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FORMULATION OF IN SITU FLIGHT PERFORMANCE TOOLBOX FOR DECISION SUPPORT SYSTEM

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A PROJECT REPORT
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The undersigned certify that they have read, and recommended to the Institute of Engineering for acceptance, a project report entitled “FORMULATION OF IN SITU FLIGHT PERFORMANCE TOOLBOX FOR DECISION SUPPORT SYSTEM” submitted by Dipesh Kunwar, Pratibha Bhandari and Swikriti Shrestha in partial fulfillment of the requirements for the Degree of Bachelor in Aerospace Engineering.

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ABSTRACT

Performance calculations for aircraft holds a major importance for flight operations and planning, which currently is relied heavily upon manufacturer specific charts. Operations in STOL fields adds further intensity to requirement of the calculations to be precise. The study aimed to enhance the efficiency of flight procedures management, fuel utilization, and flight feasibility assessment for specific circumstances through mathematical models for performance calculation in order to facilitate the flight crew, operators as well as aviation service providers with a means for quick estimation of operational requirements and performance data. A tool was developed using analytical techniques for estimation of operational requirements and performance calculation for different phases of flight which includes decision-making aids that consider the constraints imposed by the airport, aircraft, and regulations to facilitate flight operations. The results generated from the tool were validated against the performance charts included in the AFM of DHC-6, series 300 for takeoff, landing and rejected takeoff condition for which the deviations obtained were within 3%. The remaining phases of flight (i.e., climb, cruise and descent) were validated using simulated flight scenarios as well as manufacturer's supplementary charts where the discrepancies obtained were within justifiable limits. The validated performance parameters obtained through the program were then tested against imposed aircraft, airport as well as regulatory limitations to generate necessary decision aids to help make informed decisions and plan flights efficiently.

Keywords: *Decision Support System, flight operations and plan, aircraft performance calculation, STOL operations*

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LIST OF SYMBOLS

V_{app}	Approach Velocity
μ	Bank Angle
C_d	Coefficient of Drag
C_l	Coefficient of Lift
C_m	Coefficient of Moment
V_1	Decision Speed
ρ	Density
rho	Density at Given Altitude
D	Drag
n_{pr}	Efficiency
V_{flare}	Flare Velocity
S_g	Ground Run
K	Induced Drag Coefficient Factor
L	Lift
V_{max}	Maximum Velocity
n_{pu}	Percentage of Power Used
P_a	Power Available
P_{max}	Power Maximum
P_r	Power Required
V_r	Reference Speed

V_{stall}	Stall velocity
V_2	Take-off Safety Speed
T_a	Thrust Available
T_r	Thrust Required
V_{TD}	Touchdown Velocity
V	Velocity
W	Weight

LIST OF ABBREVIATIONS

AFM	Aircraft Flight Manual
AFM Supp.	Aircraft Fight Manual Supplementary
AGL	Above Ground Level
AIP	Aeronautical Information Publication
AOC	Angle of Climb
APP	Aircraft Performance Program
ATR	Avions de Transport Régional
ASDA	Accelerated Stop Distance Available
CAAN	Civil Aviation Authority of Nepal
CDL	Configuration Deviation List
CFR	Code of Federal Regulation
DHC	de Havilland Canada
DOF	Degree of Freedom
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FLIP	Flight Planning
FO	Flight Operation
FORA	Flight Operations Requirements-Aeroplane
GBIA	Gautam Buddha International Airport
GUI	Graphical User Interface

IAS	Indicated Airspeed
ICAO	International Civil Aviation Organization
IFP	Inflight performance calculation program
ISA	International Standard Atmosphere
LDA	Landing Distance Available
MEL	Minimum Equipment List
METAR	Meteorological Terminal Air Report
MLW	Maximum Landing Weight
MoCTCA	Ministry of Culture, Tourism and Civil Aviation
MSL	Mean Sea Level
MTOW	Maximum Takeoff Weight
OFP	Operation Flight Plan
OAT	Outside Air Temperature
PEP	Performance Engineers' Programs
PFPX	Professional Flight Planner X
POH	Pilot's Operating Handbook
ROC	Rate of Climb
RPM	Rotations Per Minute
SFC	Specific Fuel Consumption
STOL	Short Take-off and Landing
TAS	True Airspeed

