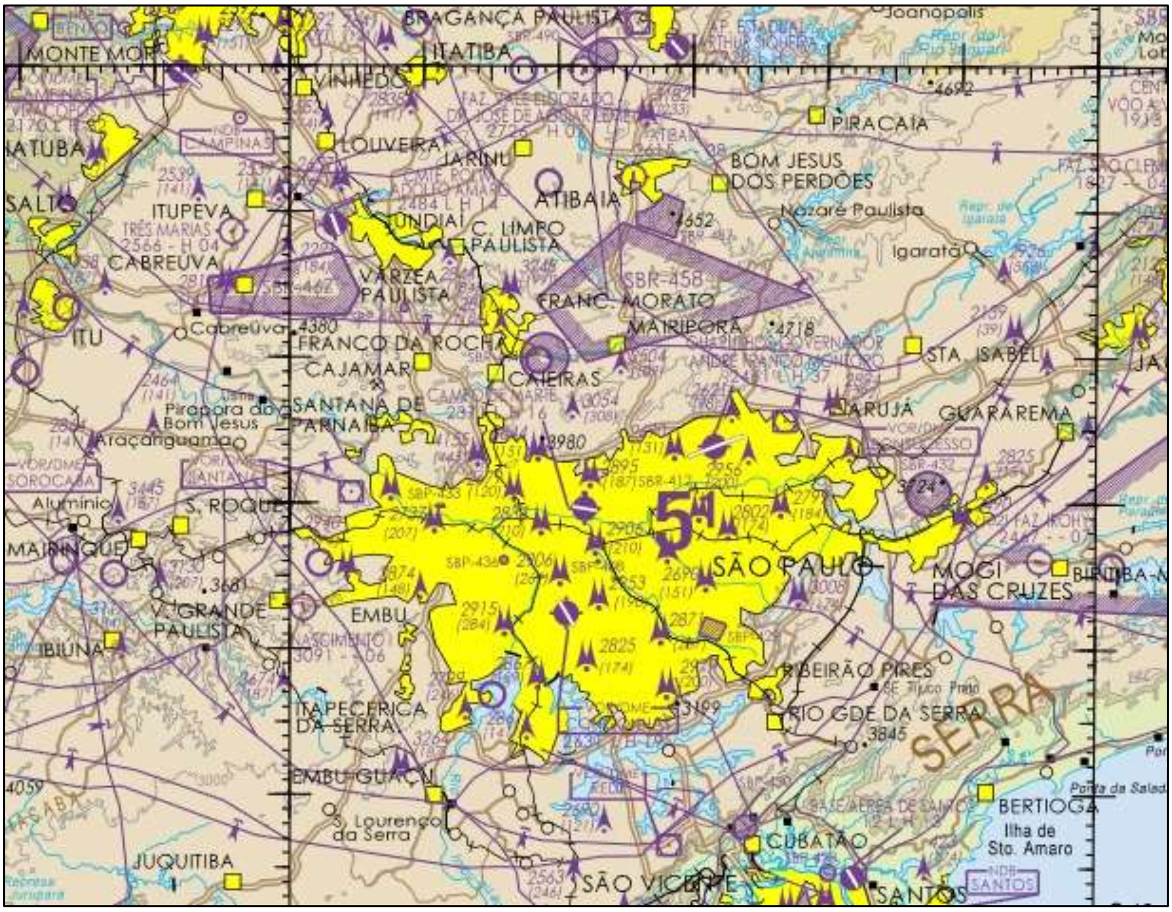

Figure 69 – WAC – World Aeronautical Chat.

Source: (https://aisweb.decea.mil.br/cartas/visuais/wac).

However, in places with high air traffic demand in order to maintain flight safety, aircraft or helicopter routes are created for the VFR flight, segregating the VFR flights. In these cases, VFR flights must fly, specifically on these routes. The main objective is that the VFR does not conflict with the IFR.

In these routes, as shown in figure 70,among other information, the directions in each route are defined, as well as maximum altitudes that must be maintained, respecting VFR.

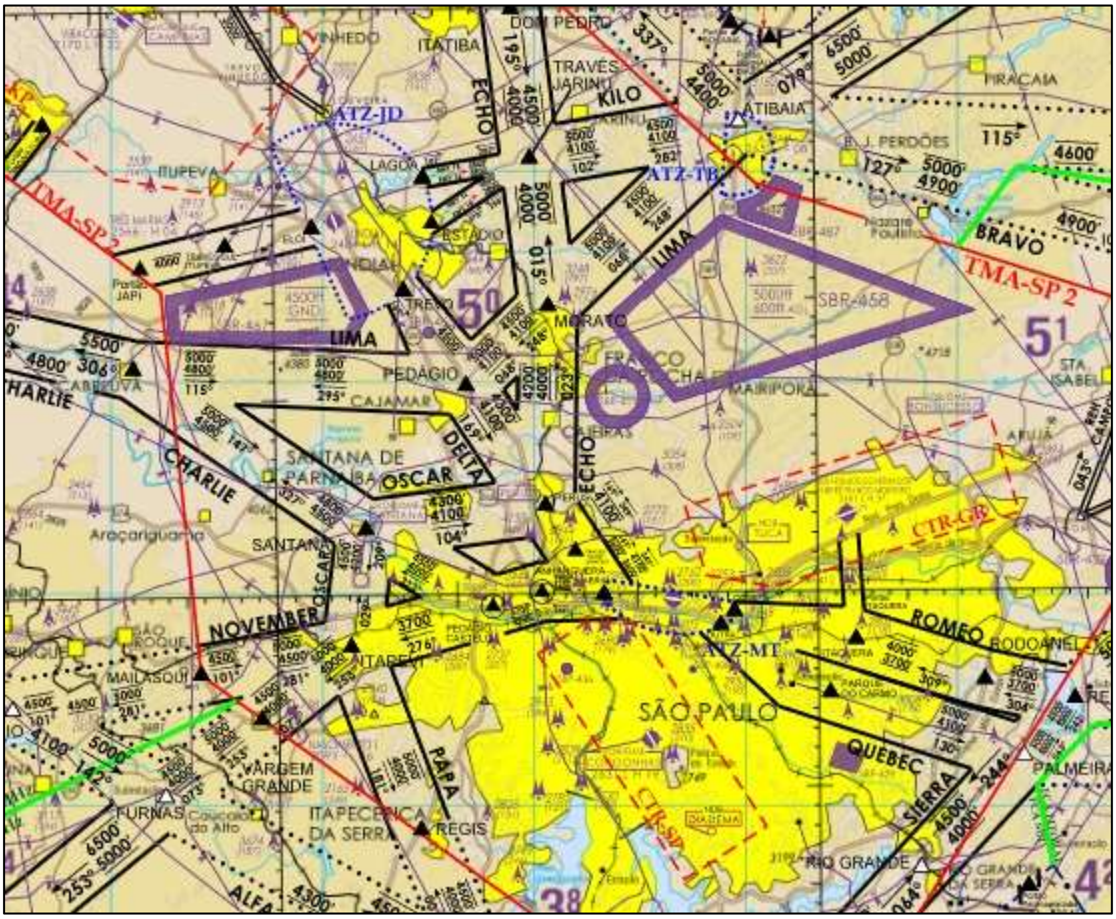

Figure 70 - Special Aircraft Routes.

Source: (https://aisweb.decea.mil.br/?i=cartas&p=visuais).

On a flight, regardless of the flight rules used, all steps must be considered in your planning, be it the departure, the cruise flight, or the approach. Specifically, in VFR, the procedure to be adopted in an approach is described in the VAC (Visual Approach Chart), being presented all the characteristics of the aerodrome, as well as the important notices. In some cases, VAC also has the purpose of separating VFR traffic and operating simultaneously at different aerodromes, as shown in figure 71.

When a VFR aircraft intends to arrive at a particular aerodrome, it must follow the trajectories defined in the respective aerodrome VAC. This is important because, due to obstacles, the procedures described for VFR approach at the aerodrome may be different, with specific guidelines: sector in which the procedure will be performed, altitudes, etc.

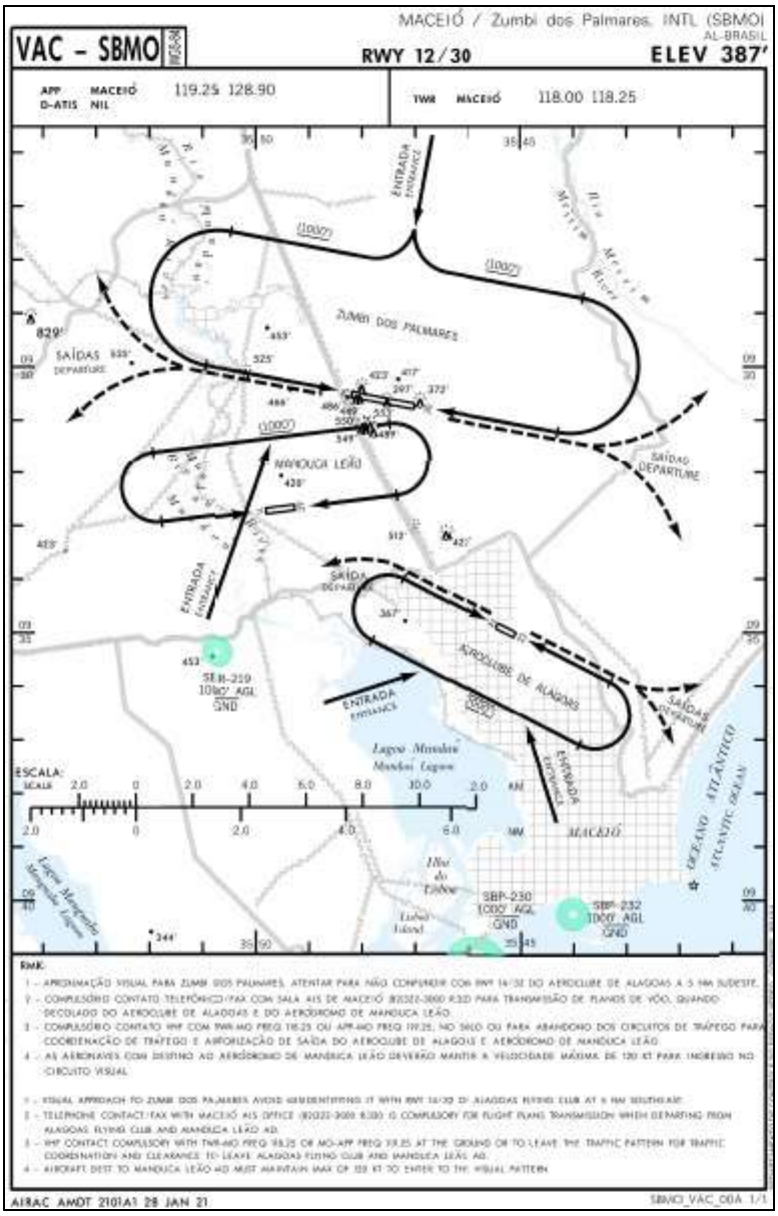

Figure 71 - Visual Approach Chart.
Source:(https://aisweb.decea.mil.br/?i=cartas).

b) Instrument Flight Rules (IFR)

On an instrument flight, the pilot will rely entirely on his onboard instruments, following the instructions issued by the air traffic control units (ATC) and the air navigation charts, depending on the phase of the flight.

