CZECH TECHNICAL
UNIVERSITY
IN PRAGUE

F3

Faculty of Electrical Engineering
Department of Control Engineering

Bachelor's Thesis

Using BADA 4 Performance Model for Aircraft Simulation

Jakub Csanda
Bachelor programme: Cybernetics and Robotics
Branch of Study: Systems and Control

2018
Supervisor: Mgr. Přemysl Volf, Ph.D.

ZADÁNÍ BAKALÁŘSKÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

Příjmení: **Csanda** Jméno: **Jakub** Osobní číslo: **459920**

Fakulta/ústav: **Fakulta elektrotechnická**

Zadávající katedra/ústav: **Katedra řídicí techniky**

Studijní program: **Kybernetika a robotika**

Studijní obor: **Systémy a řízení**

II. ÚDAJE K BAKALÁŘSKÉ PRÁCI

Název bakalářské práce:

Využití BADA 4 modelu pro simulaci letadel

Název bakalářské práce anglicky:

Using BADA 4 Performance Model for Aircraft Simulation

Pokyny pro vypracování:

1. Seznamte se s modelem BADA 4.
2. Srovnejte modely BADA 3 a BADA 4.
3. Implementujte model BADA 4 do systému AgentFly.
4. Proveďte experimenty a porovnejte model BADA 3, BADA 4 a skutečné záznamy letadel.
5. Vyhodnoťte model BADA 4 a navrhněte případné vylepšení.

Seznam doporučené literatury:

1. Official BADA performance model webpage - http://www.eurocontrol.int/services/bada
2. Nuic A., Poles D., Mouillet V.: BADA: An advanced aircraft performance model for present and future ATM systems, International Journal of Adaptive Control and Signal Processing, 2010
3. Matamoros Cid I., Prats Menendez X., and Lopez Leones J., Casado E., Vilaplana M., Mouillet V., Nuic A., Cavadini L.: Modelling flexible thrust performance for trajectory prediction applications in ATM, Proceedings of the 7th International Conference on Research in Air Transportation, 2016
4. Sislak D., Volf P., Pavlicek D., Pechoucek M.: AGENTFLY: multi-agent simulation of air-traffic management, Proceedings of the 20th European Conference on Artificial Intelligence, 2012

Jméno a pracoviště vedoucí(ho) bakalářské práce:

Mgr. Přemysl Volf, Ph.D., centrum umělé inteligence FEL

Jméno a pracoviště druhé(ho) vedoucí(ho) nebo konzultanta(ky) bakalářské práce:

Datum zadání bakalářské práce: **16.01.2018** Termín odevzdání bakalářské práce: **25.05.2018**

Platnost zadání bakalářské práce: **30.09.2019**

Mgr. Přemysl Volf, Ph.D. podpis vedoucí(ho) práce	prof. Ing. Michael Šebek, DrSc. podpis vedoucí(ho) ústavu/katedry	prof. Ing. Pavel Ripka, CSc. podpis děkana(ky)

Acknowledgement

I would like to thank my supervisor, Mgr. Přemysl Volf, Ph.D., for his advice and support. I would also like to express my sincere gratitude to my consultant, Ing. Tomáš Blovský, whose help and patience allowed successful completion of the thesis.

Declaration

I declare that the presented work was developed independently and that I have listed all sources of information used within it in accordance with the methodical instructions for observing the ethical principles in the preparation of university theses.

In Prague 25. 05. 2018

....

Abstrakt / Abstract

V této bakalářské práci je nejprve představen BADA model. Poté je vypracováno teoretické porovnání mezi předcházejícím modelem BADA 3 a současným modelem BADA 4. Následně je navržena architektura nového modelu pro implementaci do systému AgentFly spolu s krátkým představením samotné implementace. Poté jsou provedeny experimenty obsahující několik typů letadel na obou modelech. Trajektorie letu vypočtené pomocí BADA 4 modelu jsou pak porovnány s trajektoriemi vypočtenými předcházejícím modelem BADA 3 a s referenčními trajektoriemi letu. Nakonec jsou navržena vylepšení pro nový model BADA 4 založená na tomto zhodnocení výkonu.

Klíčová slova: AgentFly, Modelování trajektorie letadel, BADA, simulace letu

Překlad titulu: Využití BADA 4 modelu pro simulaci letadel

In this Bachelor's thesis, the Base of Aircraft Data (BADA) model is briefly introduced. Then a theoretical comparison between the previous model BADA Family 3 and the current model BADA Family 4 is drawn. Afterward, an architecture of the new model is designed to be implemented into the AgentFly system, along with the short presentation of the actual implementation. After that, experiments containing several different aircraft types are conducted on both models. Flight trajectories calculated by the BADA Family 4 model are then compared to those calculated by the previous model BADA Family 3 and to reference flight trajectories. Finally, improvements to the BADA Family 4 are proposed based on the evaluation of its performance.

Keywords: AgentFly, Aircraft trajectory modeling, BADA, simulation of the flight

Contents /

Tables / Figures

Chapter 1
Introduction

Ever since the first aircraft was created, mankind was seeking lots of different applications of this machine. As the technology advanced, more and more of these applications were found, which has led to a significant increase in the number of aircraft operating in Earth atmosphere. This trend, however, raised the question of safety of these operations, as flight trajectories of these aircraft would collide more often and the consequences would be devastating, as well as economic and environmental impact. Because of that, a proper and efficient air traffic management (ATM) had to be developed and maintained. To ensure that, it was necessary to estimate aircraft performances as accurately as possible.

Today there are various approaches to aircraft performance modeling for prediction and simulation of aircraft trajectories, with two main approaches being kinematic and kinetic ones. Kinematic approach models the trajectory of the aircraft without modeling the underlying physics, while kinetic approach models forces acting on the aircraft. The Base of Aircraft Data (BADA), the Aircraft Performance Model (APM) developed and maintained by Eurocontrol Experimental Centre (EEC), is based on the kinetic approach to aircraft performance modeling. [2]

The primary objective of this Bachelor's thesis is to become familiar with the BADA Family 4 and make a comparison between the BADA Family 4 model and the BADA Family 3 model, which is the previous version of the BADA currently implemented in the AgentFly system. Afterward, implementing the BADA Family 4 to the AgentFly system and conducting experiments to compare the results of simulation of both models with real flight records to evaluate the BADA Family 4 model. If necessary, improvements are to be proposed.

The main motivation for the implementation of the BADA Family 4 are deficiencies of the previous model during the final phase of the descent because the BADA Family 3 model is not able to achieve the necessary rate of descent.

The thesis is structured as follows: Chapter 2 provides an introduction of the BADA model as well as a theoretical comparison of the BADA Family 4 APM and the BADA Family 3 APM. Chapter 3 introduces the current AgentFly system and presents a new architecture design for implementation of the BADA Family 4 APM. Chapter 4 then introduces the actual implementation into the AgentFly system. In chapter 5, the results of both models and the of reference data are compared. Finally, in chapter 6, improvements of the solution are proposed to enhance usability and the evaluation of this thesis results is done.

Chapter 2
Base of Aircraft Data

In this chapter, the BADA model is introduced. After that, few differences between both models and expectations from the new model are described.

2.1 Glossary of Terms

This section provides explanation and definition of basic terms used in this thesis. All of these terms are provided by the [3].

2.1.1 Definitions and Expressions

Calibrated airspeed $\mathrm{V_{CAS}}$ or CAS [m/s] or [kt] - It is the indicated airspeed (IAS) corrected for instrument and position error. [4]

Flight phase - The BADA recognizes three separate flight phases: climb, cruise, and descent. The BADA provides speed schedule for each of these flight phases.

Flight segment - The BADA recognizes five different flight segments: take-off, initial climb, cruise, approach, and landing.

Geopotential altitude H [m] or [ft] - An altitude at which the constant gravitational field provides the same work with same initial conditions. It is a gravity adjustment to geometric altitude[1]. [5]

Geopotential pressure altitude $\mathrm{H_p}$ [m] or [ft] - If the ISA atmospheric model is used, the geopotential altitude H also represents the geopotential pressure altitude.

Indicated airspeed IAS [m/s] or [kt] - The speed of the aircraft that is read directly from the airspeed indicator. [6]

Mach number M [-] - Mach number is a ratio of the speed of the aircraft to the local speed of sound. [7]

Mean Sea Level MSL - It is used instead of standard MSL in a non-ISA atmosphere. Adjustments describing this difference are defined further in this section.

Mean Sea Level Standard MSL - An average level of the surface of Earth's oceans. In an ISA atmospheric model, it is represented by the geopotential pressure altitude $\mathrm{H_p}$ equal to zero. Standard values of atmospheric temperature, atmospheric pressure, atmospheric density and speed of sound at MSL are defined further in this section.

Pressure differential at MSL Δp [Pa] - Pressure differential represents the value of the difference between an ISA atmospheric model and a non-ISA atmosphere in terms of atmospheric pressure.

Rate of climb or descent ROCD [m/s] or [ft/min] - The ROCD is a vertical speed of the aircraft - the rate of altitude change with respect to time. [8]

Temperature differential at MSL ΔT [K] - It represents the value of the difference between an ISA atmospheric model and a non-ISA atmosphere in terms of atmospheric temperature.

[1] Geometric altitude is the elevation above mean sea level.

Transition altitude $H_{p,trans}$ [m] or [ft] - The transition altitude[1] is the geopotential pressure altitude at which calibrated airspeed and Mach number are representing the same value of true airspeed.

Tropopause $H_{p,trop}$ [m] - The tropopause is a layer that is separating troposphere and stratosphere. In the BADA atmosphere model, the tropopause is expressed as constant geopotential pressure altitude of 11 000 m.

True airspeed V_{TAS} or TAS [m/s] or [kt] - True speed of the aircraft relative to the airmass in which it is flying. [9]

2.1.2 Physical Constants

Adiabatic index of air: $\kappa = 1.4$ [-]
Gravitational acceleration: $g_0 = 9.80665$ [m/s^2]
ISA temperature gradient with altitude below the tropopause: $\beta_{T,<} = -0.0065$ [K/m]
Real gas constant for air: $R = 287.05287$ [m^2/(K $\cdot$ s^2)]

2.2 Base of Aircraft Data

The Base of Aircraft Data (BADA) model is developed and maintained by Eurocontrol Experimental Centre. It is widely used within the ATM domain for prediction and simulation of airplane trajectory in consistence with the flight plane. The BADA is composed of two components: an Aircraft Model and an Atmosphere Model. [10]

The BADA Aircraft Model is based on modeling physical forces acting on the airplane modeled as point called kinetic approach and is structured in three parts: an Aircraft Performance Model (APM), an Airline Procedure Model (ARPM) and Aircraft Characteristics.

Arguments in this section are based on [1–3, 11].

2.2.1 BADA APM

The BADA APM is used to model the underlying physical forces and is further structured into four sub-models: an Actions Model, a Motions Model, an Operations Model and a Limitations Model.

The Actions Model is a representation of the forces acting on the aircraft. These actions are responsible for the motion of the aircraft and come from three distinct categories: aerodynamic, gravitational and propulsive. Aerodynamic actions are the drag force and the lift force. The gravitational action is namely the weight force. The representative force of the propulsive category of actions is the thrust force. Apart from the thrust force, the propulsive action model provides a model to compute the fuel consumption, which affects the aircraft's mass.

The Motion Model consists of equations that describe the aircraft motion. One of these equations is the Total-Energy Model (TEM) that connects geometrical, kinematic and kinetic aspects of the aircraft motion, which is essential in order to calculate the aircraft trajectory and performance. The TEM equates the rate of work done by forces acting on the aircraft to the rate of increase in potential and kinetic energy, that is:

$$(Th - D)V_{TAS} = mg_0\frac{dh}{dt} + mV_{TAS}\frac{dV_{TAS}}{dt}, \tag{1}$$

where:

[1] Also called crossover altitude.

- Th is the thrust force acting parallel to the aircraft velocity vector [N],
- D is the aerodynamic drag force [N],
- V_{TAS} is the true airspeed of the aircraft [m/s],
- m is the aircraft's mass [kg],
- g_0 is the gravitational acceleration [m/s^2],
- $\frac{d}{dt}$ is the time derivative [s^{-1}],
- h is the geodetic altitude [m].