TLO	Takeoff and Landing Optimization
TOPCAT	Takeoff and Landing Performance Calculation Tool
TORA	Take-off Run Available
TODA	Take-off Distance Available
VFR	Visual Flight Rules

CHAPTER ONE: INTRODUCTION

Decision support systems (DSS) are computer-based information systems designed to aid decision-making process using data, models, and analytical techniques to provide insights and recommendations. In aviation, DSS are used in emergency response, flight planning, maintenance, safety management etc. In operations, these systems cover accurate prediction of performance parameters of aircraft while also complying with the relevant regulation based on weather conditions, aircraft configurations, engine performance and aircraft performance data, that might be obtained on ground or in real time. This project targets integration of ground-based performance calculations with corresponding decision support commands to formulate a decision support system.

1.1 Background

For any aircraft, calculation of required performance parameters, fuel amount, and payload an aircraft can carry for given conditions is a tedious process, and a decision to carry through or reject take-off and land intensifies the situation. Boeing [1] reported that between 2011 to 2020, the takeoff and landing were the phases where over 67% of total accidents took place though an aircraft only spends about seven percent of its flight period in the process. These stats have been reflected in major Nepalese air crashes as well throughout history. Error tendencies during calculations, runway contamination, and fluctuating weather conditions are the significant contributors to accidents [2] while during takeoff and landing like runway overrun, crashes due to too low V_1 speed calculations, negative climb gradient during takeoff, and many more [3].

In light of these conditions, general awareness and assistance to aircraft operators and pilots on the complexities that can arise during the take-off and landing phases, and aircraft's performance is required. Several factors influence performance, including aircraft weight, aircraft’s actual aerodynamic coefficients, air density, wind direction and magnitude, atmospheric pressure, runway condition, runway slope, and aircraft configuration (flap position). These factors primarily influence the available thrust and, as a result, the decision speed (V_1), reference speed (V_r), take-off safety speed (V_2), maximum permissible takeoff weight (MTOW), maximum landing weight (MLW), approach speed (V_{app}), and landing distance. The aircraft is highly challenged by the fluctuation of these conditions and parameters, which directly or indirectly affect an aircraft's characteristic performance. So, an aircraft performance calculation, monitoring and decision support to monitor and analyze performance poses an importance.

1.1.1 Current trends in performance calculation and decision support tools

Performance calculation tools that support decision-making for engineers and pilots are widely used for aircrafts and flight simulators. Software packages like PEP by Airbus [4] which are provided by the manufacturer itself are the most commonly used performance calculators among airline operators. PEP consists of computation cases for before, during, and after flight which enable performance calculations for almost all phases of flight. Relevant modules/ programs within PEP include Inflight performance calculation program (IFP), Takeoff and Landing Optimization (TLO), and Flight Planning (FLIP). Other commercially acclaimed software includes Aircraft Performance Program (APP), Takeoff and Landing Performance Calculation Tool (TOPCAT), Professional Flight Planner X (PFPX), etc. APP calculates performance parameters over a range of altitudes, speeds, and other variables as input. TOPCAT is an advanced tool/software which along with PFPX enables the user to compute an operational flight plan. This software holds the capacity of estimating takeoff and landing performance with user-specified entries like the location of departure and destination, take-off weights, payloads, fueling conditions, runway conditions, etc. The outputs include load sheets, analysis, runway tables, relevant speeds, etc. PFPX can be used independently for OFP as well.

1.1.2 Requirement of attention to STOL operations

For Nepal where more than half the total airports in current operation include STOL airfields, these airfields majorly VNLK, VNJS, VNRC, etc. serve as important transportation links for many remote places. However, operations here due to short runways, high altitude, and unpredictable weather, are typically challenging and pose a high risk of accidents which is evident throughout the years. According to Aviation Safety Report-2022, published by CAAN, the total number of accidents of STOL section flying aircraft between 2012 to 2021 was as high as 14, whereas 8 were fatal accidents. These aircrafts include DHC-6, 300 and 400, DO228-202K and LET410 [5]. So, a performance calculation and decision aid program specific to an aircraft used for STOL operation can be helpful.