In order for the ATC to become aware of a particular flight and to be able to plan for the issuance of authorizations, the pilot must present his plan in a form called Flight Plan, as shown in figure 72, describing, among other information, the route to be used, usually represented by an AWY, the destination aerodrome and the estimated flight time.

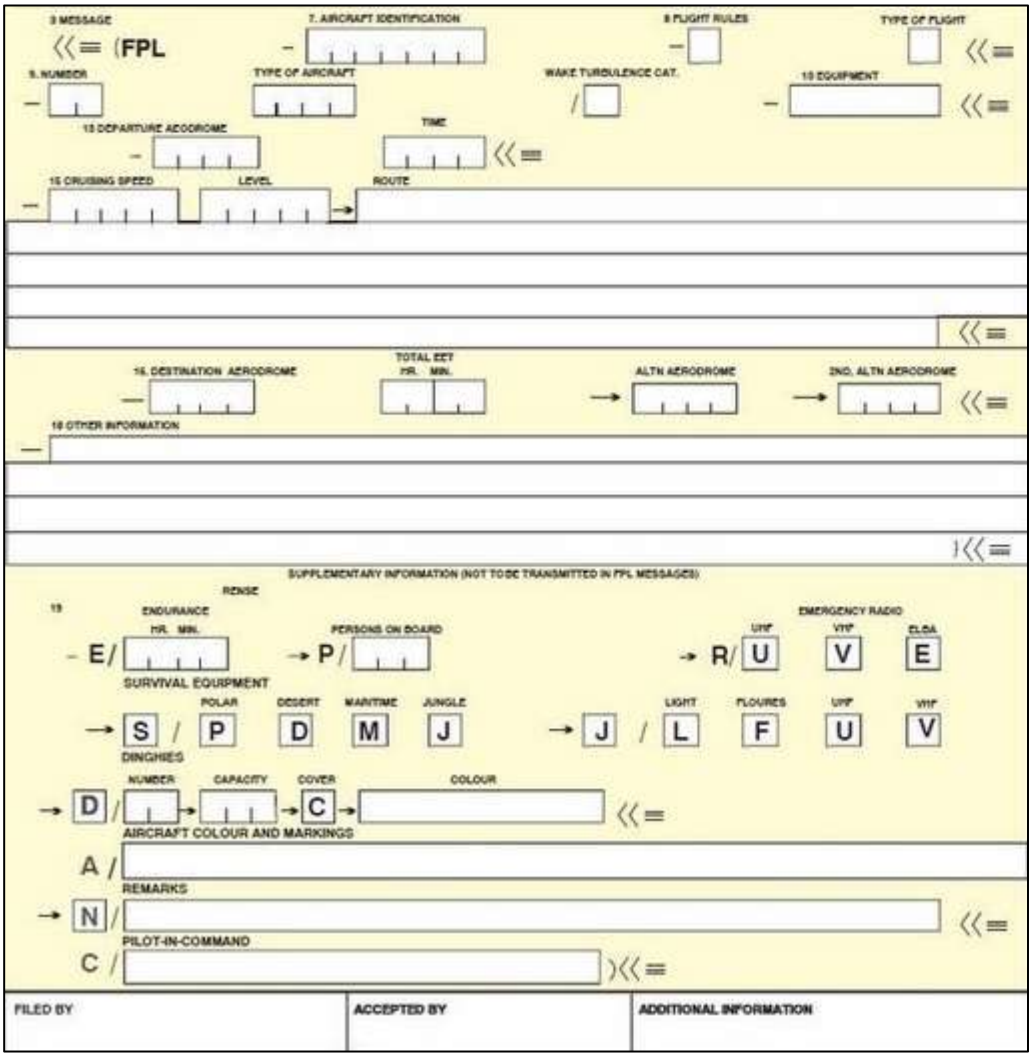

Figure 72 – Flight Plan.

Source:(https://www.faa.gov/air_traffic/publications/atpubs/fs_html/appendix_a.html)

The air traffic control units (TWR, APP and ACC) when receiving the intention to perform a certain flight with the information presented in figure 9, will take the necessary measures, within their respective area of jurisdiction.

In all phases of flight, the pilot will make radio contact with the respective ATC and will receive the appropriate instructions, according (ICAO, 2016b). When the pilot makes the initial contact with TWR, he will receive the current weather conditions at the airport, RWY in use, flight plan authorization, with changes or approved as requested and, after TWR coordinates with the APP, which will be the procedure takeoff by IFR to be performed (SID), called Standard Instrument Departure. After being authorized to start the taxi, TWR will issue all instructions for the pilot to proceed to the RWY in use and to take off. Figure 73 shows aerodrome chart of KLAX[30] containing all runways and taxiways (TWY) of the airport.

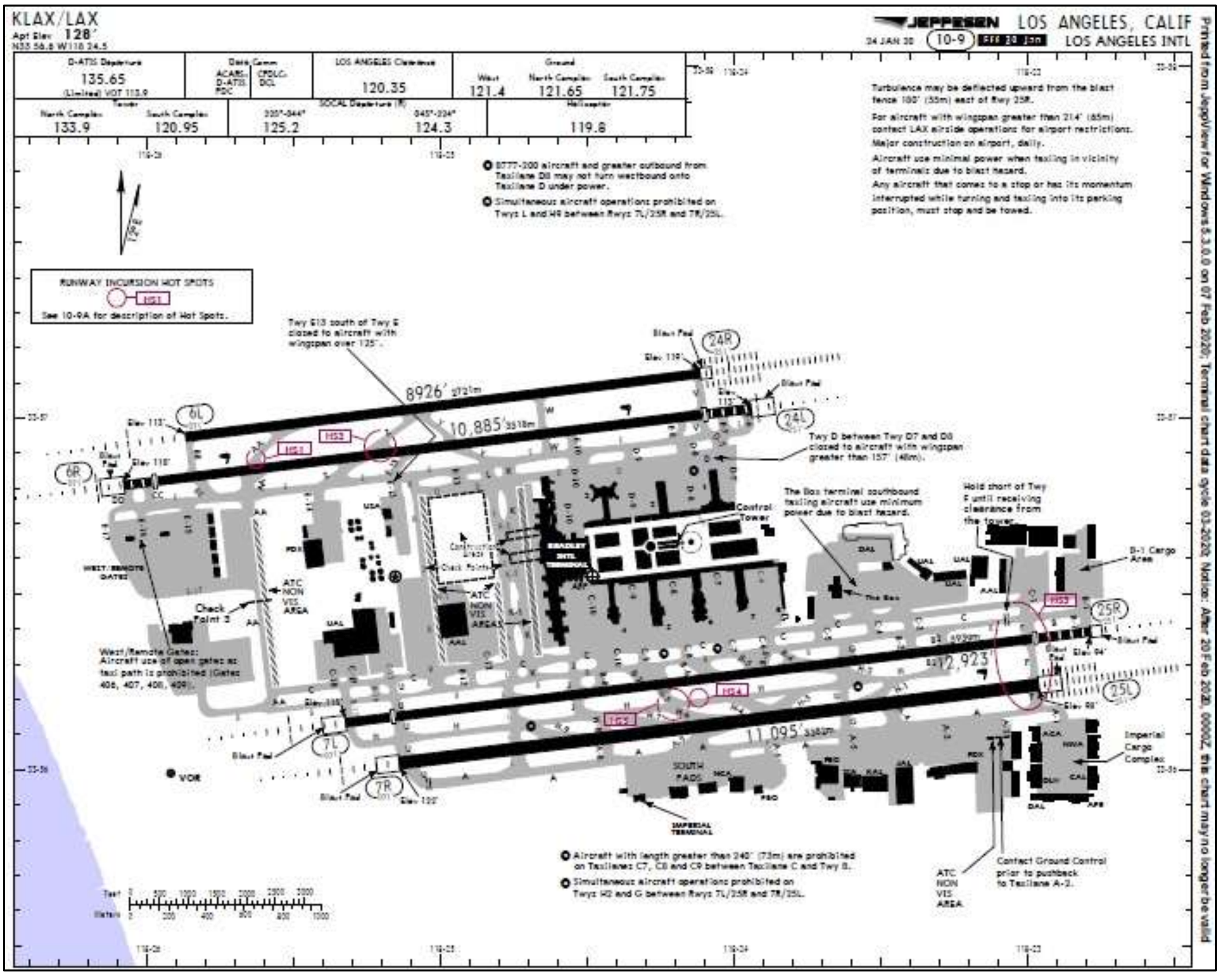

Figure 73 – KLAX Aerodrome Chart.
Source: (https://vau.aero/navdb/chart/KLAX.pdf).

The SID, shown in figure 74, describes all the trajectories that must be executed within a Terminal Control Area (TMA) until the exit of the TMA and interception of the route to be flown, that is, under the jurisdiction of the APP.

[30] LAX International Airport.