From the equation (1) can be seen that there are three variables of thrust (Th), speed (V_{TAS}) and rate of climb or descent (ROCD). In order to control the movement of an aircraft, any two of these three variables are needed to be controlled. The third one is then determined by the equation (1). This can lead to one of three possibilities of resulting control, explained below:

- Speed and Throttle controlled - If the speed and throttle variables are controlled, the equation (1) is used for the calculation of ROCD. This case is mostly used while the aircraft is in climb or descent flight phase since the speed is usually maintained at a constant value of CAS or Mach number and throttle is set to a fixed position in order to create the desired thrust (maximum for the climb, idle for the descent).
- ROCD and Throttle controlled - If the ROCD and throttle variables are controlled, then the equation (1) is used to calculate the resulting speed. This case is mostly used if the aircraft is accelerating or decelerating since the ROCD is set to zero and throttle is set to a fixed position to create the desired thrust.
- ROCD and Speed controlled - If the ROCD and speed variables are controlled, then the equation (1) is used for the calculation of the necessary thrust. This thrust is bounded by a maximum thrust and idle thrust.

It is necessary to keep in mind that although the simulation control behaves as described above, the actual flight control may vary[1].

Since climb and descent phases are more complicated than cruise phase, the case used for calculation of the ROCD is the most interesting one. Because of that, it is not unreasonable to examine it in more detail.

The time derivative of the true airspeed can be rearranged as follows:

$$\frac{dV_{TAS}}{dt} = \left(\frac{dV_{TAS}}{dh}\right)\left(\frac{dh}{dt}\right). \tag{2}$$

If substitution of the equation (2) into the equation (1) is made, resulting equation is:

$$(Th - D)V_{TAS} = mg_0\frac{dh}{dt} + mV_{TAS}\left(\frac{dV_{TAS}}{dh}\right)\left(\frac{dh}{dt}\right). \tag{3}$$

Since the preferred way of presenting the performance of an aircraft is not a vertical speed, but rather the ROCD, another substitution is made:

$$ROCD = \frac{dH_p}{dt} = \frac{dh}{dt}\frac{T - \Delta T}{T}. \tag{4}$$

By substitution of the equation (4) into the equation (3) and by isolating the ROCD on the left side of the equation, the equation rearranges as follows:

[1] For example, actual flight control in climb may have set ROCD to some fixed position.

$$\mathrm{ROCD} = \frac{\mathrm{T} - \Delta\mathrm{T}}{\mathrm{T}} \frac{(\mathrm{Th} - \mathrm{D})\mathrm{V}_{\mathrm{TAS}}}{\mathrm{mg}_0} \left[1 + \left(\frac{\mathrm{V}_{\mathrm{TAS}}}{\mathrm{g}_0}\right) \left(\frac{\mathrm{dV}_{\mathrm{TAS}}}{\mathrm{dh}}\right)\right]^{-1}. \tag{5}$$

The last term of the equation (5) can be replaced by the function of the Mach number. This function is called *energy share factor* and is defined as follows:

$$\mathrm{f}\{\mathrm{M}\} = \left[1 + \left(\frac{\mathrm{V}_{\mathrm{TAS}}}{\mathrm{g}_0}\right) \left(\frac{\mathrm{dV}_{\mathrm{TAS}}}{\mathrm{dh}}\right)\right]^{-1}. \tag{6}$$

The energy share factor (ESF) is used to specify how much of the power is allocated to climb or descent in contrast to acceleration.

Calculation of the ESF is dependant on the flight phase, on the information about which speed the aircraft follows, as well as if it flies above or below the tropopause. For example, a different equation is applied if the aircraft speed follows constant CAS above the tropopause, if it follows constant Mach below tropopause or if it accelerates or decelerates in climb or descent.

If the value of the ESF is bigger than one, it means that the ROCD benefits not only from all the available power but also from a transfer of kinetic energy to potential energy. Similarly, if the value of the ESF is lesser than one, it means that some of the power is required to maintain acceleration. In cruise, the value of the ESF is equal to zero, since the ROCD is zero and thus all the available power is allocated to the acceleration of the aircraft.

The other equation of the Motion Model expresses the variation of mass through the Fuel Consumption Model defined by the equation (7).

$$\mathrm{m} = -\mathrm{F}, \tag{7}$$

where:

- F is the amount of fuel consumed [kg].

Through the differential system formed by equations (1) and (7) can be computed the aircraft motion in the given interval at each flight segment. Aircraft trajectory is the resulting list of solutions at each flight segment.

The Operations Model is responsible for capturing aspects of the flight, which are not directly related to the Actions or the Motion model but are necessary to take into consideration while computing the aircraft motion and thus providing the information about the way the aircraft is operated. That is important for the reason that different ways of operating the aircraft may result in different trajectories.

The Limitations Model ensures that the aircraft model behavior is within certain bounds. These limitations are set to secure not only the realistic aircraft behavior and providing flight safety, but also to limit the degradation of the aircraft equipment. Based on the version of the BADA, the Limitations Model is further divided into several sub-categories.

The structure of relations in the BADA APM is represented in the figure 2.1.

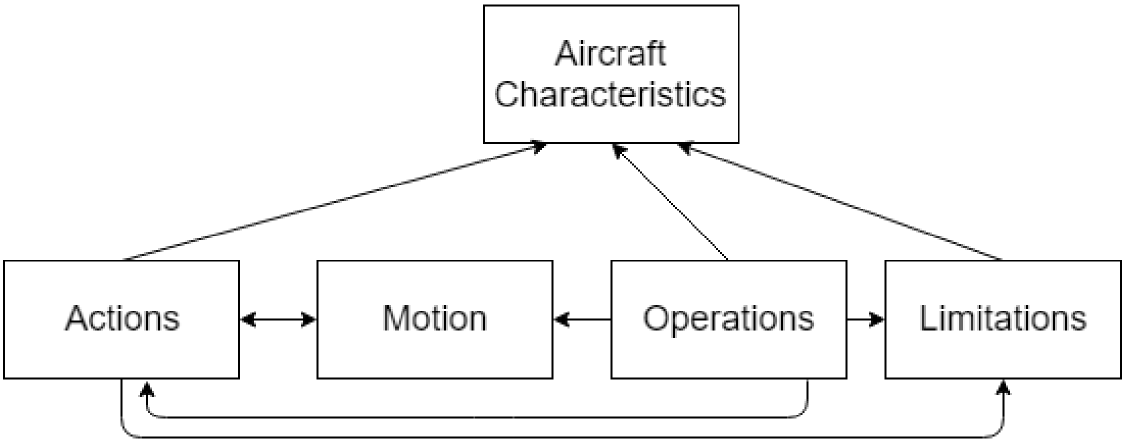

Figure 2.1. Structure of relations in the BADA APM. [1]

2.2.2 BADA ARPM

The BADA ARPM is model of standard airline procedures, and it can be used in the case when better knowledge of the way aircraft are operated is unavailable to the user. It distinguishes three separate flight phases: climb, cruise, and descent. For each of these flight phases, speed schedules are provided. There are three default speeds provided in the ARPM for each speed schedule: standard Calibrated Airspeed (CAS) below 10,000 ft, standard CAS between 10,000 ft and Mach transition altitude, and standard Mach number above Mach transition altitude. The CAS is then calculated from the speed schedule based on the altitude level[1] at which the aircraft is operated.

Due to the fact that the way an aircraft is operated differs significantly depending on operating policies and airspace procedures of local airlines, resulting speed schedules may be different depending on the geographical location and aerospace's specific aircraft operation.

The structure of relations in the BADA ARPM is represented in the figure 2.2.

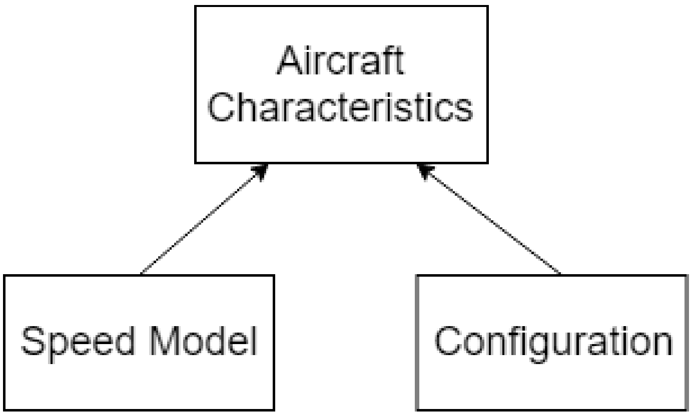

Figure 2.2. Structure of relations in the BADA ARPM. [1]

2.2.3 BADA Aircraft Characteristics

The BADA Aircraft Characteristics is a set of coefficients characterizing each aircraft model in the BADA. It is used by both the APM and the ARPM. Apart from param-

[1] Expressed in terms of geopotential pressure altitude.

eters which are used in formulas in the BADA APM, there are additional parameters provided, such as engine type.

2.2.4 Atmosphere Model

The other of the BADA components, apart from the aircraft model, is an atmosphere model. It describes the influence of the atmosphere around the aircraft model and provides expressions for the atmospheric properties as a function of altitude, based on the International Standard Atmosphere (ISA).

The ISA mathematical model divides the atmosphere into several layers based on the geopotential altitude. For the purpose of this thesis, only the troposphere, tropopause and stratosphere are relevant. The BADA can also support a non-ISA atmosphere models. The non-ISA model follows the same hypotheses applied to the ISA model but differs from the ISA model in atmospheric temperature at Mean Sea Level (MSL) or in atmospheric pressure at MSL.

Expressions provided by the BADA atmosphere model are required for a realistic simulation of the aircraft performance and conversions from CAS to True Airspeed (TAS) and Mach number. In this subsection, information from [12] are used.

TAS is calculated as a function of the Mach number as follows:

$$\mathrm{V_{TAS}} = \mathrm{M} \cdot \sqrt{\kappa \cdot \mathrm{R} \cdot \mathrm{T}}, \tag{8}$$

where:

- V_{TAS} is the true airspeed [m/s],
- M is the Mach number [-],
- κ is the adiabatic index of air, $\kappa = 1.4$ [-],
- R is the real gas constant for air; $R = 287.05287$ [$\mathrm{m^2/(Ks^2)}$],
- T is the temperature [K].

TAS is also calculated as a function of CAS, as follows:

$$\mathrm{V_{TAS}} = \left[\frac{2}{\mu}\frac{\mathrm{p}}{\rho}\left\{\left(1+\frac{\mathrm{p_0}}{\mathrm{p}}\left[\left(1+\frac{\mu}{2}\frac{\rho_0}{\mathrm{p_0}}\mathrm{V_{CAS}^2}\right)^{\frac{1}{\mu}}-1\right]\right)^{\mu}-1\right\}\right]^{\frac{1}{2}}, \tag{9}$$

where:

- $\mathrm{V_{CAS}}$ is the calibrated airspeed [m/s],
- p is the air pressure [Pa],
- ρ is the air density [$\mathrm{kg/m^3}$],
- $\mathrm{p_0}$ is the air pressure at MSL, $p_0 = 101325$ [Pa],
- ρ_0 is the air density at MSL; $\rho_0 = 1.225$ [$\mathrm{kg/m^3}$],
- μ is defined as the $\frac{\kappa-1}{\kappa}$.

One of the most important expression that the atmosphere model provides is a calculation of Mach/CAS transition altitude[1]. In general, the speed of aircraft is limited by both airspeed and the Mach number, and the aircraft typically fly towards the upper limit of their speed. While the aircraft is flying at lower altitudes, the speed of sound is higher, which means that the aircraft is most limited by the CAS. So the CAS is held constant. On the other hand, while the aircraft is flying at higher altitudes, the speed

[1] The transition altitude is defined as the geopotential pressure altitude at which CAS and Mach number represent the same TAS value.

of sound lowers, which leads to increase in the Mach number. So the speed of aircraft is then limited by the Mach since it is representing the higher value of TAS. It is, therefore, necessary to switch between staying under the CAS limit and staying under the Mach limit at some point. That point is represented by the Mach/CAS transition altitude, which can be calculated as follows:

$$\mathrm{H_{p,trans}} = \begin{cases} \frac{\mathrm{T_0}}{\beta_{T,<}} \left[\left(\frac{\mathrm{p_{trans}}}{\mathrm{p_0}} \right)^{-\frac{\beta_{T,<}\mathrm{R}}{\mathrm{g_0}}} - 1 \right] & \text{when } \mathrm{p_{trans}} \geq \mathrm{p_{trop}} \\ \mathrm{H_{P,trop}} - \frac{\mathrm{R \cdot T_{ISA,trop}}}{\mathrm{g_0}} \mathrm{Ln} \left(\frac{\mathrm{p_{trans}}}{\mathrm{p_{trop}}} \right) & \text{when } \mathrm{p_{trans}} < \mathrm{p_{trop}} \end{cases}, \tag{10}$$

where:

- $\mathrm{T_0}$ is the atmosphere temperature at MSL [K],
- $\beta_{T,<}$ is the ISA temperature gradient below the tropopause, $\beta_{T,<}$ = - 0.0065 [K/m],
- $\mathrm{p_{trans}}$ is the air pressure at transition altitude [Pa],
- $\mathrm{H_{P,trop}}$ is the geopotential altitude of the tropopause, $H_{\mathrm{P,trop}} = 11000$ [m],
- $\mathrm{T_{ISA,trop}}$ is the ISA atmosphere temperature at the tropopause [K].