1.2 Problem Statement

Many domestic operators in Nepal still use the printed flight manuals published by manufacturers to calculate the flight performance parameters, which increase error tendencies causing an evident deviation from that obtained through a digitized system. Yet, the foreign calculation tools used are too expensive and lack customization. The flights are dependent on calculations made by the crew creating possibilities of errors and inappropriate decisions during different phases of flight as seen evidently in accidents throughout the years [6, 7].

1.3 Objectives

1.3.1 Main Objective

The main objective of this project is to develop a model for a decision support system that will aid operations engineers and crew in computing flight operational and performance parameters, and flight profile.

1.3.2 Specific Objectives

- To develop a program able to compute phases of flight using analytical methods and formulae, incorporated in a Graphical User Interface (GUI).
- To establish airport, aircraft and route-specific databases for the aforementioned main objective.
- To validate the results obtained against Pilot’s Operating Handbook (POH) and Aircraft Flight Manual (AFM) of the aircrafts.
- To obtain mock flight scenarios to validate the results, and utilize mission parameters in order to simulate decision support scenarios.

1.4 Applications

- Domestic airlines relying mostly on hand calculations and printed charts included in the manuals for small aircraft, can utilize this tool, its approaches and methodologies, for operational calculations and decision making.
- With the newly inaugurated Gautam Buddha International Airport, and Pokhara Regional International Airport, this tool can be helpful in preliminary feasibility study of new aircraft that could be operated in those airports.
- The software will support aircraft operators and pilots with or without any existing Flight operation (FO) software to determine performance parameters for given flights at low computational cost and time.

1.5 Feasibility Analysis

1.5.1 Economic Feasibility

A significant portion of the budget for this project must be allocated to validation. The model was validated using simulated flight scenarios for which X-Plane licensing along with DHC-6 aircraft compatible to the X-Plane version was required. Overall, a moderate sum was required for the completion of the project on the developers' end.

While on the user's end, the program helps to compute operational and performance parameters which can be utilized for data analysis, flight profile planning with a lesser computational and operational cost than expensive commercial software.

1.5.2 Technical Feasibility

From a technical standpoint, the project required a programming platform for coding and a validation software. Thus, knowledge on any programming platform and corresponding language marks its technical feasibility.

The usage of the tools like these on the company's end can help to access performance and operational parameters with greater ease, reducing the number of trainings and technical briefs for the purpose.

1.5.3 Operational Feasibility

The final result of the project generates an executable (standalone) file which can be utilized by the user with access to a device and operating system that supports its specifications.

1.6 System Requirements

For the duration of our project, the software required were:

- MATLAB, a high-level programming language with interactive data analysis, mathematical modeling, and data acquisition capabilities, was used as base programming language to model our system. Its various math functions and built-in commands simplified mathematical calculations and helped intuitive programming for the performance parameters and plot generation, while its interface *App Designer* was utilized for developing the GUI.
- X-Plane, a flight simulating software providing realistic simulation of flight dynamics, weather and atmospheric conditions, was used for result validation by modelling mock flight scenarios and testing it against the results generated throughout the program.

Whereas, the hardware requirement for the project was a computer system with a processor and memory to back up the latest versions of MATLAB compiler as well as the X-Plane flight simulator. Moreover, the flight simulator setup at Department of Mechanical and Aerospace Engineering was utilized during validation process.

CHAPTER TWO: LITERATURE REVIEW

Decision support systems are used for dispatch assessment addressing decision support in aircraft maintenance, as well as situational awareness decision support in Air Traffic Management. Koornneef et al. [8] discussed about the unexpected issue encountered during flight and the problem faced by the pilot during the decision-making process. The main problem mentioned is finding pertinent choice support information in manuals and the lack of access to decision support information. These issues hamper the safety. In order to solve these issues, this study employs a design science research methodology. It also presents two innovative artifacts: a decision support framework for real-time decision making in aircraft dispatch and a web-based prototype tool that can be accessed via mobile devices. As a result, 70% less time was spent making decisions overall. [8]

Li et al. [9] in a study application of decision support systems for enhancing performance in flight operations, pointed out a need for a decision-making tool that can assist pilots in an emergency situation to help the pilots make an informed decision. Melnichyuk & Sudakov developed a take-off and landing decision master system utilizing aircraft and airport databases where the decisions were provided using calculated information in accordance with the rules based on MEL, CDL, or operator policy [10].