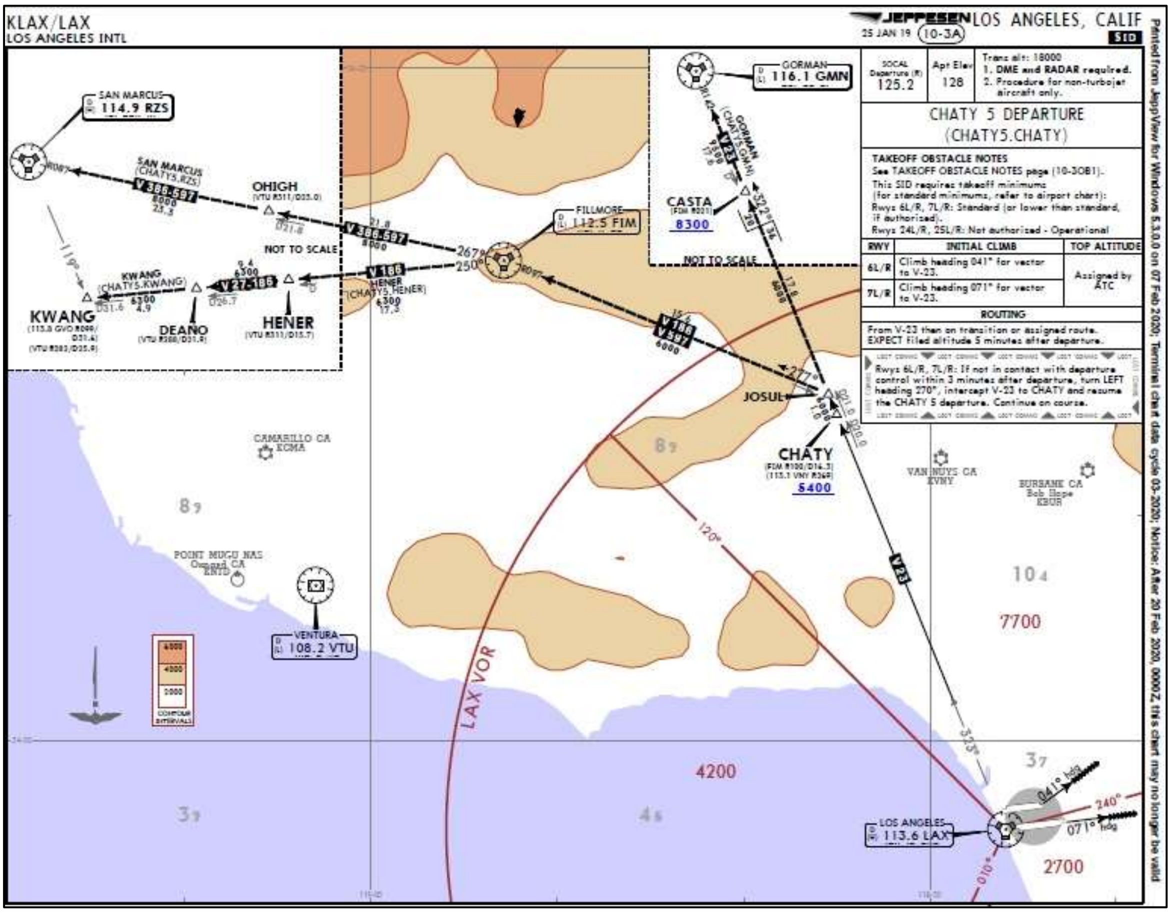

Figure 74 – SID of KLAX.

Source:(https://vau.aero/navdb/chart/KLAX.pdf).

At a point defined by the ATC, which can still be within the TMA, communications will be transferred from the APP to the ACC so that the pilot can complete his climb, intercept the route axis, often represented by an AWY. Figure 75 shows an excerpt from an ENRC with several AWYs connecting one airport to another.

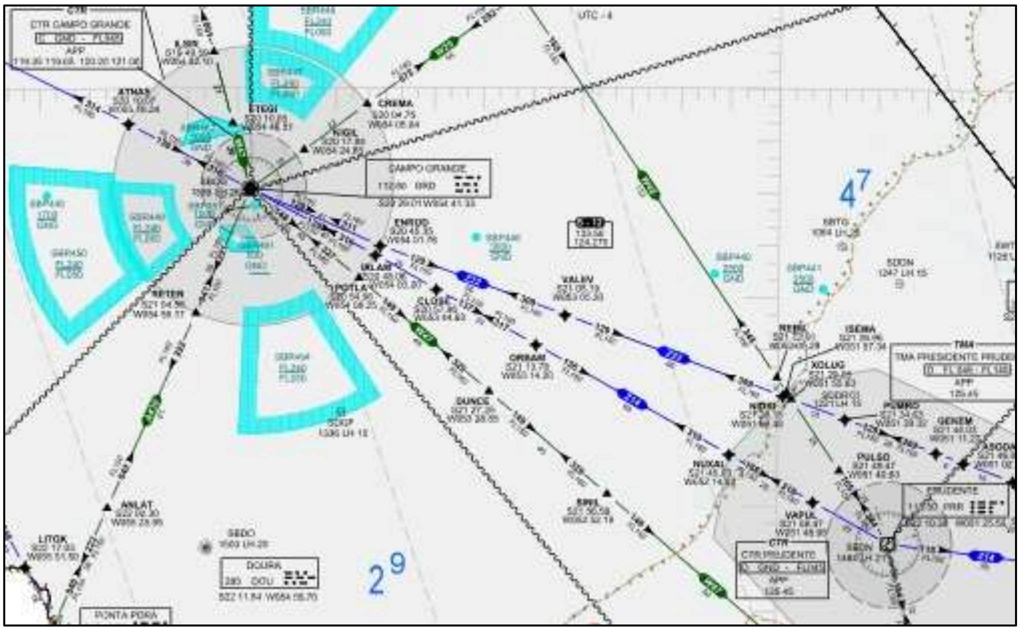

Figure 75 – AWYs (ENRC).

Source::(https://aisweb.decea.mil.br/cartas/rotas/sbxx_l5_enrc_20201203.pdf?CFID=79200974-2a82-4b0c-aaff-4f0284259541&CFTOKEN=0).

After the pilot executes the SID and flies in cruising level until close to the destination, he will carry out the approach procedures. The first procedure to be performed is the STAR (Standard Terminal Arrival Route) which will start on route, that is, with the ACC. Figure 76 shows a STAR for the KLAX (Los Angeles International Airport).

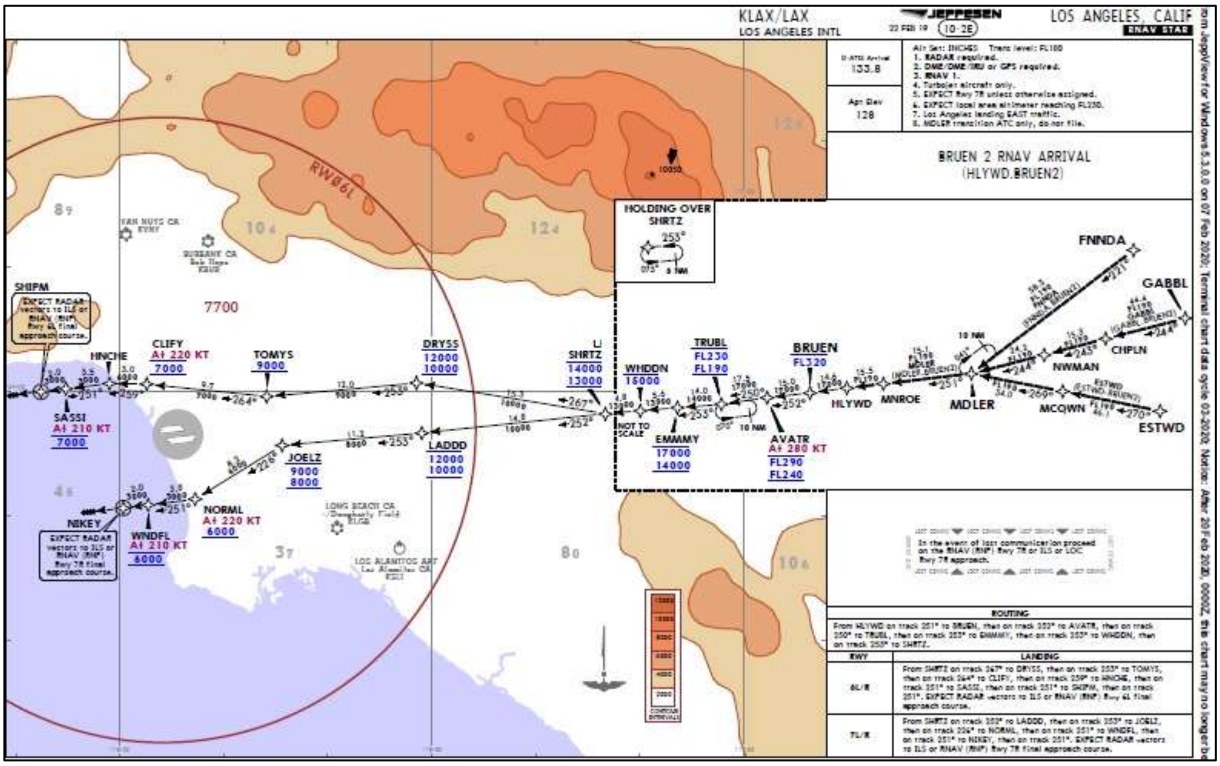

Figure 76 – STAR to KLAX.

Source:(https://vau.aero/navdb/chart/KLAX.pdf).

After the pilot completes a STAR he will perform the procedure that will take him to the landing described in an IAC (Instrument Approach Chart). In this chart, in addition to the procedures other than until landing, it describes what must be performed in case of missed approach. Figure 77 shows an IAC for Los Angeles International Airport (KLAX).

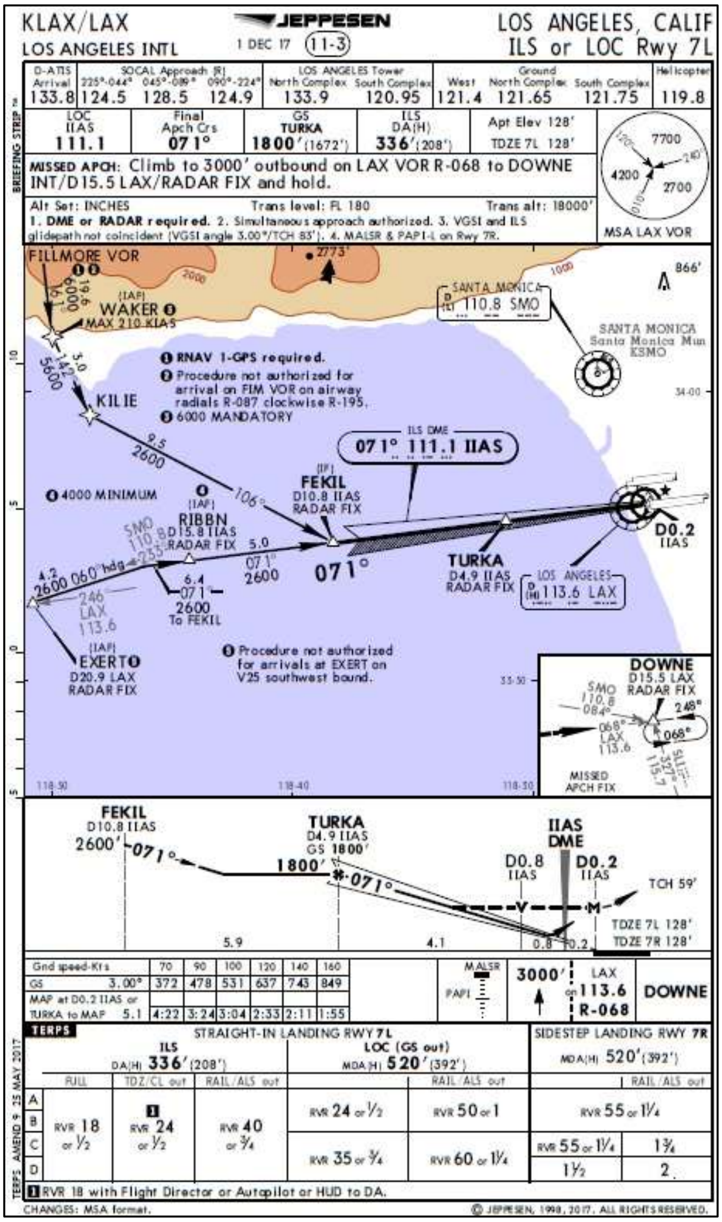

Figure 77 – IAC to KLAX.