The air pressure at transition altitude can then be computed according to the following equation:

$$\mathrm{p_{trans}} = \mathrm{p_0} \cdot \frac{\left[1 + \left(\frac{\kappa - 1}{2} \right) \left(\frac{\mathrm{V_{CAS}}}{\mathrm{a_0}} \right)^2 \right]^{\frac{\kappa}{\kappa-1}} - 1}{\left[1 + \frac{\kappa - 1}{2} \mathrm{M}^2 \right]^{\frac{\kappa}{\kappa-1}} - 1}, \tag{11}$$

where:

- $\mathrm{a_0}$ is the speed of sound in standard atmosphere at MSL [m/s].

2.3 BADA Family 3

This section provides an introduction to the BADA Family 3 model [11]. The BADA Family 3[1] is currently the standard model for modeling the aircraft performance. It covers nearly 100% of aircraft types emerging in the European Civil Aviation Conference (ECAC) area. It provides 194 native models[2] and 325 synonym models[3]. Native models then represent up to 95% of total traffic in the ECAC, while the synonym models extend the field of application with remaining 5%.

This section is focused mainly on those parts of the model that differs significantly from the BADA Family 4.

2.3.1 Atmosphere Model in the BADA Family 3

The atmosphere model provided by the BADA Family 3 is the one that is introduced in section 2.2.4 of this thesis. It is also the same one as provided by BADA Family 4.

1 BADA version 3.13.
2 Models that are developed using reference aircraft performance data sources.
3 Types of aircraft that has been identified as equivalent to native models.

2.3.2 Drag Model in the BADA Family 3

In the BADA Family 3, drag force is computed as follows:

$$D = \frac{C_D \cdot \rho \cdot {V_{TAS}}^2 \cdot S}{2}, \tag{12}$$

where:

- C_D is the drag coefficient [-],
- S is the wing reference area [m^2].

The drag coefficient is specified as a function of the lift coefficient C_L, and it is computed based on whether the aircraft is approaching, landing or in any different situation. The formula for computation of the drag coefficient, in general, is specified as follows:

$$C_D = C_{D0} + C_{D2} \cdot {C_L}^2, \tag{13}$$

where C_{D0} and C_{D2} are coefficients provided by the BADA and are specified differently for every situation mentioned above.

2.3.3 Thrust Model in the BADA Family 3

The BADA Family 3 provides the computation of following thrust levels:

- maximum climb and take-off,
- maximum cruise,
- descent.

For each type of engine (jet[1], turboprop, and piston) there is a different formula used for computation of the maximum climb thrust. The formula for the jet is dependent only on the geopotential pressure altitude, while other two are also dependent on TAS. For each engine, there are three climb thrust coefficients provided, from which the maximum climb thrust can be calculated. Maximum climb thrust is used for take-off and climb phases.

Maximum cruise thrust is calculated as a ratio of the maximum climb thrust as follows:

$$(Thr_{cruise})_{MAX} = C_{Tcr} \cdot Thr_{maxclimb}, \tag{14}$$

where:

- C_{Tcr} is coefficient uniformly set for all aircraft [-],
- $Thr_{maxclimb}$ is the maximum climb thrust [N].

The formula for calculation of the descent thrust is identical to the equation (14), with the only difference being the usage of the different coefficient. There are four coefficients used regardless of the type of engine. Their usage is, however, depending on the altitude of the airplane and the flight phase. First two coefficients are used based on the flight phase (approach or landing), while the other two are used for every other phase based on the altitude.

[1] In the BADA Family 4, a jet is also called turbofan in some cases.

2.3.4 Fuel Consumption Model in the BADA Family 3

In the BADA Family 3, the thrust specific fuel consumption is specified as a function of the true airspeed for the jet and turboprop engines.

The nominal fuel flow is computed from this thrust specific fuel consumption and the thrust force. The nominal fuel flow is used in all phases except for the cruise and idle descent.

For the cruise phase, the cruise fuel flow is calculated from the nominal fuel flow and coefficient called cruise fuel flow factor.

For the idle descent, the minimum fuel flow is calculated as a function of the geopotential altitude. The fuel flow for idle descent is then selected as the maximum value between the nominal and minimum fuel flow.

For the piston engines, the nominal fuel flow and the minimum fuel flow are specified to be constants. The cruise fuel flow is computed similarly with the jet and turboprop engines, meaning that it is calculated from the nominal fuel flow and cruise fuel flow factor.

2.3.5 Flight Segments

Five different configurations, called flight segments, are specified with the stall speed, as well as with the threshold altitude, in the BADA Family 3. Since the usability of these segments is further expanded in the BADA Family 4, they are described in more detail in the section 2.4 dedicated to the new model.

2.4 BADA Family 4

This section introduces the newly developed model, the BADA Family 4[1][3]. It covers 70.72% of total traffic in ECAC area with models for 73 different aircraft types that are designed using reference aircraft performance data. It provides better identification of aircraft performances than the BADA Family 3, eventually targeting to replace the previous model for as many aircraft types as possible.

In this section, the focus is mainly on those parts that differ significantly from the previous model, the BADA Family 3.

2.4.1 Atmosphere Model in the BADA Family 4

The atmosphere model provided by the BADA Family 4 is equivalent to that one provided by the BADA Family 3.

2.4.2 Aerodynamic Model in the BADA Family 4

Although the previous model introduces aerodynamic configurations, the BADA Family 4 provides few improvements in this area. Since the aerodynamic forces are the result of the interaction between the airmass and aircraft surface, the new model counts with the influence of the position of the high-lift devices, landing gear, and speed brakes.

High-lift devices, such as flaps and slats, have a different number of positions defined, depending on the type of the aircraft. There are also two defined position of the landing gear, retracted (or up) and extracted (or down). The position of the high-lift devices and the landing gear is called aerodynamic configuration and can be either clean (the high-lift devices and the landing gear are retracted) or non-clean (any other scenario).

[1] Version BADA 4.1.3

For every flight segment[1], there is at least one aerodynamic configuration defined in all aircraft models. In every model, there is also defined a time needed to complete the transition from one position to another one.

The BADA Family 4 also introduces a simple speed brakes model that increases the drag coefficient if speed brakes are in use.

2.4.3 Drag Model in BADA Family 4

Similarly to the previous model, the drag force acting on the airplane is computed following the formula (12). The computation of the drag coefficient is where the new model provides improvements. It introduces different formulas for computation of the drag coefficient for non-clean and clean configurations, as well as for the transition between configurations. If the position of the high-lift devices or landing gear is in transition between configurations, 2D linear interpolation is used to obtain the drag coefficient.

Formulas for computation of the drag coefficient use up to 15 coefficient per formula along with more complex dependence on the lift coefficient.

2.4.4 Thrust Model in BADA Family 4

The computation of the thrust force in the BADA Family 4 is different from the computation in the previous model. In the new model there is a uniform formula for calculation of the thrust force, which is:

$$\mathrm{Th} = \delta \cdot \mathrm{W_{mref}} \cdot \mathrm{C_T}, \tag{15}$$

where:

- δ is the atmospheric pressure ratio [-],
- $\mathrm{W_{mref}}$ is the weight force at reference mass [N],
- $\mathrm{C_T}$ is the thrust coefficient [-].

The thrust coefficient is calculated based on the type of engine and a predefined setting called rating[2] for turbofan[3] and turboprop engines. Piston engine, however, is usually operated by direct control of the throttle, for which reason only simple rating-based model is introduced for the sake of consistency with other two engine types.

For turbofan and turboprop engines, more complex models are presented, both using a similar structure of different formulas. If the idle rating is used, the formula for computation of the thrust coefficient is the function of the Mach number and the atmospheric properties, while each model has up to 32 different coefficients for computation. If the non-idle rating is used, the formulas are even more complicated, because for the computation of the thrust coefficient are needed several tens of different coefficients.

2.4.5 Fuel Consumption Models in the BADA Family 4

The BADA Family 4 formulates the fuel consumption, F [kg/s], as follows:

$$\mathrm{F} = \begin{cases} \mathrm{TFA} \cdot 60^{-1} & \text{during taxi (if TFA is defined)}, \\ \delta \cdot \theta^{\frac{1}{2}} \cdot \mathrm{W_{mref}} \cdot \mathrm{a_0} \cdot \mathrm{L_{HV}^{-1}} \cdot \mathrm{C_F} & \text{otherwise} \end{cases}, \tag{16}$$

where:

[1] Flight segments are take-off, initial climb, cruise, approach, and landing.
[2] Following ratings are defined: low idle thrust (LIDL), maximum climb thrust (MCMB), maximum cruise thrust (MCRZ) and maximum take-off (MTKF).
[3] In the BADA Family 4, turbofan is also called jet in some cases.

- TFA is the taxi fuel allowance [kg/min],
- θ is the atmospheric temperature ratio [-],
- L_{HV} is the fuel lower heating value [m^2/s^2],
- C_F is the fuel coefficient [-].

Three fuel consumption submodels are designed, each for every type of engine.

For turbofan and turboprop fuel consumption models, the fuel coefficient is determined by the rating used as follows:

$$C_F = \begin{cases} C_{F,idle} & \text{when idle rating is used,} \\ \max\left(C_{F,gen}, C_{F,idle}\right) & \text{when a non } - \text{ idle rating or no rating is used} \end{cases}, \qquad (17)$$

where:

- $C_{F,idle}$ is the idle fuel coefficient [-],
- $C_{F,gen}$ is the general fuel coefficient [-].

Idle fuel consumption is calculated as a function of the Mach number and atmospheric properties, while general fuel coefficient as a function of the Mach number and thrust coefficient (for turbofan) or power coefficient (for turboprop). Both models provide set of coefficients used in these calculations.

Since the piston engine's rating model is defined just for the sake of consistency, piston fuel consumption model does not define idle and general fuel coefficients. The fuel consumption is instead computed as the function of the power coefficient and the atmospheric conditions.

2.5 Advantages of the BADA 4 Model

Since the BADA Family 4 was developed several years later than the previous model, it was possible to use the better computing capabilities, as well as reference data of higher quality from aircraft manufacturers, to develop a more precise model. This model contains a significantly higher number of coefficients than aircraft model in the previous version. In general, the greater the number of independent parameters used, the better performance is to be expected. And since the biggest difference between models is in the computation of the thrust and the drag forces, it is to be expected that the BADA Family 4 increases the precision of these forces which are essential to the Total-Energy Model (1), the equation responsible for the calculation of the aircraft motion.

However, it must be emphasized that the BADA Family 4 is not yet in its final version and will probably be further modified. Those modifications could include more aircraft models to cover as much aircraft traffic as possible in the European Civil Aviation Conference area. Until then, it can not be considered as an adequate replacement for the previous model.

Chapter 3
Architecture Design

This chapter introduces the AgentFly system. Afterward, it explains why it is necessary to design a new architecture, and this architecture is subsequently introduced.

3.1 AgentFly System

The AgentFly is a multi-agent system for the simulation of the air traffic management and the air traffic control. It supports fast-time simulation, which is suitable for example for the analysis of the increase in the traffic. It also supports real-time simulation used for example for the communication between the aircraft.

The architecture of the AgentFly system is designed to be modular with two major components. The first component is the simulation of aircraft, while the second component is the simulation of the air traffic control. The control of the simulation allows the creation of new models, sectors, etc. in a way that preserves deterministic and repeatable approach. The system works with the random seed. If the same random seed is used, the results of the simulation are identical to the previous run. If, however, the used random seed is different, simulations run with different parameters and thus providing the different results.

The simulation of aircraft is based on the kinetic BADA performance model developed by the Eurocontrol. The BADA model is further introduced in the chapter 2.

The simulation of the air traffic control is based on the Multiple Resource Theory with use of VCAP model. These two models define the human, such as the pilot or the traffic manager, as the computation unit with four resources - Visual, Cognitive, Auditory and Psychomotor. Each human activity then defines how much of which resource is used for that activity. With the definition of atomic actions, such as waiting for the response from the pilot, the whole duration of some task can be determined along with needed resources.

3.2 Planning of the Flight Path

The BADA model is used to calculate the 4D trajectory from the flight plan. This flight plan is in the implementation of the AgentFly system represented by waypoints. The position of these waypoints is then taken as the target position for the plane to reach. The horizontal profile of the flight is then created based on these waypoints, but the creation itself is not a part of this thesis.