In a comparative study of a six-year-old and a soon-to-be-delivered 747-400, Anderson & Hanreiter [11] obtained a total fuel mileage deterioration of 0.85% and a drag deterioration of 0.55%. A study of aircraft performance utilizing flight data [12] also stated that the aircraft usage through time causes a degradation of the aircraft's aerodynamics coefficients. The study points out that substantially accurate and complete actual performance characteristics can be obtained utilizing updated aerodynamic coefficients rather than manufacturer-specified theoretical parameters. The change in the aerodynamic characteristics according to Krajček, can be obtained by monitoring fuel consumption or specific range method at steady cruise conditions [12].

ZHU et al. [13] while calculating takeoff and landing performance under varied environmental coefficients, concludes that an increase in altitude, tailwind, temperature as well as increased TOW/LW has an average negative impact on landing performance. Though the effect in real life is much more complex, a requirement of analysis of those meteorological conditions is stated.

Poudel et al. [14] developed a takeoff and landing performance calculation tool for domestic propeller aircrafts in Nepal, where the calculations nearly confirmed to POH data, yet the effect of variation of temperature, pressure, Reynold's number as well as runway conditions weren't taken in consideration. Following the proceedings of Poudel et al., a complete aircraft performance calculation and optimization tool was developed [15], where a MATLAB based GUI (named APRECOT) capable of calculating various performance parameters during takeoff, landing, and cruise. A recommendation for inclusion of regulatory database as well as further addition of aircrafts in operations in Nepal was provided.

Di Gravio et al. [16] emphasized the importance of ATM monitoring in ensuring safety as it is of utmost concern and incorporating decision support methods as an Aerospace Performance Factor (APF). The specific tool developed assists in the analysis of each event's safety and risk. It provides the average single value of safety performance and tends to aid in the formulation of appropriate countermeasures while remaining within the guidelines and safety limits.

These works of flight performance modelling [14, 15, 16] show a forward trend as well as the need for such tools for determining flight performance and ensuring safety.