Source:(https://vau.aero/navdb/chart/KLAX.pdf).

Figure 78 illustrates all the procedures that will be performed by the pilot from the takeoff to the destination, , the steps will be: takeoff performing the procedures described in the SID, keep the AWY specific until the destination level, start the descent describing the procedures STAR and perform the IAC until landing or the start of the missed approach. It should be noted that, as shown in figure 78, the airports of origin and destination may be at different altitudes[31], which will be represented on the respective charts.

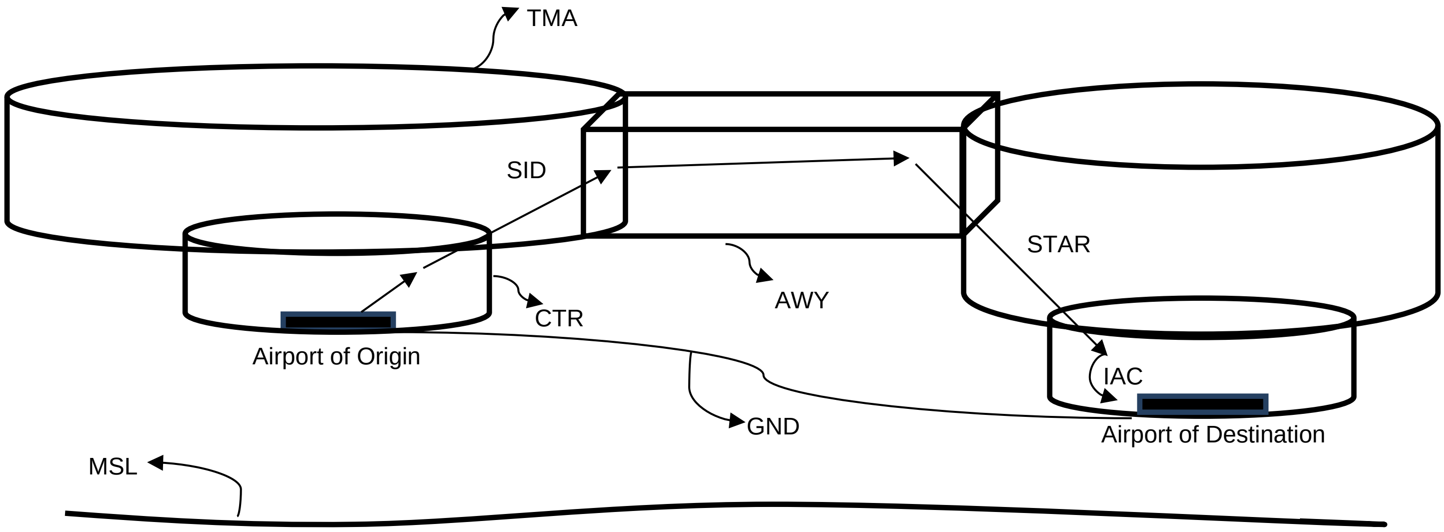

Figure 78 - All the procedures that will be performed by the pilot from the takeoff to the destination

4. Trajectory Based Operation (TBO)

TBO enables airspace users to operate as close as feasible to their preferred trajectories and to perform continuous descent and climb (EUROCONTROL, 2019), considering four dimensional (4D) trajectories (latitude, longitude, altitude, time) and velocity to enhance global ATM decision making. A key emphasis is on integrating all flight information to obtain the most accurate trajectory model for ground automation (ICAO, 2016a).

Airspace users are then obliged to fly their aircraft along the agreed trajectory with the required precision and accuracy in the four dimensions. ANSPs (Air Navigation Service Provider)[32] and airports, for their part, are obliged to facilitate that trajectory (AYHAN; SAMET, 2016)(RADISIC; NOVAK; JURICIC, 2017).

[31] The vertical distance of a level, a point or an object considered as a point, measured from mean sea level (MSL)
[32] ACC, for example

The key elements of TBO include (https://www.faa.gov/air_traffic/technology/tbo/):

- Time Based Management (TBM), which helps manage traffic flows and trajectories by *scheduling* and *metering* aircraft through congested NAS (National Airspace System) resources or constraint points.
- Performance Based Navigation (PBN), which enables aircraft to more accurately navigate along their trajectories, and enables decision support tools to improve *feasibility of schedules* for constraint points as well as achieve greater *compliance to schedules*.
- Enabling Technologies, which expand and automate sharing of common information about aircraft trajectories, and include System-wide Information Management (SWIM), Data Communications, enhanced data exchange and many others.

5. System-Wide Information Management (SWIM)

SWIM (System Wide information Management) consists of standards, infrastructure and governance enabling the management of ATM information and its exchange between qualified parties via interoperable services. It is a distributed processing environment which replaces data level interoperability and closely coupled interfaces with an open, flexible, modular and secure data architecture totally transparent to users and their applications (EUROCONTROL, 2019).

SWIM consists of standards, infrastructure and governance enabling the management of the ATM-related information and its exchange between qualified parties via interoperable services (ICAO, 2015b).

According to (DECEA, 2019) the benefits of ground-to-air SWIM are:

- allows ATC and pilot to share up-to-date meteorological and aeronautical information, helping to make the decision-making process more appropriate and timely;
- it allows the flight crew to have more adequate access to flow restrictions and airspace restriction information, assisting teams in the re-planning of their flights. In addition, it facilitates access to information that supports proper ATFM negotiations or allows seamless coordination of flight plan updates initiated by ATC; and

- improves decision making by all ATM participants during all strategic, pre-tactical and flight tactic phases (pre-flight, during flight and post-flight), with sharing of situational awareness and greater availability of quality data and information from official sources.

SWIM is an information-sharing infrastructure which facilitates the exchange of ATM system information, e.g. airport operational status, weather information, flight data, the Flexible Use of Airspace (FUA) information, etc., to a wide range of ATM stakeholders in real time, as shown in figure 79 (SINGAPORE; THAILAND; AMERICA, 2018).

Figure 79: Real Time information sharing enabled by SWIM.
Source: (SINGAPORE; THAILAND; AMERICA, 2018)

APPENDIX B: BAYESIAN NETWORK CONCEPTS

For decades conditional probabilities of events of interest have been computed from known probabilities using Bayes' theorem. Given two events H and E such that P(H) ≠ 0 and P(E)) ≠ 0, according to the equation 29.

Equation 29: Bayes' Theorm

$$P(H|E) = \frac{P(E|H)\,P(H)}{P(E)} = P(E|H)\,\frac{P(H)}{P(E)}$$

There are two main strands of probabilistic reasoning:

1) Bayesian Reasoning: Determines the probability of occurrence of a hypothesis from a set of known evidence (with a certain degree of uncertainty)➔ $P(H|E)$.
2) Frequentist Reasoning: Determines the probability of occurrence of an evidence by sampling a population assuming that a hypothesis is totally true or totally false➔ $P(E|H)$

As proposed in (NEAPOLITAN, 2013), considering figure 37, let Ω be the set of all objects in figure 80, and assign each object a probability of 1/13. Let "One" be the set of all objects containing a 1, "Two" be the set of all objects containing a 2, and "Black" be the set of all black objects.

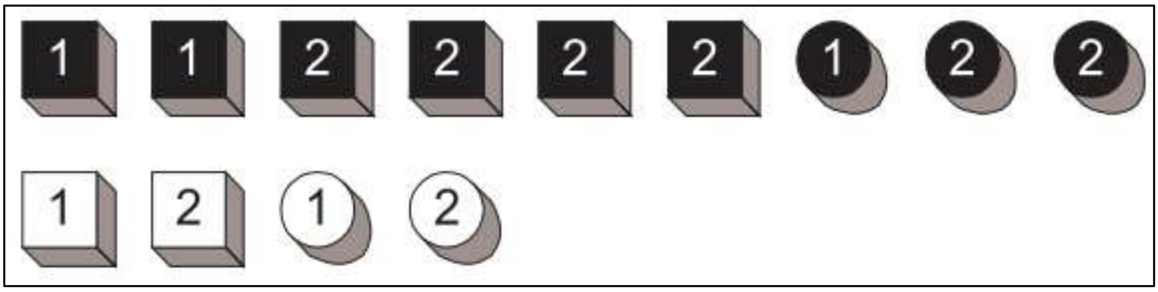

Figure 80: Sample Space.

Source: (NEAPOLITAN, 2013).

Define the probability that the object belongs to the set “One”, considering that it belongs to the set “Black” ➔ $P(One|Black)$. The is presented in equation 30.

Equation 30: Resolution - $P(One|Black)$

$$P(One|Black) = \frac{P(Black|One)\ P(one)}{P(black)} = \frac{(3|5)\ (5/13)}{9/13} = \frac{1}{3}$$

Consider the situation where one feature of an entity has a direct influence on another feature of that entity. For example, the presence or absence of a disease in a human being has a direct influence on whether a test for that disease turns out positive or negative. For decades, Bayes’ theorem has been used to perform probabilistic inference in this situation (NEAPOLITAN, 2013).

Now, consider the situation where several features are related through inference chains. For example, as presented in (NEAPOLITAN, 2013), whether or not an individual has a history of smoking has a direct influence both on whether or not that individual has bronchitis and on whether or not that individual has lung cancer. In turn, the presence or absence of each of these diseases has a direct influence on whether or not the individual experiences fatigue. Also, the presence or absence of lung cancer has a direct influence on whether or not a chest X-ray is positive. In this situation, we would want to do probabilistic inference involving features that are not related via a direct influence. We would want to determine, for example, the conditional probabilities both of bronchitis and of lung cancer when it is known an individual smokes, is fatigued, and has a positive chest X-ray. Yet bronchitis has no direct influence (indeed no influence at all) on whether a chest X-ray is positive. Therefore, these conditional probabilities cannot be computed using a simple application of Bayes’ theorem. The random variables are represented in table 56.

There is a straightforward algorithm for computing them, but the probability values it requires are not ordinarily accessible; furthermore, the algorithm has exponential space and time complexity: Bayesian networks. BN were developed to address these difficulties.

Table 56: Values of the features.

Feature	Value	When the Feature Takes this Value
H	$h1$	There is a history of smoking
	$h2$	There is no history of smoking
B	$b1$	Bronchitis is present
	$b2$	Bronchitis is absent
L	$l1$	Lung cancer is present
	$l2$	Lung cancer is absent
F	$f1$	Fatigue is present
	$f2$	Fatigue is absent
C	$c1$	Chest X-ray is positive
	$c2$	Chest X-ray is negative

SOURCE: (NEAPOLITAN, 2013).