The calculation of the vertical profile is done with the BADA model and can not be done analytically since the behavior of aircraft changes in time. Because of that, it has to be approached analytically [13]. This means that some approximation of the optimal solution must be made. For that reason, the *flight state* is introduced. The flight state keeps the following information about the plane in one particular moment:

- geopotential pressure altitude,
- mass,
- fuel that is still available,
- total fuel burned during flight,
- the amount of fuel that is burned per second,
- speed of the aircraft expressed in CAS and TAS,
- acceleration,
- rate of climb or descent,
- time,
- total distance traveled expressed in air and ground distances,
- thrust and drag forces,
- energy share factor.

The vertical profile is constructed by the conjunction of several segments represented by the list of flight states. These segments are monotonic and based on the clearances from the air traffic control, it is decided whether the airplane is climbing, cruising, or descending in a particular segment. The computation of segments is done by simulation methods in the BADA models. These methods are provided with the following input:

- flight phase,
- global parameters (e.g. the limit height for the take-off phase),
- initial flight state,
- time step,
- condition,
- plane data.

The flight phase and the condition are based on the clearances from the air traffic control. For example, the climb clearance to reach the target altitude is given to the airplane. The simulation than simulates the climb to that altitude from the initial flight state. If no new clearance is given to the aircraft after this climb, the flight phase is changed to cruise after reaching the target altitude. The plane remains in this phase until a new clearance appears. The simulation of the climb and descent phase typically runs in multiple iterations. The results are then compared with each other and one is chosen as the segments of the vertical profile, while others are discarded. It is also worth noting the importance of the time step in the calculation of segments. While the plane is climbing or descending, when the altitude changes rapidly, it is important to choose small time step to preserve correct information about aircraft behavior. In the cruise phase, the value of the time step can be chosen bigger as the altitude is constant, thus reducing the demand for computing.

This way, the vertical profile is constructed for whole horizontal profile. The output of this is the 4D trajectory of the airplane represented by the list of flight states.

3.3 Introduction of the Architecture

Since the approach to the implementation of the previous version, the BADA 3, is not suitable for the implementation of the BADA 4, there is a need to propose a new one. Because of the fact that AgentFly system is not limited to airplanes, but supports many other types of aircraft, the proposed architecture is suitable for further implementation even for those aircraft rather than exclusively for airplanes.

3.3.1 Model Architecture

To meet this requirement, model architecture is proposed as shown in the figure 3.1.

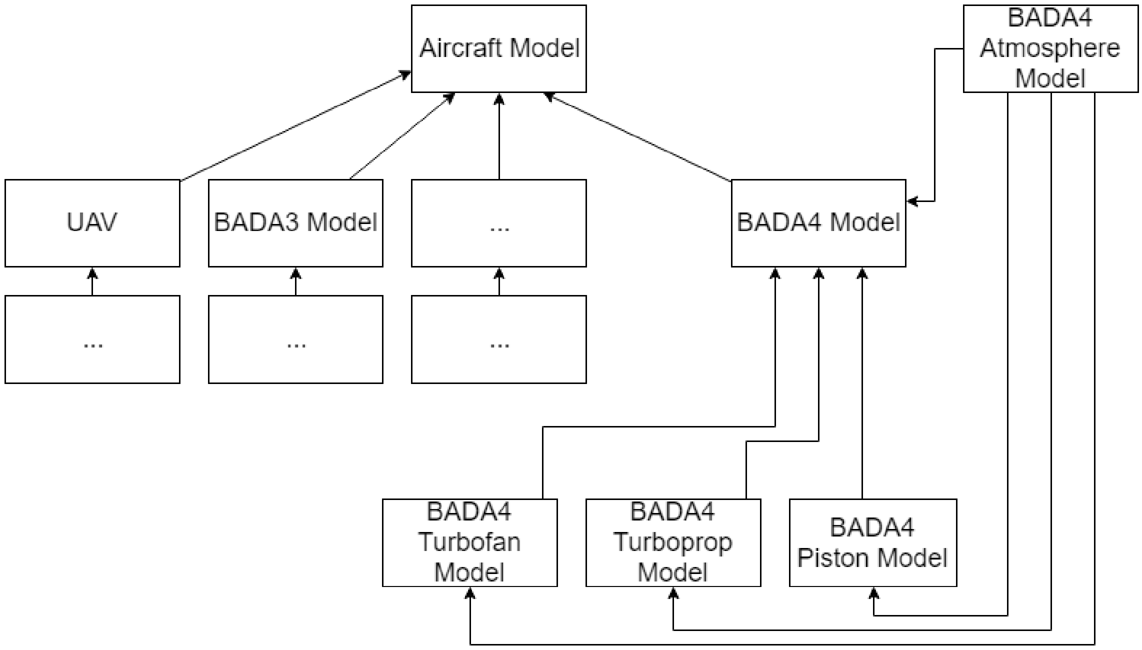

Figure 3.1. Structure of the model architecture.

In the figure 3.1 can be seen that there is one main component called Aircraft Model. This Aircraft Model is designed to represent any type of aircraft modeled within Agent-Fly system.

In the next layer of the structure, there are components representing specific aircraft models, such as the BADA Family 3 and the BADA Family 4. The figure is further focused on the structure of the BADA Family 4.

It can also be observed that there are three components that extend the model depending on the engine of the airplane that is to be modeled. The BADA Family 4 supports three types of airplane engines: Turbofan, Turboprop, and Piston.

The last component present is a model of the atmosphere introduced by the BADA Family 4. It is modeled as the ISA atmosphere and plays a fundamental role in modeling the aircraft performance and motion.

In the current implementation, the BADA 3 model acts as a separate unit with a few simulation methods composed of a lot of duplicate parts of the code, while only small part of a code changes in each method. One of the ideas in the proposed architecture is to create only one method for simulation as a replacement for those duplicate methods. This targets to reduce the number of lines in the program by several hundred. That way, the code is more clear, easier to work with and to maintain.

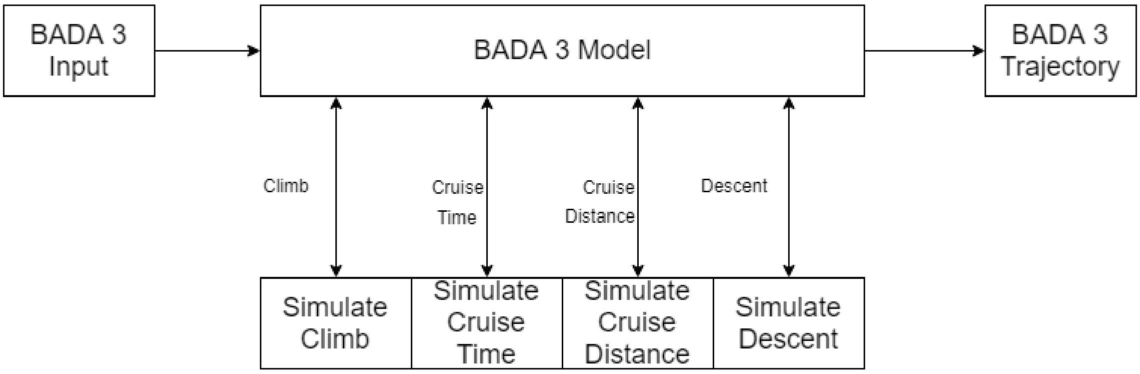

Figure 3.2. Current BADA 3 architecture.

The newly designed architecture contains an interface element, from which different models can be inherited, effectively unifying them. The BADA Family 4 model is designed to replace all of those duplicate simulation methods with one that covers all types of simulation.

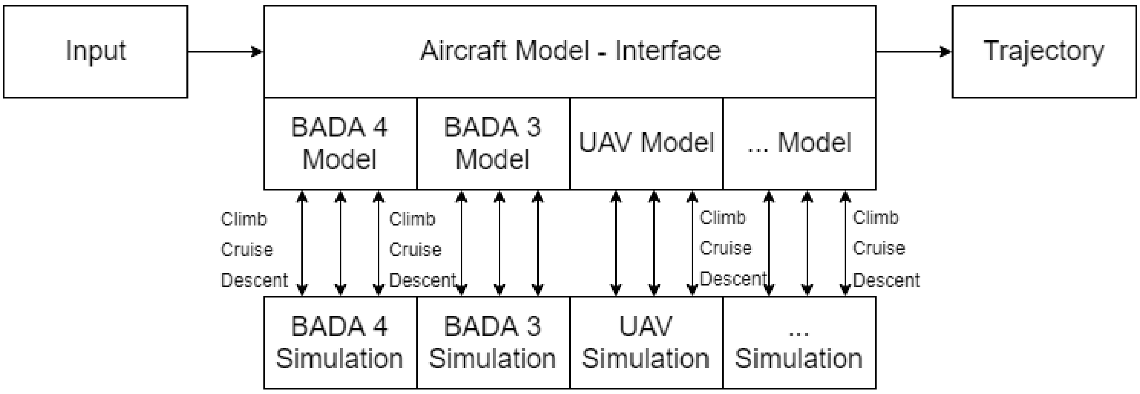

Figure 3.3. Proposed design of the architecture.

These ideas are described in more detail in the sections 3.3.2, 3.3.3 and 3.3.4.

3.3.2 Input Structure

Since each model needs different parameters for the simulation, the input is designed to be structured as follows:

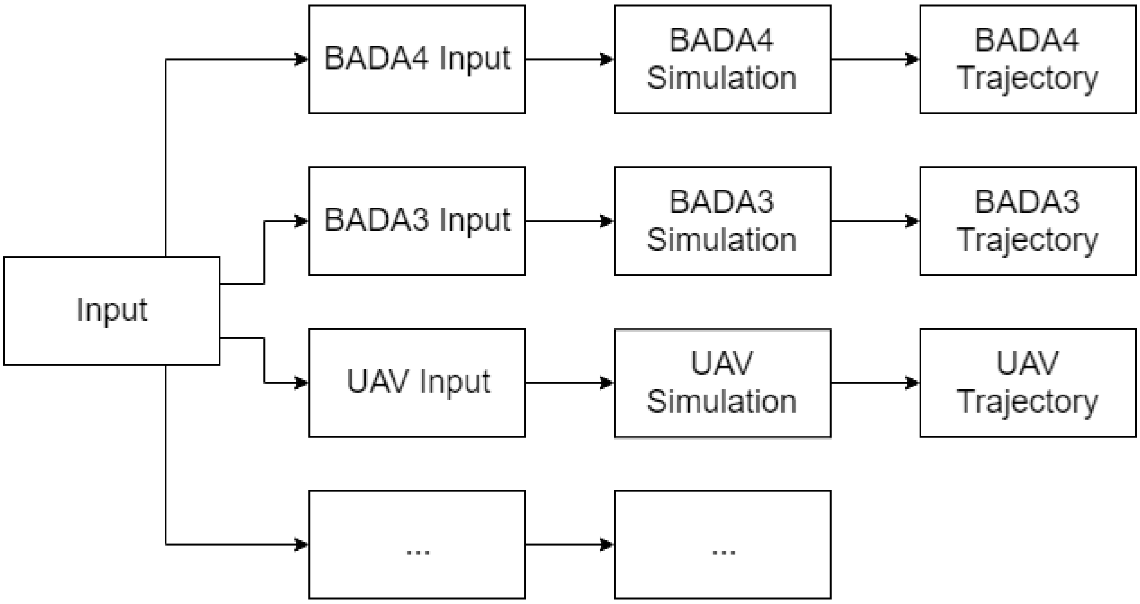

Figure 3.4. Structure of the simulation.

It can be observed in the figure 3.4 that the idea is to have a common input, from which the model used would extract relevant information needed to carry out the simulation. The BADA models, for example, need to know the initial Flight State, some type of condition to terminate the simulation, flight phase to be simulated, the data about the plane and time step of the simulation.

3.3.3 BADA Inputs

In the section 3.3.2, it is shown that input for the BADA Family 3 and the BADA Family 4 are represented by the different component. The reason underlying this choice is the fact that the BADA Family 4 needs more parameters to carry out the simulation than the BADA Family 3. These parameters are used to model aerodynamic configurations such as the position of landing gear or speed brakes. Difference between inputs can be observed in figures 3.5 and 3.6.