CHAPTER THREE: METHODOLOGY

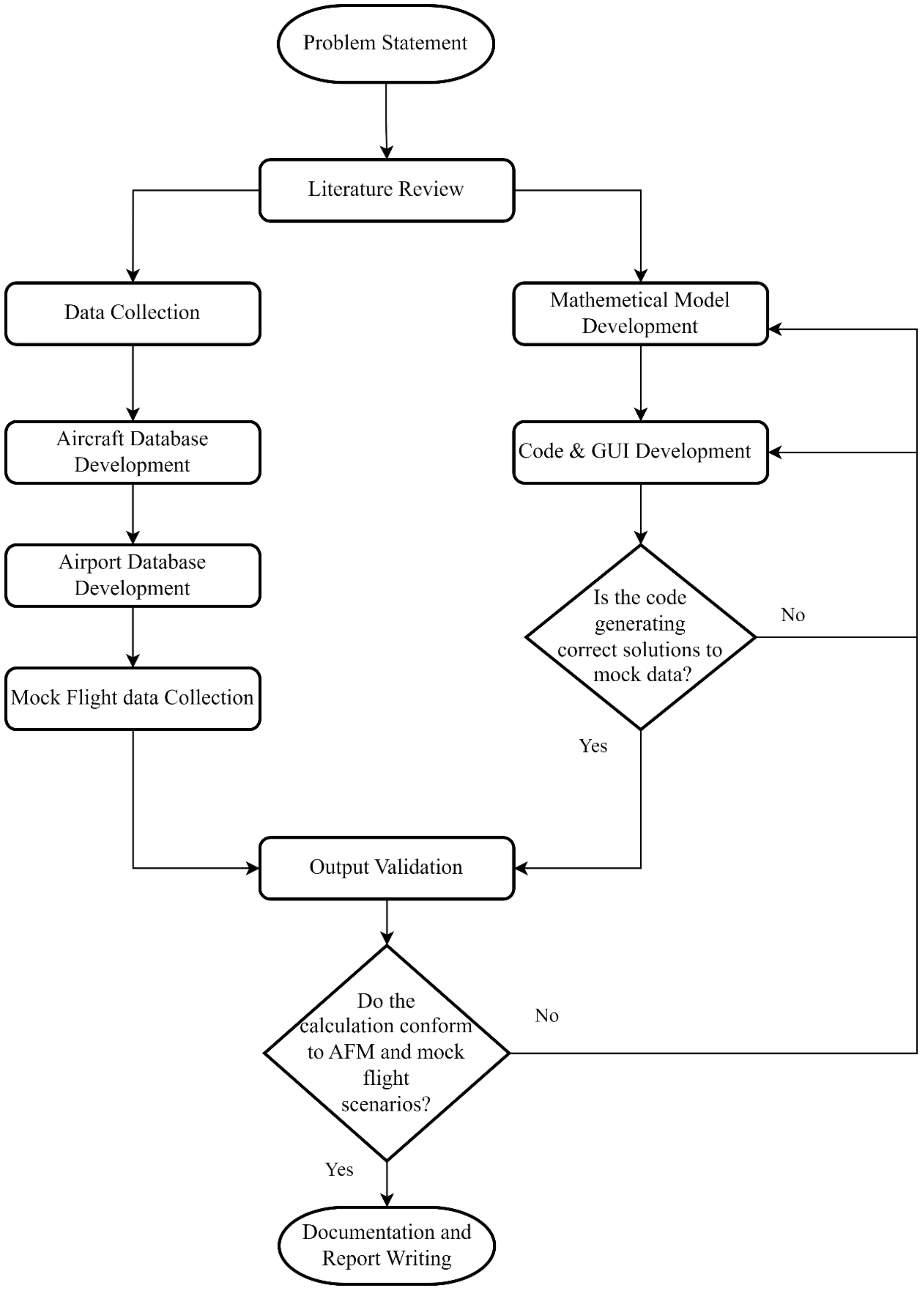

Figure 3.1: Flowchart for the Methodology

3.1 Mathematical Model

Aircraft's performance parameters were reviewed using journals and research papers. Books on "Flight Dynamics" were referred to gain further knowledge of aircraft's performance [17, 18, 19]. Similarly, research articles on the effect of meteorological parameters and runway conditions on aircraft performance were studied, along with the incorporation of aircraft's data and its characteristic coefficients at various flight scenarios not included in the AFM through reverse engineering. The formulae required for the project were then determined and listed for formulation of a mathematical model for performance calculation.

3.2 Data Collection

Among aircrafts like DHC-6 Twin Otter, ATR-72, ATR-42, etc. under domestic operation in Nepal, DHC-6 Twin Otter was chosen for initial data collection as it is currently operating in challenging routes and airports of Nepal. In addition to this, specialized software that address the performance calculations are not available for this aircraft and operations engineers need to rely on performance charts.

The relevant data for DHC-6 Twin Otter were collected from POH and AFM [20]. POH includes weight and balance data, performance specifications and limitations with normal operating and emergency procedures. AFM remains more specific to a particular aircraft that include the operation of that aircraft, its performance parameters and limitations. These data assisted in establishing the aircraft database which includes crucial aircraft specifications such as maximum power, maximum propeller RPM, MTOW, propeller efficiency etc. This further helped in restricting the calculations within the aircraft's specified limit, as a result of which outputs are more realistic.

Civil Aviation Authority of Nepal (CAAN) issues the Aeronautical Information Publication (AIP) [21] and its amendments which include details on aerodrome specifications, en-route rules, procedures and navigation guidance for aircrafts operating in Nepal's airspace. Thus, necessary data on Nepalese Airport such as airport elevation, runway designation, runway type, TORA, TODA, ASDA etc. were obtained from these publications. For airport database, a database of ten airports in Nepal was established, based on type (international, domestic non-STOL, or STOL) and air-traffic mobility trends [22], which can be further extended if needed.

The parameters included in the database for aircraft and airport are tabulated in Table 3.1.

Table 3.1: Parameters Included in the Database

Aircraft Database			**Airport Database**
Aircraft Name	Max. Climb Power Failure	Max. Thrust	ICAO Name
Aspect Ratio	Max. Continuous Power	Max. Torque	TODA and TORA
Category	Max. Continuous Power Failure	Propeller RPM Max.	ASDA and LDA
Parasitic Drag	Max. Cruise Power	Slenderness Ratio	Runway Elevation
Coefficient of Lift Max.	Max. Cruise Power Failure	Ratio of Fuselage Diameter to Wing	Runway Slope
Empty Weight	Max. Fuel Weight	SFC	Nearest Obstacle
Gear Ratio	Max. Landing Weight	Top Engine Failure	Runway Designation
Induced Drag Coefficient Factor	Max. Reverse Power	Top Engine Running	Runway Type and Friction Coefficient
Idle Thrust	Max. Power	Wing Area	Take-off Altitude
Height of Wing	Max. Payload	Wing Span	Take-off Gradient
Jet RPM Max.	Max. Ramp Wt.	Wing Sweep	METAR station
Max. Climb Power	Max. Take-off Wt.	CAS	Traffic Permitted