A BN is a Directed Acyclic Graph (DAG) consisting of nodes representing relevant properties of a given system or process, and directed arcs (links) describing the probabilistic dependence between pairs of nodes (PEARL; RUSSEL, 2003).

Each node denotes a random variable, and each arc denotes a direct dependence between the variables. Each node is characterized with a set of exhaustive and mutually exclusive values (either discrete or continuous ones) which represent alternative states of the property corresponding to that node. Each random variable is associated with a set of local probability distributions (parameters in the Conditional Probability tables, CPT).

Therefore, the DAG that results from the construction of a BN is quantified through a series of conditional probabilities based either on data, on information available on the system or problems, or on expert knowledge elicitation (COMENDADOR et al., 2018).

Figure 81 shows a Bayesian network representing the probabilistic relationships among the features presented in table 56 and the values of the features represent in that network.

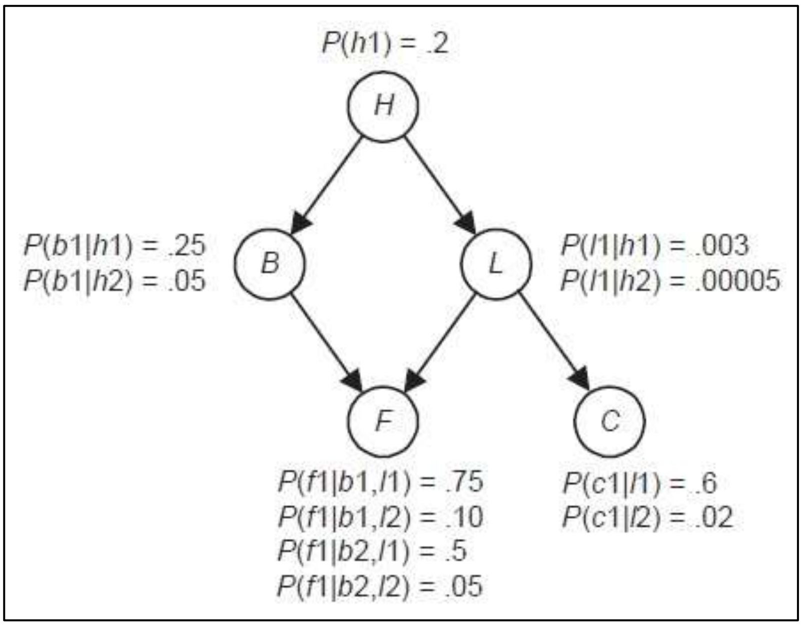

Figure 81: Bayesian Network for the example given.
Source: (NEAPOLITAN, 2013).

As identified in several surveys, such as (COMENDADOR et al., 2019), was used a computational tool to aid in the assembly, arrangement and handling of the BN, as presented in figure 82.

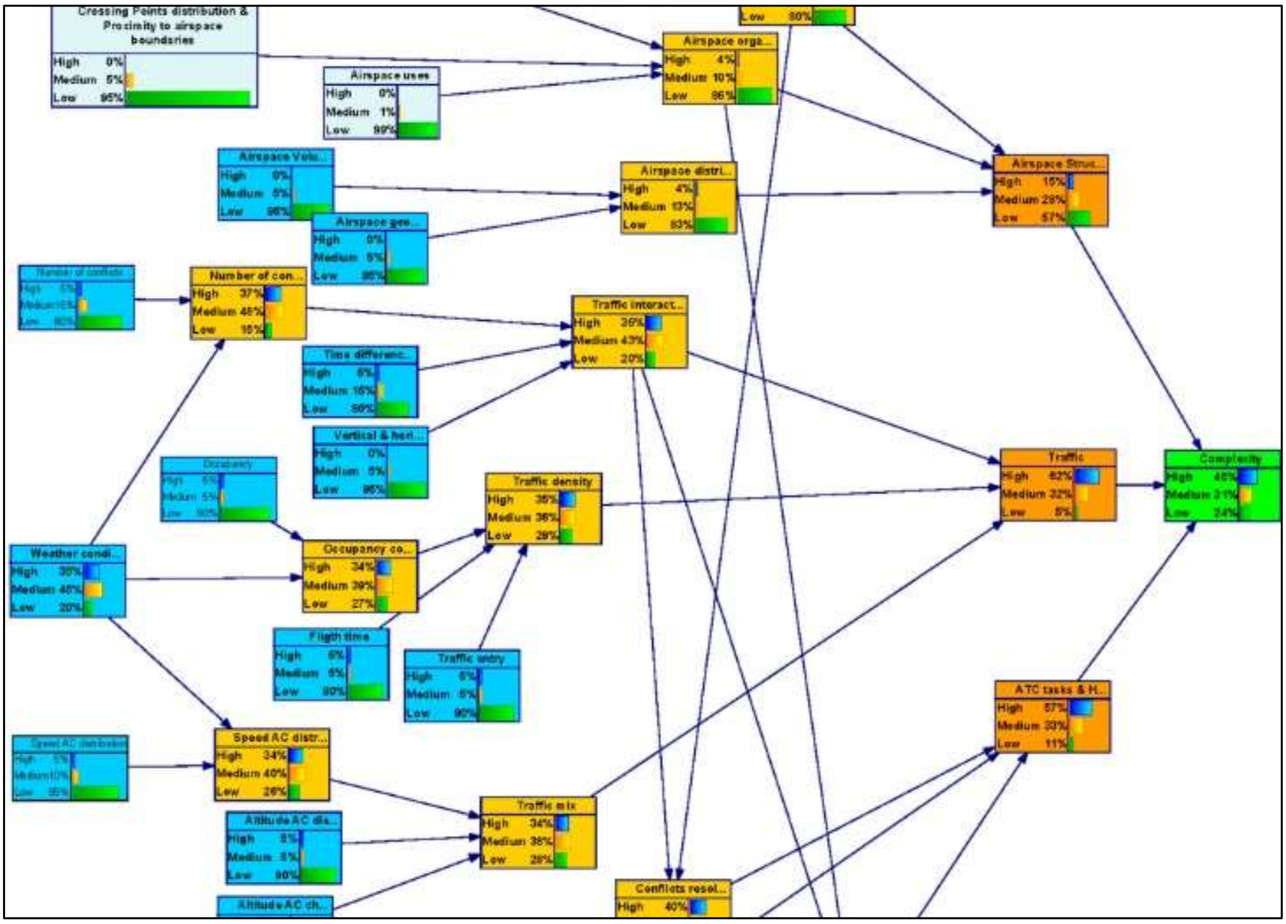

Figure 82: Example of BN using structure using a computational tool.
Source: (COMENDADOR et al., 2019)

As presented in https://www.kdnuggets.com/software/bayesian.html, here are some useful tools to aid in the assembly, arrangement and handling of the BN. Our choice was to use a GeNIe, with a free version.

According (GENIE, 2020), GeNIe Modeler is a graphical user interface (GUI) to SMILE Engine and allows for interactive model building and learning. It is written for the Windows environment but can be also used on macOS and Linux under Wine. It has been thoroughly tested in the field since 1998, has received a wide acceptance within both academia and industry, and has thousands of users world-wide.

APPENDIX C: THE PROCESS OF DEFINING DECILES LIMITS

The first step was to carry out 100 simulations for each of the 2048 different scenarios. Figure 83 shows Netlogo configured to perform one hundred simulations for the 1st scenario, which will be presented below, together with the 2048 scenarios.

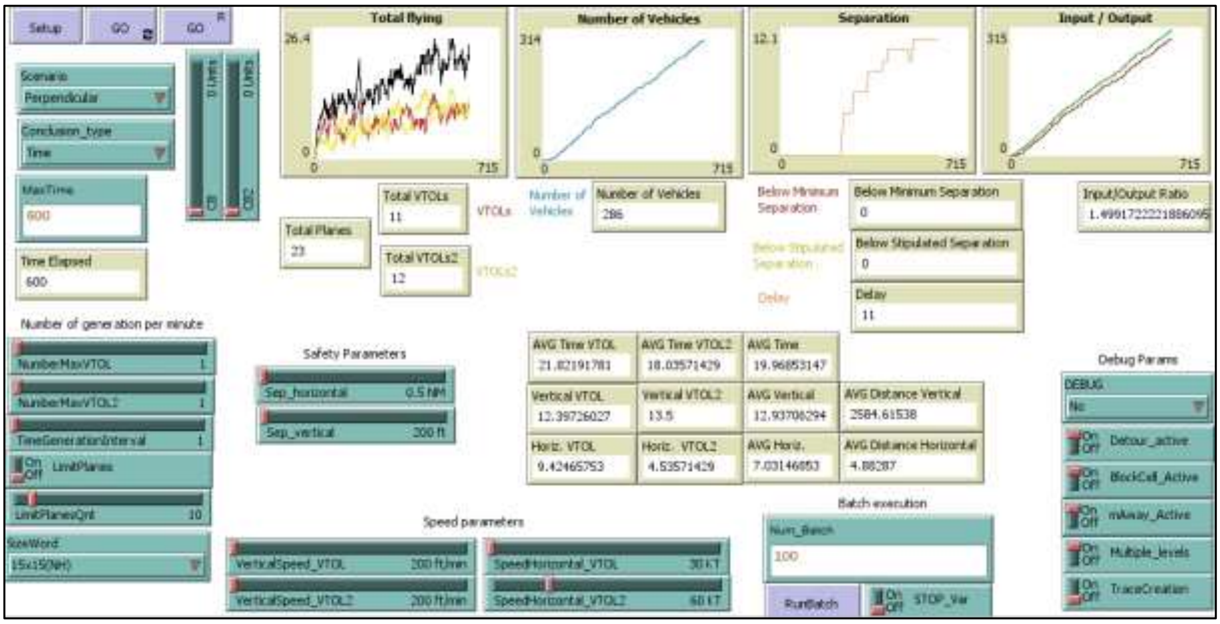

Figure 83: Netologo: Scenario 1.

Source: The author.

Part of the 2048 scenarios obtained are represented in table 57. All 2048 scenarios are represented in the spreadsheet available at:

https://drive.google.com/drive/u/2/folders/0AM17VnQapbkfUk9PVA

Table 57: Part of the 2048 scenarios.