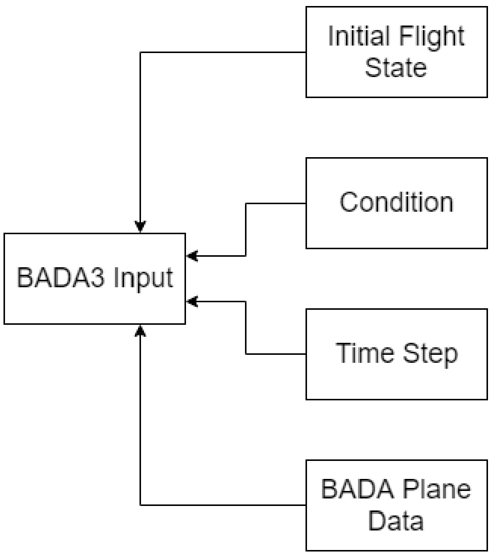

Figure 3.5. Composition of the BADA 3 input

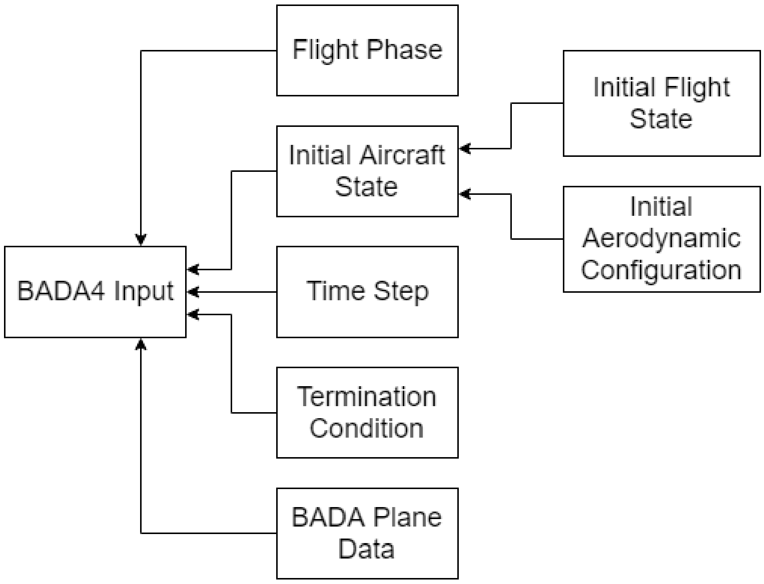

Figure 3.6. Composition of BADA 4 input.

First, there is a component called Aircraft State present. It can be seen that it is effectively extending the Flight State component by parameters needed for BADA Family 4 to work correctly. The Aircraft State component keeps the same information about the plane as the Flight State component (see section 3.2), but also the information about the position of the high-lift devices, the position of the landing gear, the position of speed brakes and whether the aircraft is taxiing. In the proposed architecture, with the Aircraft State component present, the information about the flight is stored in this component. This aims to be easier to work with in the future maintenance and updates of the code. The Aircraft State component is updated throughout the simulation and because it is basically an extension of the Flight State component, it is able to generate Flight State instances, which is used to preserve a unified output between simulations.

A second difference is in the information about the current flight phase. The reason behind this is described more in the section 3.3.4.

Both models also need the information about the time step of the simulation[1]. This time step is typically lower in the climb or descent flight phase than in cruise flight phase, since the behavior of the aircraft changes more in those phases and to capture the trajectory more precisely, it is needed to store the information about flight more often. In the cruise flight phase, the aircraft tries to follow the target speed and does not change the altitude. Because of that, the simulation step can be bigger, thus providing data of equal quality with less memory needed to store that data.

Other components present in inputs of both models are the condition by which the simulation should be terminated and the BADA Plane Data, which provides the information about the model such as coefficients needed to calculate necessary forces acting on planes.

3.3.4 Simulation Structure

In the section 3.3.3, it is mentioned that inputs for both BADA models are designed to be different to cover more parameters introduced by the BADA Family 4. It is also mentioned that the information about flight phase is added to the input of the BADA 4 simulation.

[1] After how much time a new information about the flight is stored in the output of the simulation.

In the BADA Family 3, there are several simulation methods implemented for every flight phase. Each of these methods, however, has many common features with other methods. And because it is generally easier to maintain, update, and work with as few methods as possible, it is proposed to find a way to implement the simulation in the new model as a unified method.

The structure of simulation in the previous model is presented in the figure 3.7.

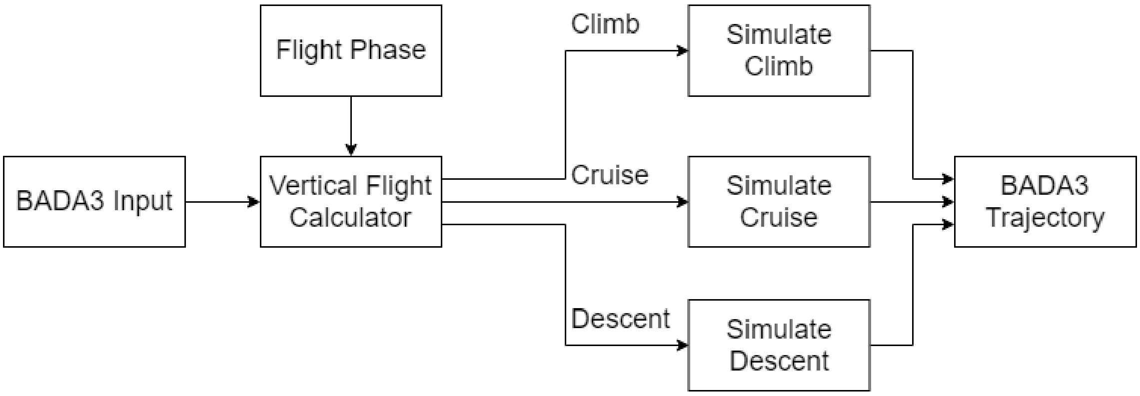

Figure 3.7. Structure of the BADA 3 simulation.

It can be seen that in the previous model, the information about the flight phase is also present, but it is passed to the Vertical Flight Calculator component later rather than by the input. The Vertical Flight Calculator component represents the BADA Family 3 model and its current implementation. The information about the flight phase is used to call the corresponding method, such as the method to simulate climb.

The methods representing the simulation of flight phases, however, are branched even more as a result of different requirements for simulation. These requirements can be, for example, cruise for a given time or cruise for a given ground distance. This approach requires implementation of whole new methods in case of adding new termination condition for simulation, making it harder to work with.

To prevent these problems, the new structure is designed to be implemented in the new model presented in the figure 3.8.

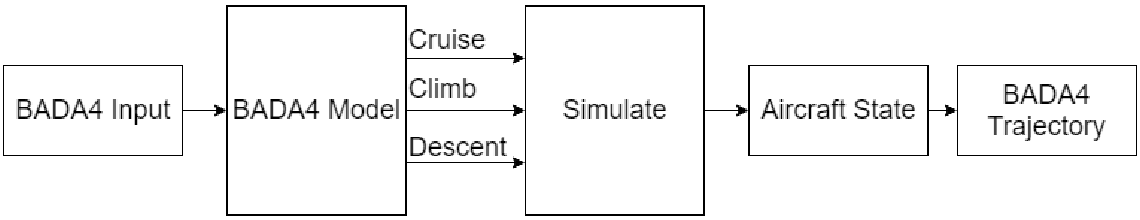

Figure 3.8. Structure of the BADA 4 simulation.

It can be observed that the new model passes information about the flight phase to the simulation, but rather than branching into several simulation methods, there is only one method designed and based on the flight phase, it provides different calculation.

It is also worth noting that the simulation method has its termination condition designed to which the information about the simulation is passed and based on the type of condition, its fulfillment is checked. Because of that, it is not needed to create new simulation methods in case of adding new termination condition, but it is sufficient to implement only the condition check. This approach targets to achieve easier maintenance of the code as well as easier work with the new model.

Chapter 4
Implementation

In this chapter, implementation of designed architecture is described. Classes representing components from the section 3 are introduced along with the most important methods.

4.1 Aircraft Model

An *AircraftModel* class is created as the base class for representation of aircraft. It serves as a parent class for different models, such as BADA Family 4 or its previous version. *AircraftModel* holds information about aircraft identification such as the type of aircraft model and ID.

4.2 AMB4

Classes inheriting directly from the *AircraftModel* represents a specific model of aircraft. For the sake of this thesis, the class *AMB4* is created as the representation of airplanes modeled by the BADA Family 4. It holds information about the type of the airplane, such as the name of the aircraft model or the type and the name of the engine. An *AMB4* class consists of the set of methods representing underlying physical principles that are common to all types of airplanes. Method for the simulation of the aircraft behavior is also localized in this class as it has very little aspects specific to each type of airplane in contrast with common aspects. There are methods for computation of the calibrated airspeed according to speed schedules present as well, but they are further modified in specific cases in subclasses introduced in section 4.3.

4.2.1 Simulation Method

At the beginning of the simulation method, the stall speed is computed and limitations are applied. First steps of the cycle are the computation of the target altitude and speed. The computation of the speed draws on ideas from [14]. Afterward, the thrust and drag forces are calculated. Computation of thrust force depends on the flight phase, and its implementation is shown in the figure 4.1.

```
if (phase.equals(FlightPhase.CRUISE)) {
    thrust = drag + (mass * acceleration_target);
    maxThrust = compute_Th(airState, Rating.MCRZ);
    minThrust = compute_Th(airState, Rating.LIDL);
    if (thrust > maxThrust) {
        thrust = maxThrust;
        acceleration_target = (thrust - drag) / mass;
    }

    if (thrust < minThrust) {
        thrust = minThrust;
        acceleration_target = (thrust - drag) / mass;
    }
} else {
    thrust = compute_Th(airState);
}
```

Figure 4.1. Implementation of the thrust computation.

It can be observed that the thrust computation depends on whether or not the aircraft is in the cruise phase. If it is not, then the calculation of the thrust is done based on the formula introduced by the BADA Family 4 model. If, however, the plane is cruising, it is necessary to have the thrust set depending on the drag and the acceleration of the aircraft. Thrust computed this way, however, is limited by two values. Those values are maximum cruise thrust and idle thrust. If the thrust is bigger or smaller than the limit, the current implementation forces aircraft to change its acceleration accordingly.

After the thrust is computed, energy share factor, the rate of climb and descent, and the value of the actual acceleration are calculated. From these parameters is calculated the next *AircraftState* instance, from which can be generated the *FlightState*[1] instance. At last, if the *TerminationCondition* passed to the method is fulfilled, the cycle is ended. The figure 4.2 shows the implementation of the logic of handling the condition.

[1] Output of the simulation is the list of flight states.

```
if (condition.checkCondition(airState)) {
    if (condition.isExceeded(airState)) {
        mass += fuelChange;
        availableFuel += fuelChange;
        time -= timeStep;
        airDist -= airDistanceChange;
        groundDist -= groundDistanceChange;
        consumedFuel -= fuelChange;

        airState = condition.interpolateAircraftState(lastAirState, airState);
        if (phase.equals(FlightPhase.CLIMB) || phase.equals(FlightPhase.DESCENT)) {
            airState.setRocd(0);
        }
        if (Double.isInfinite(availableFuel)) {
            mass = Math.max(mass, type.getALM().getDLM().getOEW());
        }
        list.add(airState.generateFlightState());
        break;
    } else {
        if (phase.equals(FlightPhase.CLIMB) || phase.equals(FlightPhase.DESCENT)) {
            airState.setRocd(0);
        }
        list.add(airState.generateFlightState());
        break;
    }
}

list.add(airState.generateFlightState());
```

Figure 4.2. Logic of handling the condition.

At first, it is checked whether the *AircraftState* instance fulfills the *TerminationCondition*. If not, the simulation continues and the new *FlightState* instance is generated. If, however, the *TerminationCondition* is fulfilled, it is checked whether it is also exceeded, meaning if the checked value of the *AircraftState* is different from the value of the *TerminationCondition* value by more than it is negligible. In that case, the interpolation is needed to generate the last *FlightState*. It is also worth noting that it is necessary to set the ROCD of the last *FlightState* to zero in order to keep the altitude of the cruise on the desired value.

4.3 AMB4 Subclasses

Because the BADA Family 4 model distinguishes three separate types of airplanes with different attributes, three subclasses of an *AMB4* class are needed. These subclasses are an *AMB4Turbofan* class representing airplanes propelled by turbofan engines, an *AMB4Turboprop* class representing airplanes propelled by turboprop engines, and an *AMB4Piston* class representing airplanes propelled by piston engines.

These classes provide additional methods to cover physical principles specific to each of them, as well as methods that modify the computation of the calibrated airspeed according to speed schedules unique to each type of the airplane. They are also final pieces of the chain of inherited classes representing the BADA Family 4 airplanes models.

4.4 Aircraft State

Furthermore, a structure containing information about the current state of the airplane is proposed in an *AircraftState* class. In the implementation of the previous version of the BADA, there is a similar structure implemented in a *FlightState* class. However, the creation of a new one is done because the greater complexity of the BADA 4 model introduces more attributes needed to identify the state of the airplane.

The *AircraftState* can be extended further extended in order to cover more types of aircraft besides airplanes. Also, the *AircraftState* object contains a method to generate the *FlightState* instance, making it an effective replacement for the *FlightState* object. This feature is used in the BADA Family 4 to maintain a unified output of the flight simulations with the previous model.

4.5 Environment

The class called *Environment* is also created. The purpose of this class is to model an atmosphere in which the aircraft operates, specifically the one that is introduced by the BADA Family 4 model. The atmospheric properties provided by this model are based on the International Standard Atmosphere (ISA) and are required for calculation of aircraft performances and conversions from CAS to Mach number and TAS. These conversions are implemented in the *Environment* class because they are the atmospheric properties.

4.6 Support Classes

The creation of a few support classes is done. These classes are designed to contain some of the related parameters together.

First of these is a class *ConfigurationParameters*, which is responsible for holding information about the aerodynamic configurations of the airplane.

Another one is a class called *AirSpeed*. The *AirSpeed* is created to hold the value of the aircraft speed in all three ways of representation, meaning that if an altitude in which aircraft is operated is known, CAS, TAS, and Mach number values held within the *AirSpeed* are representing the same value of speed.

Last of these structures is a class *SimulationInput*, which contains all relevant information in order to perform a simulation.

4.7 Termination Conditions

Last part of the architecture design is a *TerminationCondition* class. This class is responsible for ending the simulation and, if the simulation should exceed set value of the condition, providing information about how to deal with extrapolation of the last state.

Since there can be different requirements on how to perform a simulation, subclasses of this class are also created in order to cover these requirements effectively. For the sake of this thesis, four subclasses are created: a *ClimbAltitudeTerminationCondition*, a *DescendAltitudeTerminationCondition*, a *DistanceTerminationCondition* and a *TimeTerminationCondition*. These four are selected due to the fact that most simulations are performed for a given time or until the aircraft reaches the given altitude or distance.

4.8 Printer

To compare the results of simulations, the Matlab software is used for its friendly approach to plotting graphs. A *TextPrinter* class is created as a tool for saving the list of the *FlightState* instances representing a fragment of trajectory into a text file, from which the data can be transferred easily to Matlab.

A class *ListMerger* is created to merge several lists of the *FlightState* instances into one that represents the whole trajectory of the flight. This list then can be printed and easily compared with real flight trajectory, as well as with the output of the previous model.

Chapter 5
Results

In this section, experiments are carried out to compare both BADA Families with the reference data. Several jet and turboprop planes from different weight categories are selected as the representative set of aircraft in these experiments. This set is shown in the table 5.1. They are separated into two sections: arrivals to the Václav Havel Airport Prague and departures from the same airport. Results of these simulations are compared to real flights with the arrival to or the departure from this airport between the 12th and the 13th of July 2017. The reference data provide information about the time, the altitude and the ground distance of the flight. Because of that, the comparison of the dependence of the altitude on the ground distance is drawn.

type of model	type of engine	MTOW [kg]
ATR45	turboprop	18600
ATR75	turboprop	22000
B738	jet	79016
B763	jet	186880
A320	jet	77000
E170	jet	38600

Table 5.1. Types of chosen aircraft.

As can be seen from the table 5.1, the selection of the airplane types is based on their weight, namely the MTOW[1]. While the B738 and A320 have similar weight, both are selected as the two most produced jet planes.

It is important to mention the fact that real flights are controlled by instructions from the real air traffic control, while simulations are controlled by instructions from the simulated air traffic control. Because of that, both can have different clearances for descent or climb. The comparison between the real data and data from simulations makes sense only when those clearances are similar.

5.1 Arrivals

For the simulation of arrivals, two different turboprop and four different turbofan planes are chosen. Labels on the x-axis are modified in to represent the ground distance remaining to reach the airport.

5.1.1 Turboprop planes

Two selected turboprop planes are the ATR45 (Avions de Transport Regional 42-500) and the ATR75 (Avions de Transport Regional 72-500).

[1] Maximum take-off weight.

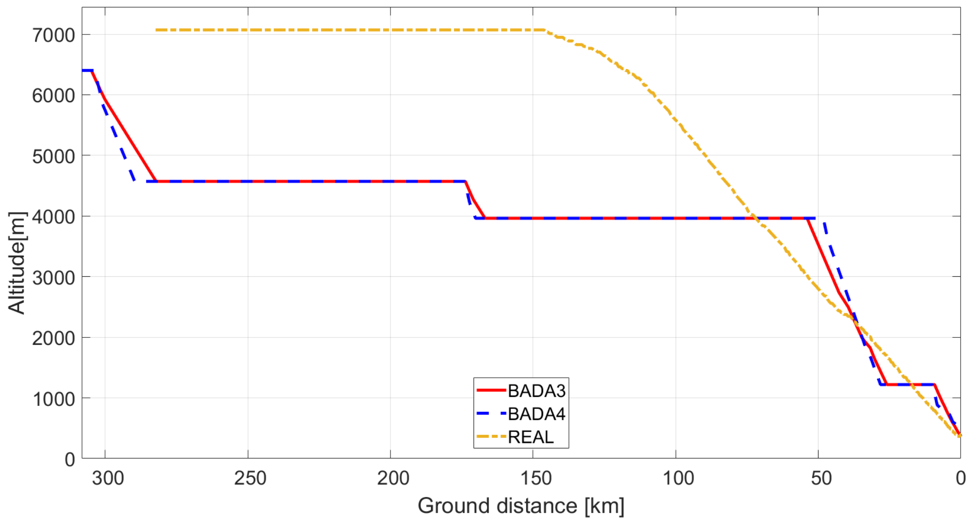

Figure 5.1. Simulation of the ATR45 arrival.

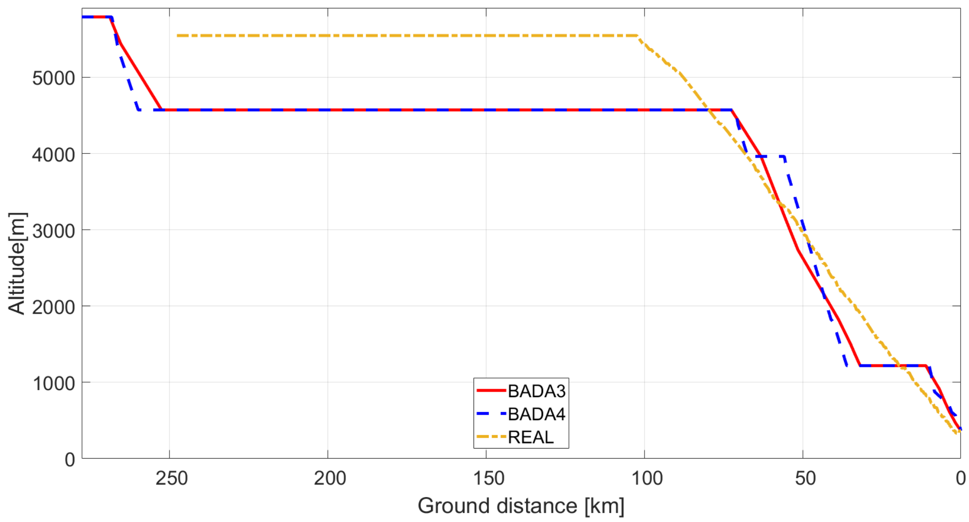

Figure 5.2. Simulation of the ATR75 arrival.

In the figure 5.1 it can be seen that both BADA models behave similarly. The main difference is that the BADA Family 4 descends faster than the BADA Family 3. Closer to the airport, however, the trajectories of descent are diverging. In the fragment of the trajectory where the BADA Family 3 model keeps a straight line, the BADA Family 4 trajectory breaks into more smaller fragments. These differences are caused by the improved model of the BADA Family 4, which defines the low idle thrust rating used while in descent, as well as the definition of the aerodynamical configuration used while in landing phase that improves the computation of the drag force acting on the aircraft.

It can be observed in figures 5.1 and 5.2 that the behavior of both models is similar for both tested turboprop planes. That is, in both cases, the BADA Family 4 descends faster than the BADA Family 3.

5.1.2 Turbofan planes

From turbofan planes, four different types are chosen to be included in the simulation. These are the B738 (Boeing 737-800), B763 (Boeing 767-300), A320 (Airbus 320) and E170 (Embraer 170).

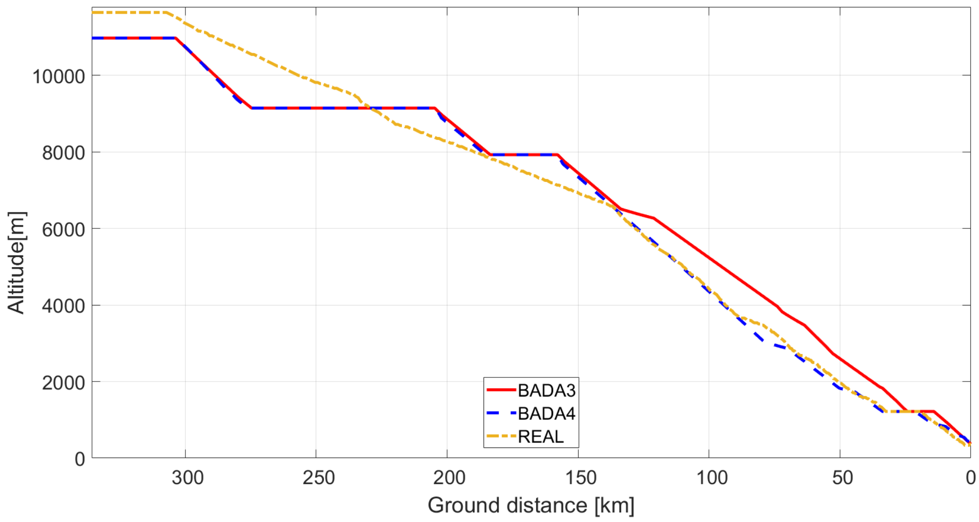

Figure 5.3. Simulation of the B738 arrival.

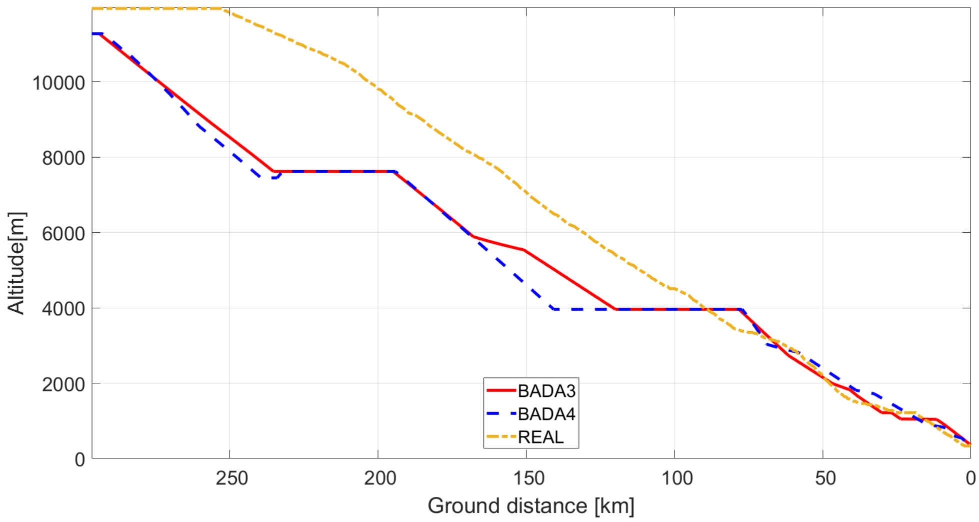

Figure 5.4. Simulation of the B763 arrival.

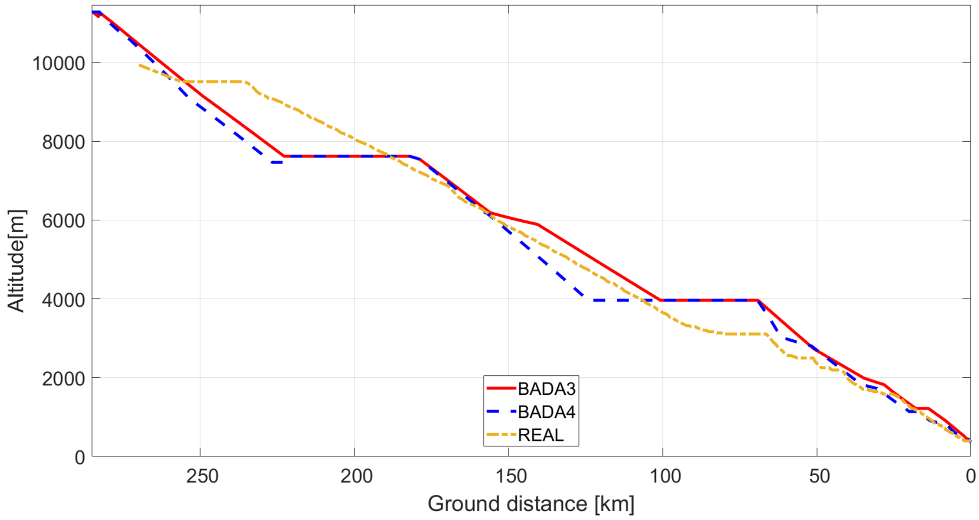

Figure 5.5. Simulation of the A320 arrival.