	Na	MS	SS	De	Sc	N1	N2	CB	Size	VS 1	HS 1	VS2	HS2	SH	SV	Aco	Cap Index	VH	H	AC	L	IN
1	283,0808081	0,222222222	0,222222222	3,666666667	perpendicular	1	1	0	15 X 15	200	30	200	30	0,5	200	0,38674	2,5857	0,7843	0,1616	0,0404	0,0303	0,0034
2	555,1414141	1,656565656	1,656565656	38,41414141	perpendicular	3	1	0	15 X 15	200	30	200	30	0,5	200	1,14233	0,8754	0,5084	0,0101	0,1246	0,2761	0,0808
3	939,1515152	1,656565657	1,656565657	38,41414141	perpendicular	1	3	0	15 X 15	200	30	200	30	0,5	200	1,485	0,6734	0,4949	0,0135	0,0774	0,3266	0,0875
4	746,5656566	4,121212121	4,121212121	114,7171717	perpendicular	3	3	0	15 X 15	200	30	200	30	0,5	200	-1,88041	-0,5318	0,3906	0	0	0,1246	0,4848
5	182,8787879	1,575757576	1,575757576	59,24242424	perpendicular	1	1	100	15 X 15	200	30	200	30	0,5	200	2,80034	0,3571	0,4916	0	0,34%	0,3939	0,1111
6	329,6666667	5,737373737	5,737373737	176,8585859	perpendicular	3	1	100	15 X 15	200	30	200	30	0,5	200	-1,18821	-0,8426	0,5502	0	0	0,0572	0,5926
7	329,6565656	8,242424242	8,242424242	171,3636364	perpendicular	1	3	100	15 X 15	200	30	200	30	0,5	200	-1,2025	-0,8316	0,3535	0	0	4,71%	0,5985
8	434,090909	11,91919192	11,91919192	345,4747475	perpendicular	3	3	100	15 X 15	200	30	200	30	0,5	200	-1,00685	-0,9932	0,3333	0	0	0,0067	0,6599
9	283,7474747	0,080808081	0,080808081	1,262626263	perpendicular	1	1	0	30 X 30	200	30	200	30	0,5	200	0,34657	2,8854	0,9394	0,0471	0	0,0135	0
10	385,020202	0,323232323	0,323232323	3,676767677	perpendicular	3	1	0	30 X 30	200	30	200	30	0,5	200	0,38814	2,5117	0,7508	0,165	0,0537	0,0471	0,34%
11	561,8	0,28	0,28	6,64	perpendicular	1	3	0	30 X 30	200	30	200	30	0,5	200	0,39825	2,5116	0,7441	0,1582	0,0539	0,0404	0,0034
12	831,88	0,7	0,7	15,54	perpendicular	3	3	0	30 X 30	200	30	200	30	0,5	200	0,57458	1,741	0,5657	0,1111	0,165	0,1313	0,0269
13	232,85	0,18	0,18	15,15	perpendicular	1	1	100	30 X 30	200	30	200	30	0,5	200	0,43292	2,3099	0,6431	0,101	0,2323	0,0168	0,0067
14	460,41	0,9	0,9	43,79	perpendicular	3	1	100	30 X 30	200	30	200	30	0,5	200	1,33156	0,751	0,5455	0	0,0168	0,4108	0,0269
15	462,01	1	1	44,55	perpendicular	1	3	100	30 X 30	200	30	200	30	0,5	200	1,29153	0,7744	0,5387	0	0,037	0,3939	0,0303
16	676,94	2,24	2,24	87,51	perpendicular	3	3	100	30 X 30	200	30	200	30	0,5	200	2,14116	0,4666	0,3333	0,1333	0,2	0	0,3333
17	287,1212121	0,823232323	0,823232323	3,545454545	perpendicular	1	1	0	15 X 15	1000	30	200	30	0,5	200	0,38372	2,6061	0,8081	0,138	0,0067	0,0404	0,67%
18	570,97	0,74	0,74	13,65	perpendicular	3	1	0	15 X 15	1000	30	200	30	0,5	200	0,53319	1,8755	0,5859	0,1212	0,1616	0,1077	0,0236
19	547,03	1,38	1,38	32,9	perpendicular	1	3	0	15 X 15	1000	30	200	30	0,5	200	0,96731	1,0338	0,5253	0,0135	0,1414	0,2492	0,0707
20	799,22	2,8	2,8	71,99	perpendicular	3	3	0	15 X 15	1000	30	200	30	0,5	200	-153,848	-0,0065	0,4411	0	0,0337	0,2121	0,5151
21	185,75	1,94	1,94	57,04	perpendicular	1	1	100	15 X 15	1000	30	200	30	0,5	200	8,48896	0,1178	0,4478	0	0	0,451	0,1212
22	342,48	5,94	5,94	159,18	perpendicular	3	1	100	15 X 15	1000	30	200	30	0,5	200	-1,207	-0,8285	0,3535	0	0	0,0505	0,596
23	330,95	5,9	5,9	171,3	perpendicular	1	3	100	15 X 15	1000	30	200	30	0,5	200	-1,21734	-0,8214	0,3569	0	0	0,037	0,6061
24	458,65	11,44	11,44	322,35	perpendicular	3	3	100	15 X 15	1000	30	200	30	0,5	200	-1,00321	-0,9968	0,3333	0	0	0,0034	0,6633
25	285,9	0,08	0,08	0,77	perpendicular	1	1	0	30 X 30	1000	30	200	30	0,5	200	0,34218	2,9226	0,965	0,0269	0	0,0101	0
26	574,1	0,26	0,26	2,2	perpendicular	3	1	0	30 X 30	1000	30	200	30	0,5	200	0,36307	2,7543	0,8822	8,75%	0	0,0236	0,0067
27	566,94	0,24	0,24	3,88	perpendicular	1	3	0	30 X 30	1000	30	200	30	0,5	200	0,37834	2,6431	0,8182	0,1279	0,0135	0,0404	0
28	847,06	0,56	0,56	8,87	perpendicular	3	3	0	30 X 30	1000	30	200	30	0,5	200	0,43743	2,2861	0,6835	0,165	0,0741	0,064	0,0135
29	235,52	0,54	0,54	14,71	perpendicular	1	1	100	30 X 30	1000	30	200	30	0,5	200	0,4635	2,1575	0,6128	0,1111	0,2189	0,0556	0,0034
30	468,97	1,12	1,12	40,49	perpendicular	3	1	100	30 X 30	1000	30	200	30	0,5	200	1,34372	0,7442	0,552	0	0,0404	0,3906	0,037
31	464,93	0,96	0,96	41,07	perpendicular	1	3	100	30 X 30	1000	30	200	30	0,5	200	1,16904	0,8554	0,5522	0	0,0438	0,367	0,037

Souce: The author.

Follows the meaning of each of the columns in table 57 follows.

- Na – index for number of aircraft
- MS- Index for number of aircraft below the stipulated minimum separation.
- SS- Index for the number of aircraft below the stipulated minimum separation.
- De – Index for delay.
- From SC to SV are the parameters of each of the CG (inputs).
- Cap Index- Índice capacidade from equation 21:

$$Capacity\ Index = 3 * VH + 2 * H + A - 2 * L - 3 * I$$

Where VH (Very High); H (High); A (Acceptable); L (Low); and IN (Insignificant) are the probabilities for the capacity levels found in the Bayesian Network.

- From VH to IN are the probabilities found in the Bayesian Network for the capacity levels found.

All one hundred simulations of the 2048 scenarios were extracted, according to table 60, which presents only a few scenarios. However, access to the results of the 2048 scenarios can be obtained from:

https://drive.google.com/drive/u/2/folders/0AJLHhYZHURjWUk9PVA

For each scenario, as showns in table 58, the averages of the outputs (CM) were extracted and placed in ascending order to define the limits of the deciles. After defining the limits of the deciles, for each scenario of the 2048 developed, were distributed the one hundred simulations in the respective deciles and find the probability for each decile. Table 59 presents this distribution in one of the scenarios. This table can be checked when accessing each of the 2048 scenarios, available on the link above.

Table 58: Different scenarios.

Results_Perpendicular_1_1_1_0CBs_0CB2_15x15(NH)_VTOL_200FtMin_30KT_VTOL2_200FtMin_30KT_SepHorizontal_0.5_SepVertical_200.csv
Results_Perpendicular_1_1_1_0CBs_0CB2_15x15(NH)_VTOL_200FtMin_30KT_VTOL2_200FtMin_30KT_SepHorizontal_0.5_SepVertical_400.csv
Results_Perpendicular_1_1_1_0CBs_0CB2_15x15(NH)_VTOL_200FtMin_30KT_VTOL2_200FtMin_30KT_SepHorizontal_1_SepVertical_200.csv
Results_Perpendicular_1_1_1_0CBs_0CB2_15x15(NH)_VTOL_200FtMin_30KT_VTOL2_200FtMin_30KT_SepHorizontal_1_SepVertical_400.csv
Results_Perpendicular_1_1_1_0CBs_0CB2_15x15(NH)_VTOL_200FtMin_30KT_VTOL2_200FtMin_150KT_SepHorizontal_0.5_SepVertical_200.csv
Results_Perpendicular_1_1_1_0CBs_0CB2_15x15(NH)_VTOL_200FtMin_30KT_VTOL2_200FtMin_150KT_SepHorizontal_0.5_SepVertical_400.csv
Results_Perpendicular_1_1_1_0CBs_0CB2_15x15(NH)_VTOL_200FtMin_30KT_VTOL2_200FtMin_150KT_SepHorizontal_1_SepVertical_200.csv
Results_Perpendicular_1_1_1_0CBs_0CB2_15x15(NH)_VTOL_200FtMin_30KT_VTOL2_200FtMin_150KT_SepHorizontal_1_SepVertical_400.csv
Results_Perpendicular_1_1_1_0CBs_0CB2_15x15(NH)_VTOL_200FtMin_30KT_VTOL2_1000FtMin_30KT_SepHorizontal_0.5_SepVertical_200.csv
Results_Perpendicular_1_1_1_0CBs_0CB2_15x15(NH)_VTOL_200FtMin_30KT_VTOL2_1000FtMin_30KT_SepHorizontal_0.5_SepVertical_400.csv
Results_Perpendicular_1_1_1_0CBs_0CB2_15x15(NH)_VTOL_200FtMin_30KT_VTOL2_1000FtMin_30KT_SepHorizontal_1_SepVertical_200.csv
Results_Perpendicular_1_1_1_0CBs_0CB2_15x15(NH)_VTOL_200FtMin_30KT_VTOL2_1000FtMin_30KT_SepHorizontal_1_SepVertical_400.csv
Results_Perpendicular_1_1_1_0CBs_0CB2_15x15(NH)_VTOL_200FtMin_30KT_VTOL2_1000FtMin_150KT_SepHorizontal_0.5_SepVertical_200.csv
Results_Perpendicular_1_1_1_0CBs_0CB2_15x15(NH)_VTOL_200FtMin_30KT_VTOL2_1000FtMin_150KT_SepHorizontal_0.5_SepVertical_400.csv
Results_Perpendicular_1_1_1_0CBs_0CB2_15x15(NH)_VTOL_200FtMin_30KT_VTOL2_1000FtMin_150KT_SepHorizontal_1_SepVertical_200.csv
Results_Perpendicular_1_1_1_0CBs_0CB2_15x15(NH)_VTOL_200FtMin_30KT_VTOL2_1000FtMin_150KT_SepHorizontal_1_SepVertical_400.csv
Results_Perpendicular_1_1_1_0CBs_0CB2_15x15(NH)_VTOL_200FtMin_150KT_VTOL2_200FtMin_30KT_SepHorizontal_0.5_SepVertical_200.csv
Results_Perpendicular_1_1_1_0CBs_0CB2_15x15(NH)_VTOL_200FtMin_150KT_VTOL2_200FtMin_30KT_SepHorizontal_0.5_SepVertical_400.csv
Results_Perpendicular_1_1_1_0CBs_0CB2_15x15(NH)_VTOL_200FtMin_150KT_VTOL2_200FtMin_30KT_SepHorizontal_1_SepVertical_200.csv
Results_Perpendicular_1_1_1_0CBs_0CB2_15x15(NH)_VTOL_200FtMin_150KT_VTOL2_200FtMin_30KT_SepHorizontal_1_SepVertical_400.csv
Results_Perpendicular_1_1_1_0CBs_0CB2_15x15(NH)_VTOL_200FtMin_150KT_VTOL2_200FtMin_150KT_SepHorizontal_0.5_SepVertical_200.csv
Results_Perpendicular_1_1_1_0CBs_0CB2_15x15(NH)_VTOL_200FtMin_150KT_VTOL2_200FtMin_150KT_SepHorizontal_0.5_SepVertical_400.csv
Results_Perpendicular_1_1_1_0CBs_0CB2_15x15(NH)_VTOL_200FtMin_150KT_VTOL2_200FtMin_150KT_SepHorizontal_1_SepVertical_200.csv
Results_Perpendicular_1_1_1_0CBs_0CB2_15x15(NH)_VTOL_200FtMin_150KT_VTOL2_200FtMin_150KT_SepHorizontal_1_SepVertical_400.csv

Source: The author.

Table 59: Distribution of probabilities in deciles.

acft	amount	%		below sep	amount	%		below sti	amount	%		delay	amount	%
Decile 1	32	0.323232323		Decile 1	82	0.828282828		Decile 1	99	1		Decile 1	28	0.282828283
Decile 2	34	0.343434343		Decile 2	0	0		Decile 2	0	0		Decile 2	29	0.292929293
Decile 3	33	0.333333333		Decile 3	0	0		Decile 3	0	0		Decile 3	24	0.242424242
Decile 4	0	0		Decile 4	0	0		Decile 4	0	0		Decile 4	15	0.151515152
Decile 5	0	0		Decile 5	0	0		Decile 5	0	0		Decile 5	3	0.03030303
Decile 6	0	0		Decile 6	0	0		Decile 6	0	0		Decile 6	0	0
Decile 7	0	0		Decile 7	14	0.141414141		Decile 7	0	0		Decile 7	0	0
Decile 8	0	0		Decile 8	0	0		Decile 8	0	0		Decile 8	0	0
Decile 9	0	0		Decile 9	3	0.03030303		Decile 9	0	0		Decile 9	0	0
Decile 10	0	0		Decile 10	0	0		Decile 10	0	0		Decile 10	0	0

Source: The author.

APPENDIX D: NUMBER OF SIMULATIONS

To define the limits of the deciles, the average found for each of the different CM was used, considering the 2048 different scenarios. Thus, it was necessary to define the number of simulations that would statistically meet the averages found. or this, two different scenarios were selected (4 and 1016), considering different complexities, as shown in table 60.

Table 60: selected scenarios

	Sc	N1	N2	CB	Size	VS 1	HS 1	VS2	HS2	HS	VS	ACI
4	perpendicular	3	3	0	15 X 15	200	30	200	30	0,5	200	-0.5318
1016	perpendicular	3	3	100	15 X 15	1000	150	1000	150	1,0	400	-2.9966

For each scenario, 10, 50, 100 and 500 simulations were performed, repeating the process 10 times (10 sequences). Thus, the means for each of the CM were extracted. Considering that the behaviors were similar, the results for the CM delay will be presented.

Initially, simulations were carried out for scenario 4, which is less complex. Table 61 presents the means in each of the sequences and then the mean of the means, as well as the standard deviation of the mean of the means (figure 84).

Table 61: Simulation Results- low complexity

	DE (10)-AVERAGE	DE (10)-STDEV	DE (50)-AVERAGE	DE (50)-STDEV	DE (100)-AVERAGE	DE (100)-STDEV	DE (500)-AVERAGE	DE (500)-STDEV
sequência 1	104	20,28135433	111,5	25,76522732	114,3	29,70647652	115,628	30,87828611
sequência 2	130	26,39444386	116,48	32,15411866	116,82	32,06665407	115,15	32,15499008
sequência 3	117,3	37,87714057	111,9	27,70342202	109,99	29,8942564	114,452	31,05796017
sequência 4	125,2	35,08022552	113,56	34,1773048	116,69	33,33687708	115,28	31,78651231
sequência 5	121,6	26,90394436	111,42	31,36753163	111,89	32,3862095	115,696	31,01127185
sequência 6	120,9	46,51272227	113,7	34,42249502	116,78	32,92556036	115,912	32,05125304
sequência 7	125,4	27,49626237	121,14	31,53230284	116,45	29,51232408	113,032	31,096446
sequência 8	102,1	34,97125804	117,38	33,01940679	115,74	32,62973175	118,864	32,67495692
sequência 9	107,1	39,13921023	110,5	30,20153395	113,6	31,50757485	113,996	30,03077887
sequência 10	127,6	32,66734693	124,76	26,55956725	121,83	30,67195442	116,94	31,53876642
AVERAGE	118,12	32,73239085	115,234	30,69029103	115,409	31,4637619	115,495	31,42812218
STDEV	10,1767491	7,634192931	4,701707019	3,078658138	3,234970204	1,422348492	1,606813064	0,766492208

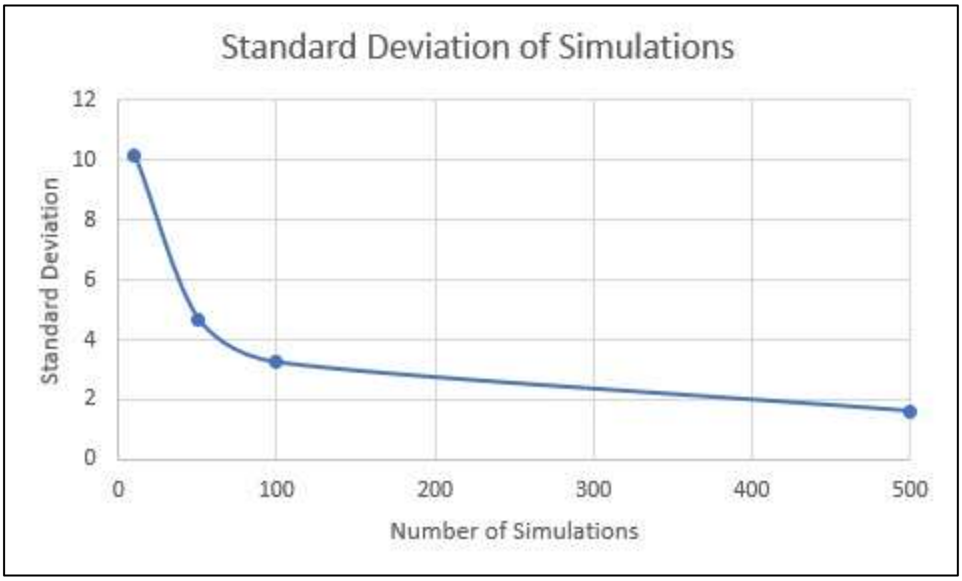

Figure 84: Standard Deviation of Simulations o low complexity

Then, the same simulations were carried out considering scenario 1016, which is more complex. Table 62 presents the means in each of the sequences and then the mean of the means, as well as the standard deviation of the mean of the means (figure 85).

Table 62: Simulation Results – high complexity

	DE (10)-AVERAGE	DE (10)-STDEV	DE (50)-AVERAGE	DE (50)-STDEV	DE (100)-AVERAGE	DE (100)-STDEV	DE (500)-AVERAGE	DE (500)-STDEV
sequência 1	381	38,89301565	383,62	33,69968812	383,89	33,04172294	387,626	35,25870782
sequência 2	401,4	36,13001215	393,34	35,97709589	387,08	34,96251384	388,846	36,2519336
sequência 3	386,4	23,66995282	382,98	29,28501044	385,5	32,26578386	386,43	34,79468984
sequência 4	395,6	44,65223648	390,04	36,02321247	387,36	33,33924796	388,262	34,45768448
sequência 5	380,6	26,1074702	391,66	34,94229062	389,28	32,59022596	388,236	33,00337482
sequência 6	385,6	36,01296063	386,72	35,57632783	388,49	34,03132692	386,928	34,27220425
sequência 7	378,4	43,46186068	389,98	38,81956692	386,71	35,20941535	388,326	34,25373499
sequência 8	382,2	29,91023608	391,48	39,43283621	389,21	37,1824046	387,644	35,24181089
sequência 9	407	22,3258694	389,64	34,95814407	387,32	34,18602704	388,744	34,23534111
sequência 10								
AVERAGE	388,6888889	33,46262379	388,8288889	35,41268584	387,2044444	34,08985205	387,8935556	34,64105353
STDEV	10,1976032	8,328730026	3,616505373	2,945275342	1,738211086	1,534177344	0,812295376	0,903273818

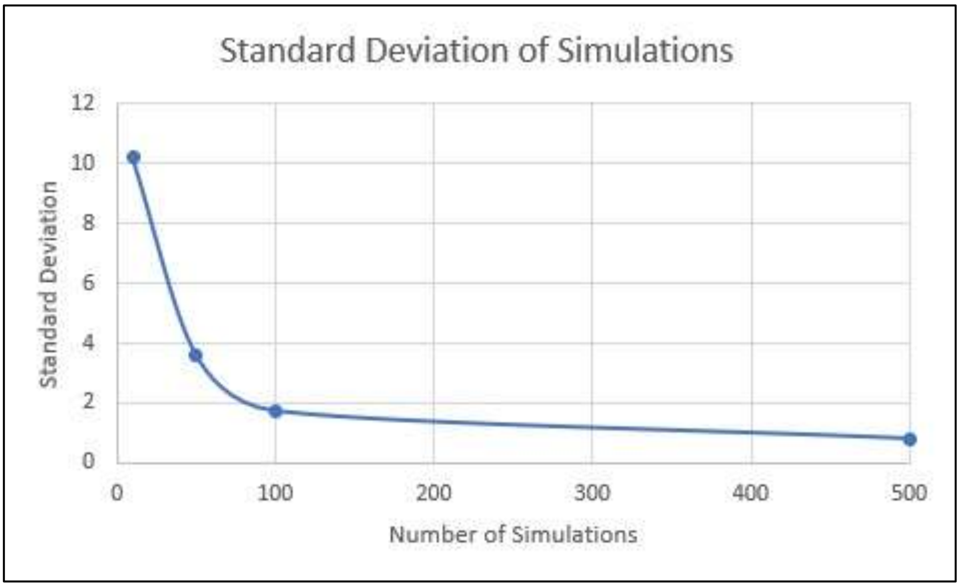

Figure 85: Standard Deviation of Simulations – high complexity

Due to the high simulation time required for 500 simulations, considering that there are 2048 different scenarios and considering that, both for the less complex scenario as well as for the more complex scenario, 100 simulations had a lower standard deviation of the means, considerably lower than 50 simulations, it was decided to carry out 100 simulations per scenario.