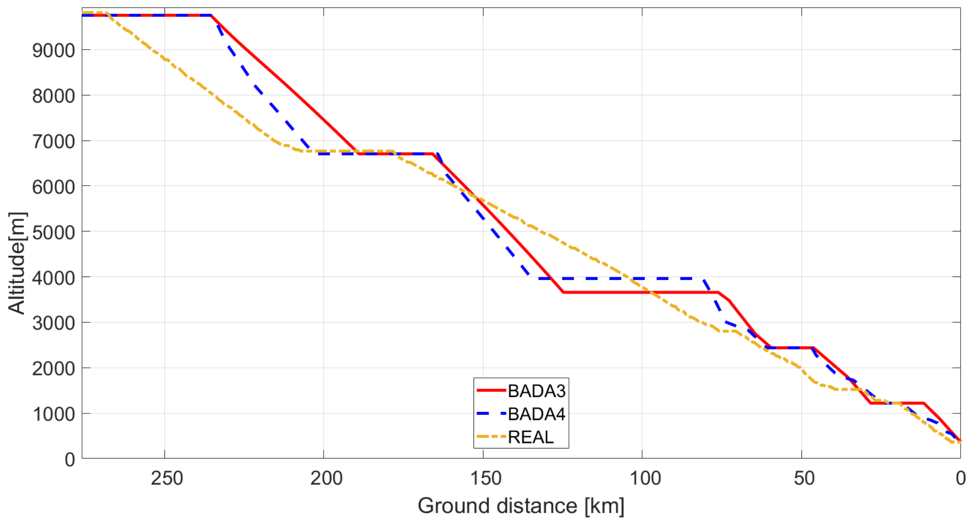

Figure 5.6. Simulation of the E170 arrival.

In figures 5.3, 5.4, 5.5 and 5.6 and from the experiments carried out in section 5.1.1, it can be observed that the behavior of both BADA models is similar for both types. The BADA Family 4 again descends faster than the BADA Family 3. The simulation of turbofan planes arrivals, however, seems to provide a more accurate prediction of the trajectory than the simulation of turboprop planes arrivals. It appears that the BADA Family 4 simulation provides slightly better arrival trajectory than the previous model. The differences between the trajectories of both models are again caused by the improved model of the BADA Family 4 and its low idle thrust rating and landing aerodynamic configuration.

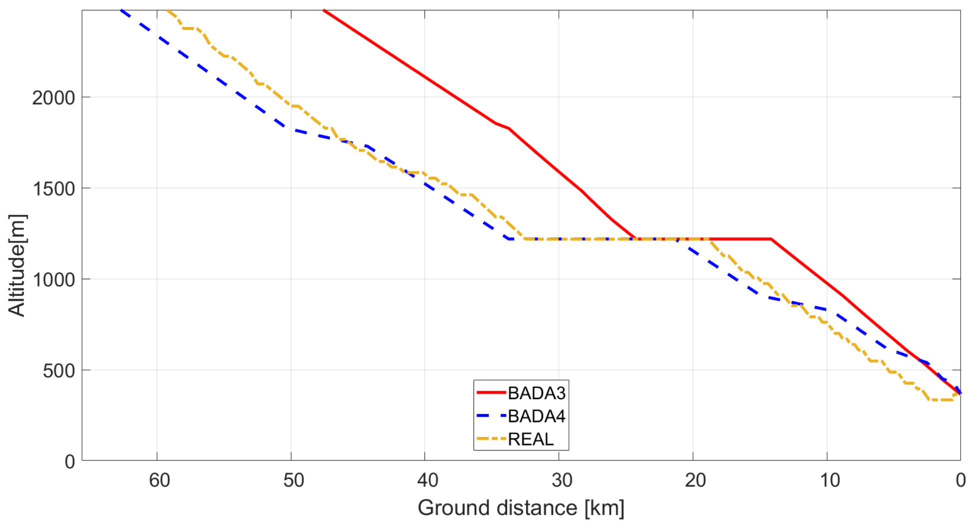

Figure 5.7. Landing of the B738 airplane.

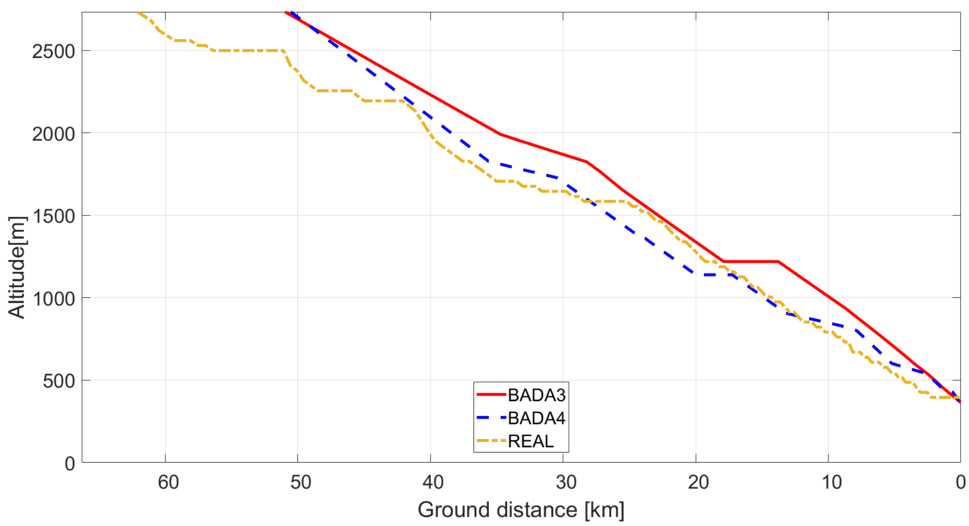

Figure 5.8. Landing of the A320 airplane.

In figures 5.7 and 5.8 is shown the final phase of descending to the airport. It can be observed that the faster descend allowed by the BADA Family 4 model provides more accurate simulation than the previous model. Since the main motivation for the implementation of this model is the better performance in landing phase where the previous model is not able to keep up with the value of the ROCD of the real flight, this result can be considered as its fulfilling.

5.2 Departures

In the simulation of departures are used same airplanes as in the simulation of arrivals.

5.2.1 Tubroprop planes

In this subsection, the results of experiments on the ATR45 and the ATR75 planes are shown.

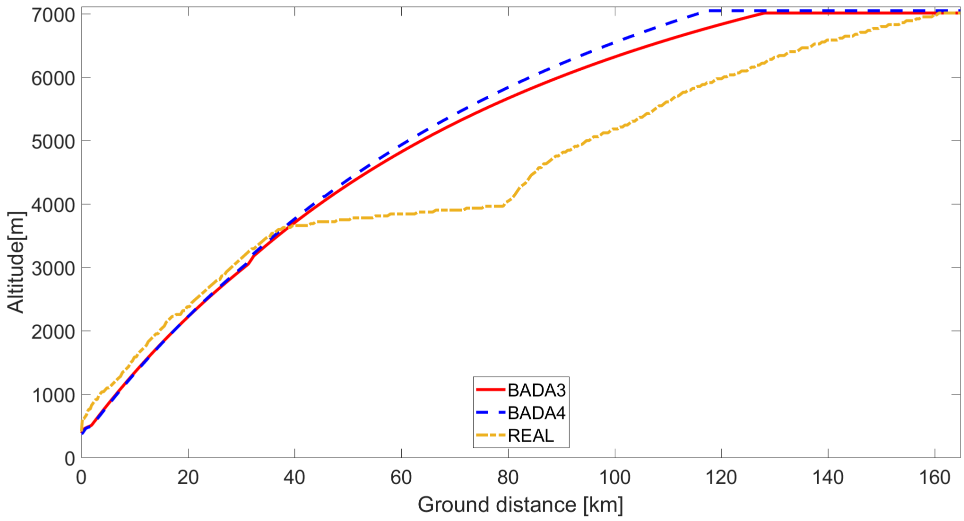

Figure 5.9. Simulation of the ATR45 departure.

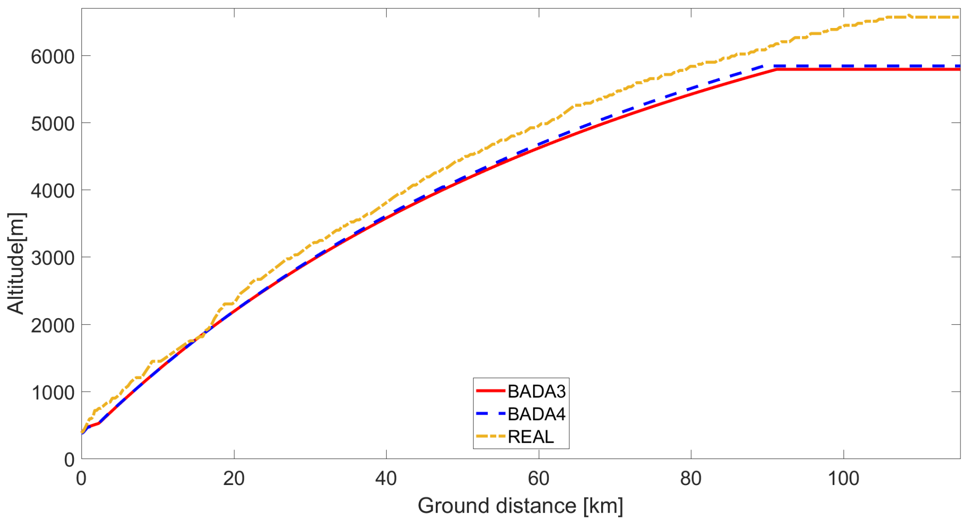

Figure 5.10. Simulation of the ATR75 departure.

In figures 5.9 and 5.10 it can be observed that the departure trajectory modeled by the BADA Family 4 climbs faster than the one modeled by its previous model. The reason behind this is described in the section 5.2.2.

5.2.2 Turbofan planes

In this subsection, the results of experiments carried out on the B738, the B763, the A320 and the E170 planes are shown.

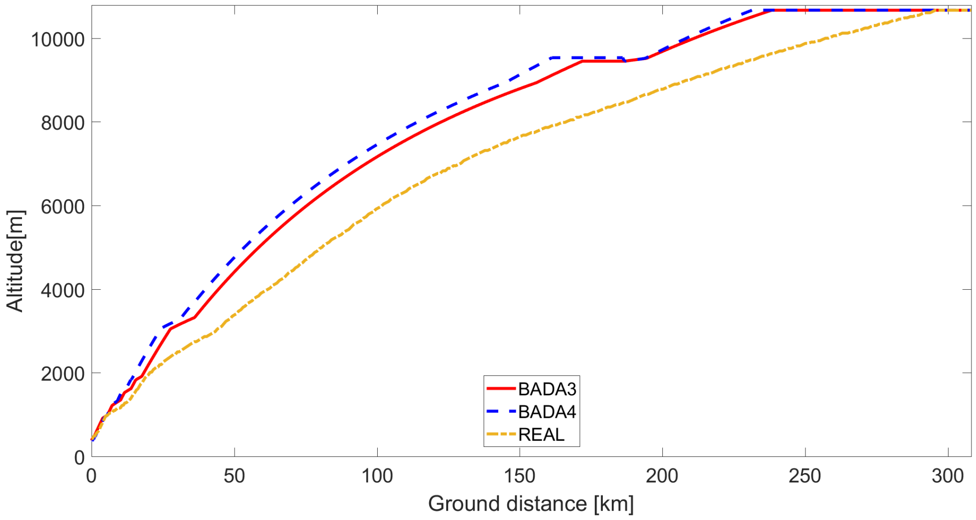

Figure 5.11. Simulation of the B738 departure.