APPENDIX E: PROPOSED BAYESIAN NETWORK AND VALIDATED BAYESIAN NETWORK

Proposed BN and Validated BN can be handled on the link,being necessary to download the GENIE in advance:

https://drive.google.com/drive/u/2/folders/0AL0PfF1jxs3RUk9PVA

To download GENIE, academic version, access the link below: https://download.bayesfusion.com/files.html?category=Academia

The proposed BN is presented in figure 86.

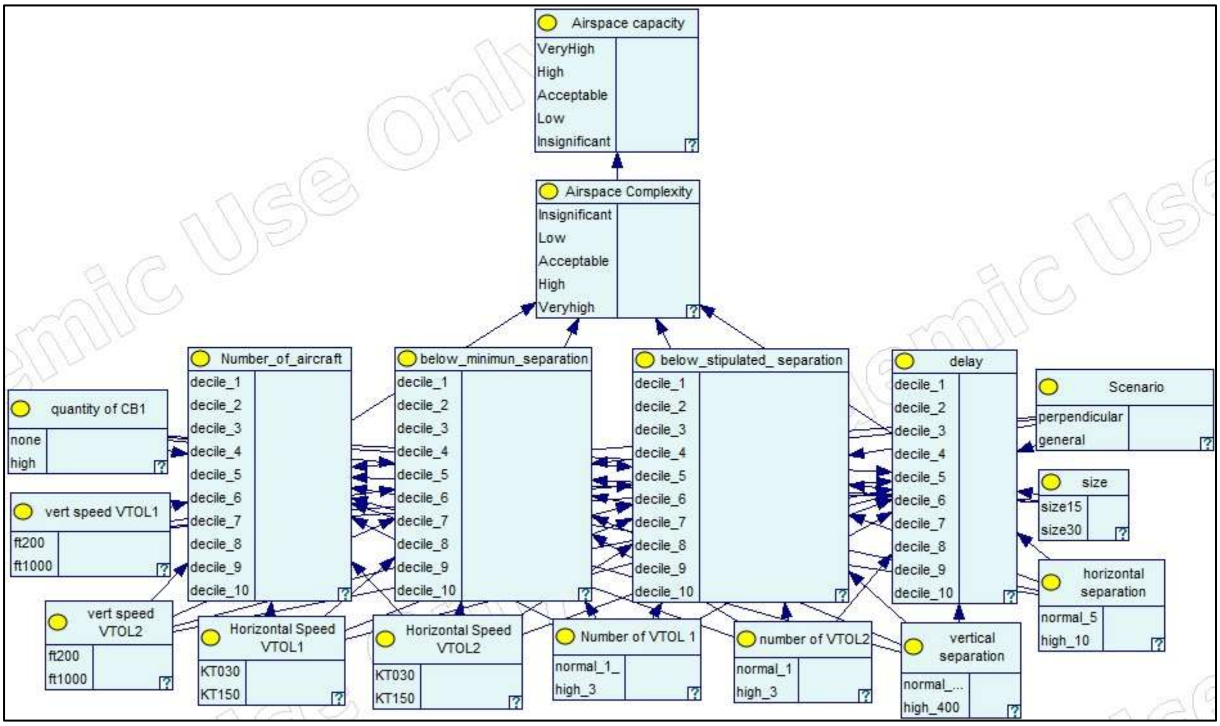

Figure 86: Proposed Bayesian Network.
Source: The author.

For the network to be handled, first, the input parameters must be selected, according to the desired scenario., Figure 87 presents some selected parameters.

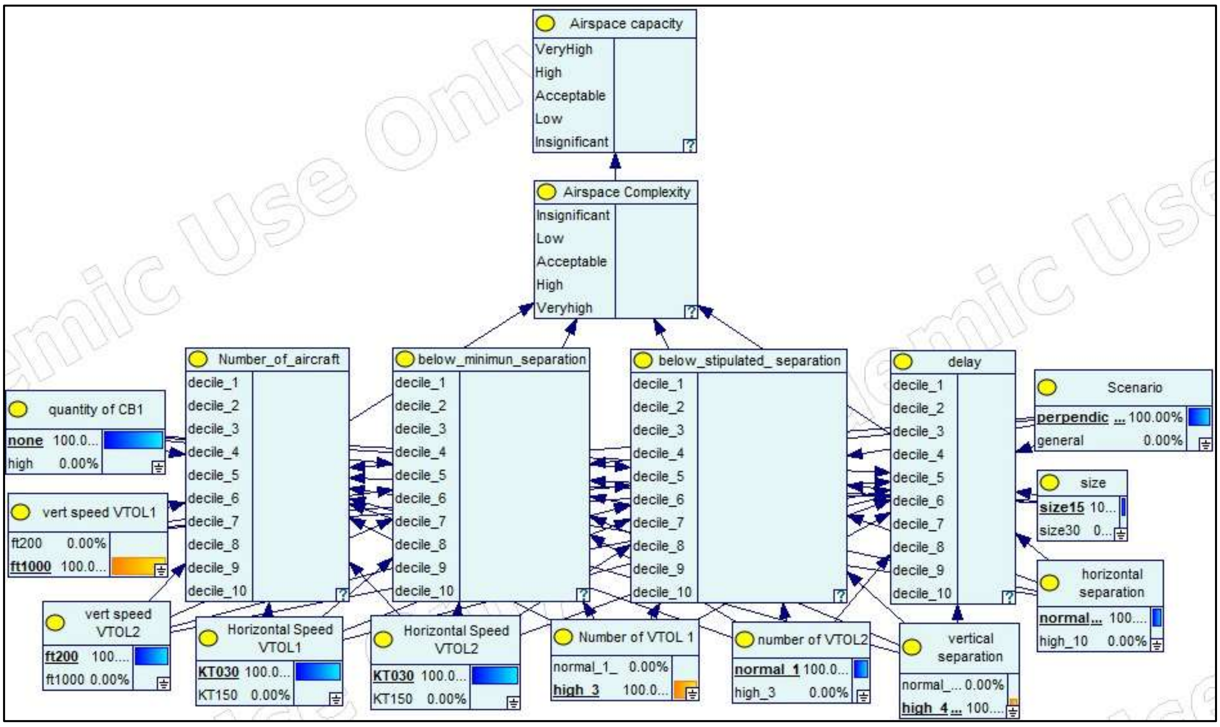

Figure 87: Proposed Bayesian Network with selected scenario.

Source: The author.

For the Bayesian Network to present the results, the “Update” command must be given, as shown in figure 88.

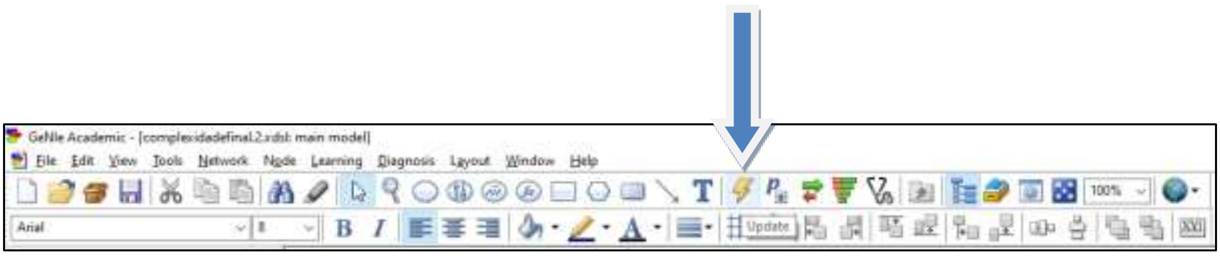

Figure 88: Update Command.

Source: (GENIE, 2020).

To use the network in a new scenario, select any parameter of “Airspace Capacity” From the right mouse button select “Clear All Evidence”, as shown in figure 89.

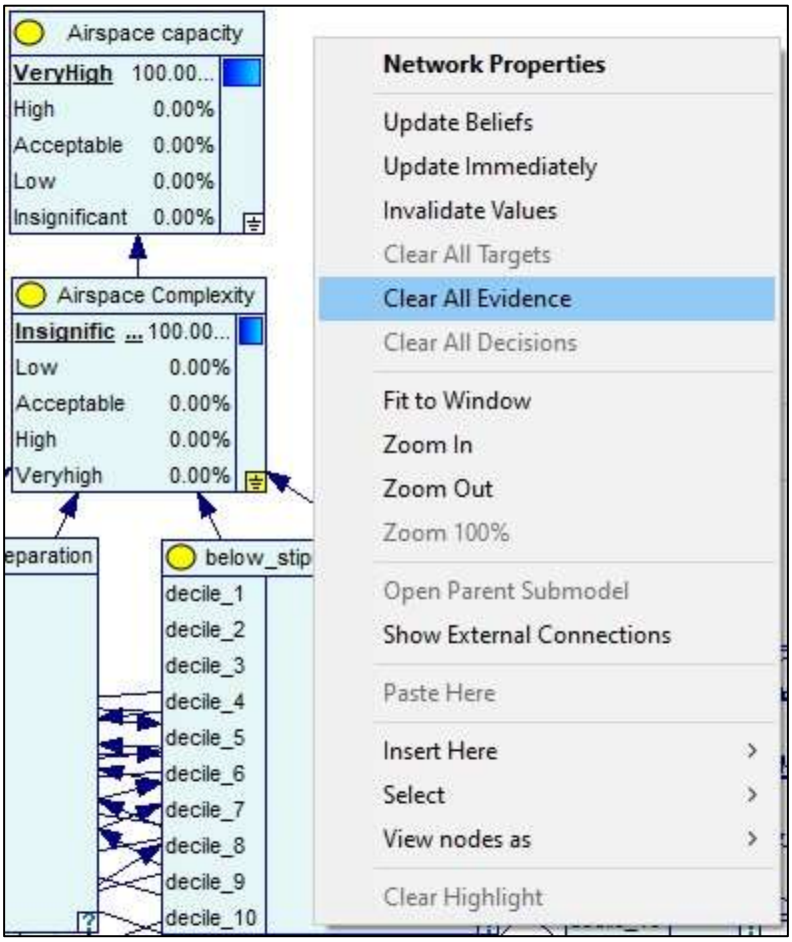

Figure 89: Clear all evidence.

Source: (GENIE, 2020).