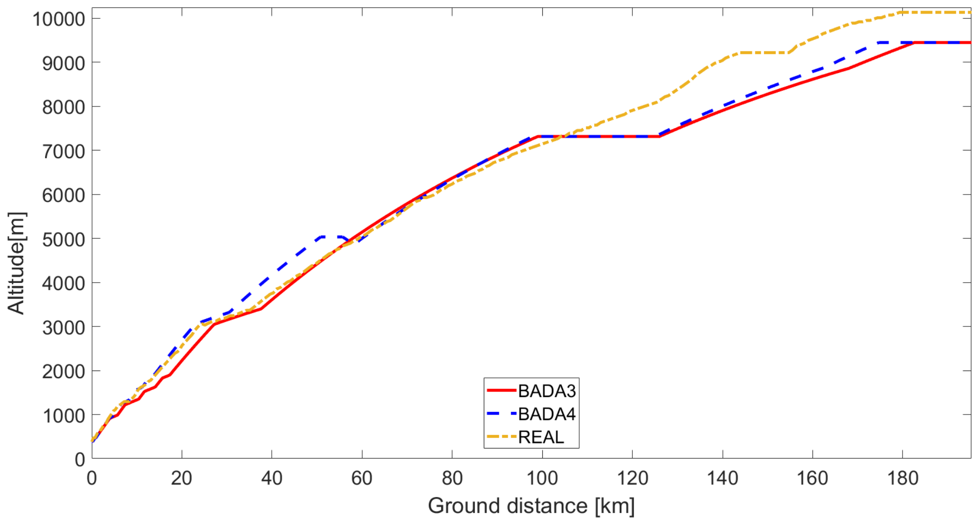

Figure 5.12. Simulation of the B763 departure.

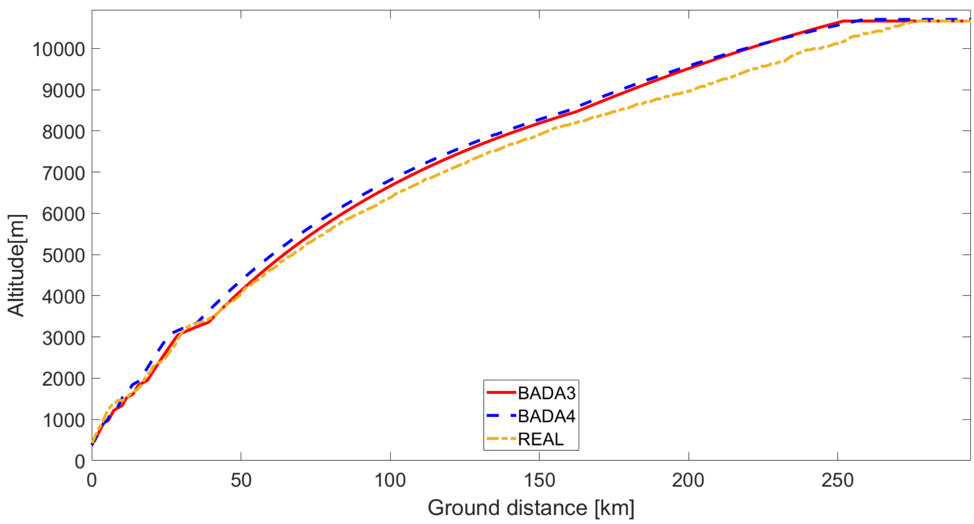

Figure 5.13. Simulation of the A320 departure.

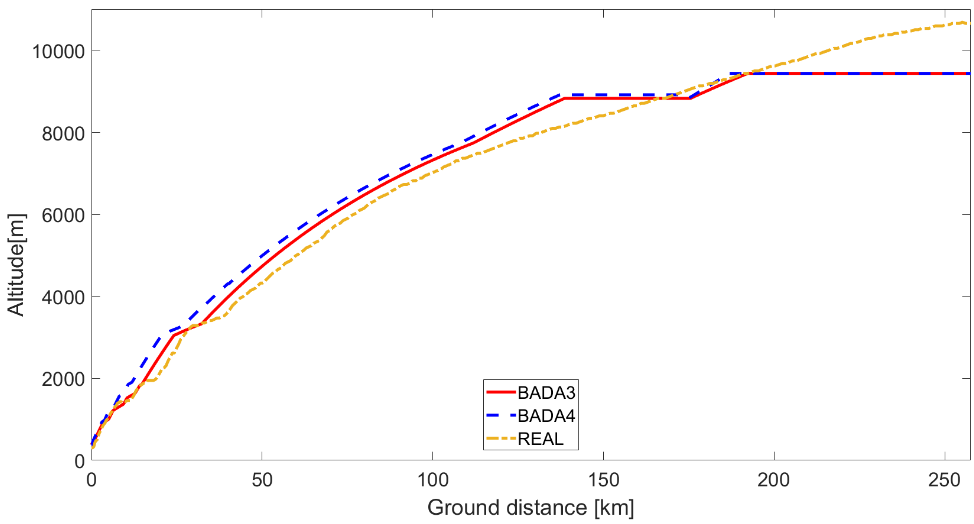

Figure 5.14. Simulation of the E170 departure.

As can be seen in figures 5.9, 5.10, 5.11, 5.12, 5.13, and 5.14, the trajectory of the departure of all planes from the airport modeled by the BADA Family 4 climbs faster than the one modeled by the previous model.

The reason why the BADA Family 4 climbs faster is the improved model of the BADA Family 4. This model introduces more parameters in the computation of the maximum climb thrust as well as enhanced drag model. And because these forces are essential in the computation of the aircraft motion, the more precise they are, the more precise is the trajectory computed. It can also be observed that the BADA Family 4 climbs even faster for turbofan planes at lower altitudes. That is caused by the definition of the aerodynamic configuration which is to be used in the take-off phase, thus improving the performance while in this segment of the climb phase. It is worth noting that in some simulations, both models are cruising at a different altitude than the reference data. This is caused by restrictions of altitude that are not applied in the AgentFly system simulations.

5.3 Evaluation

From sections 5.1 and 5.2, it can be observed that both models behave very similarly. The BADA Family 3, however, is slower in descent phase, resulting in worse accuracy in the prediction of the trajectory of landing. These experiments, therefore, suggest that the BADA Family 4 can be used instead of the BADA Family 3 while providing slightly improved performances. Because the reference data does not provide information about the fuel consumption, it is not possible to compare which of the BADA models is more accurate in the simulation of this attributes. These experiments also fulfill the expectation from the BADA Family 4 in better performance while in the landing phase.

Chapter 6
Conclusions

The objective of this Bachelor's thesis is the familiarization with the BADA Family 4 model and its differences with the previous model and its implementation into the AgentFly system. The next objective is the conduction of experiments in order to compare the results of the BADA Family 4 model, the previous model, and the reference data. As the last objective of the thesis, improvements to the implementation are proposed.

The introduction of the BADA and theoretical comparison of both models is described in the chapter 2. The BADA Family 4 uses a bigger number of coefficients and better analysis of the underlying forces, which suggests better performance.

The completion of the next objective of this thesis, the implementation of the BADA Family 4 model into the AgentFly system is divided into two parts. The first one is the development of the architecture design. This part is described in more detail in the chapter 3. The second part is the actual implementation of this architecture. More information about the implementation can be found in the chapter 4.

As the last objective of this thesis, experiments on several different airplanes are conducted as shown in the chapter 5. Since the reference data does not provide information needed to conduct experiments of other attributes, the only examined attribute is the dependence of the altitude on the ground distance. From these experiments, it can be observed that the BADA Family 4 has similar behavior as its previous model with more precise results.

To conclude, all of the objectives of this Bachelor's thesis are fulfilled. The BADA Family 4 model has proved to descend faster than the previous model, which is the main motivation for its implementation. Because of its better performances, the BADA Family 4 has shown to be not only usable but also able to replace the BADA Family 3 model if necessary. In section 6.1, the future work on the implementation is proposed to enhance its usability as well as its performance.

6.1 Future work

In this section, the future work on the BADA Family 4 is discussed.

6.1.1 Descent Speed

One of the focus of the future work that is proposed is the optimization of speed changes while in descent. Each aircraft has defined a speed schedule for descent flight phase. In this schedule, maximum allowed speed changes with altitude. In the current implementation, this change is performed when the aircraft altitude drops under the relevant level. This, however, causes that the aircraft speed is for a moment over the speed limit.

The update of the descent speed calculation to predict when the relevant level of altitude is reached can be done in the future. That way, aircraft can decelerate to the limit speed in time, thus providing more realistic and accurate simulation.

6.1.2 Deeper Familiarization With Aircraft Behavior

The BADA Family 4 introduces new parameters. However, for some of these parameters, aircraft models do not define values to be used.

A typical example of this is speed brakes, which are in general used while the aircraft is descending, but the BADA Family 4 does not define when or how to use them. In the current implementation, this is solved so that the speed brakes are not used. This, however, can have a considerable effect on the simulation of descent phase of the aircraft, since speed brakes significantly increase the drag coefficient used in the computation of the drag force acting on the aircraft.

Another example is the transition between aerodynamic configurations. Some aircraft models lack coefficients needed to calculate the drag coefficient while in transition between some of the configurations. In the current implementation, the transition time is not used[1], thus evading the computation of the drag coefficient in between configurations.

These and other problems are to be solved by deeper familiarization with aircraft behavior by developing a new set of rules to define the missing values.

6.1.3 Optimization of the Flight

Another possible focus of future work is the optimization of the flight. The flight can be optimized to take as little time as possible, to consume as little fuel as possible or to change the altitude as quickly as possible. It can be seen that there is a great number of optimization criteria, opening a great window of possible modifications to the model. These modifications can draw on ideas from [13].

6.1.4 Wind Application

To improve the current implementation of the BADA Family 4, the effect of the wind can be applied in the future. That way, the simulation of the flight can provide enhanced performance.

6.1.5 Modification of the BADA Family 3 Implementation

Last proposed improvement does not directly affect the implementation of the BADA Family 4, but rather the whole design. Since the current implementation of the BADA Family 3 is not compatible with the designed architecture, it would be a good idea to rewrite this previous model to meet the architecture requirements. That way, it is easier to work with both models at once, providing that some rules are set.

Let the example of these rules be the case when the BADA Family 4 models are used when defined and the BADA Family 3 models are otherwise. This approach can lead to yet another improvement in performance of the simulation by providing a temporary replacement for the undefined models of the BADA Family 4.

[1] The transition time is considered to be equal to 0.

References

[1] Poles, Damir, Angela Nuic, and Vincent Mouillet. Advanced Aircraft Performance Modeling For ATM: Analysis Of Bada Model Capabilities. *29th Digital Avionics Systems Conference*. Salt Lake City, October, 2010. "[cit. 26-April-2018]".

[2] Nuic, Angela, Chantal Poinsot, Mihai-George Iagaru, Eduardo Gallo, Francisco A. Navarro, and Carlos Querejeta. Advanced Aircraft Performance Modeling for ATM: Enhancements to the BADA Model. *24th Digital Avionics System Conference*. Washington D.C., 2005. "[cit. 8-May-2018]".

[3] Nuic, A., and Mouillet, V. *User Manual for the Base of Aircraft Data (BADA) Family 4.* "[cit. 15-April-2018]".

[4] contributors, Wikipedia. *Calibrated airspeed — Wikipedia, The Free Encyclopedia.*
`https://en.wikipedia.org/w/index.php?title=Calibrated_airspeed&oldid=799419608`. "[online; cit. 15-May-2018]".

[5] contributors, Wikipedia. *Geopotential height — Wikipedia, The Free Encyclopedia.*
`https://en.wikipedia.org/w/index.php?title=Geopotential_height&oldid=840944253`. "[online; cit. 13-May-2018]".

[6] contributors, Wikipedia. *Indicated airspeed — Wikipedia, The Free Encyclopedia.*
`https://en.wikipedia.org/w/index.php?title=Indicated_airspeed&oldid=824911769`. "[online; cit. 15-May-2018]".

[7] contributors, Wikipedia. *Mach number — Wikipedia, The Free Encyclopedia.*
`https://en.wikipedia.org/w/index.php?title=Mach_number&oldid=841197130`. "[online; cit. 15-May-2018]".

[8] contributors, Wikipedia. *Rate of climb — Wikipedia, The Free Encyclopedia.*
`https://en.wikipedia.org/w/index.php?title=Rate_of_climb&oldid=835842165`. "[online; cit. 15-May-2018]".

[9] contributors, Wikipedia. *True airspeed — Wikipedia, The Free Encyclopedia.*
`https://en.wikipedia.org/w/index.php?title=True_airspeed&oldid=788535886`. "[online; cit. 15-May-2018]".

[10] Base of Aircraft Data (BADA) Factsheet.
`http://www.eurocontrol.int/sites/default/files/publication/files/bada-factsheet.pdf`. "[online; cit. 27-April-2018]".

[11] Nuic, A. *User Manual for the Base of Aircraft Data (BADA) Revision 3.13.* "[cit. 13-April-2018]".

[12] Poles, D. Revision of Atmosphere Model in BADA Aircraft Performance Model. February, 2010. "[cit. 27-April-2018]".

[13] Doubek, J. *Optimization of vertical in-flight parameters of an aircraft according to BADA model.* "[cit. 28-March-2018]".

[14] Yoon, Joe. *Types of Airspeed*.
http://www.aerospaceweb.org/question/instruments/q0251.shtml. "[online; cit. 15-May-2018]".

Appendix A
Attachments

- csanda_bada4.zip - Zip file containing the source code.