Similarly, CAAN, International Civil Aviation Organization (ICAO), and Federal Aviation Administration (FAA) publications specify the prevailing rules and regulations for operating jet and propeller aircrafts in Nepal. Since, DHC-6 Twin Otter falls under the Normal Category-Level Four aircraft. For STOL operations specific to DHC-6, CAAN’s Flight Operations Requirements-Aeroplane (FORA) [23]. The collected regulatory information helped to restrict the output within the permitted limits for decision aids.

3.3 Program Development

Utilizing the data and formulae collected, a system able to take specific input from the user or pull the data from the embedded database, run performance calculations for various phases and display decision support parameters considering multiple environmental conditions was developed. The model for the software architecture is as follows:

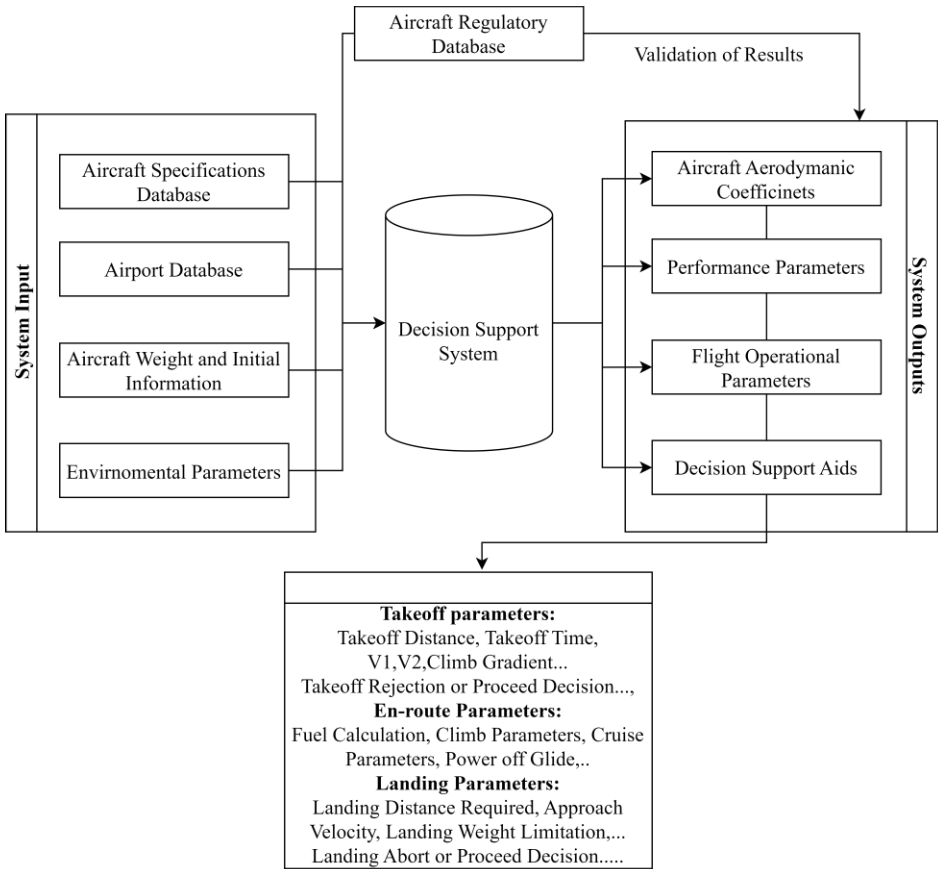

Figure 3.2: Software Architecture

The system comprises of system inputs, which incorporates pre-defined databases (airport database, aircraft specification database, aircraft regulatory database), a manual input for parameters like aircraft's weight and initial configuration, and environmental parameters which could be extrapolated through meteorological reports like METAR or simply through user input parameter. These inputs are then passed into the system where the input data is processed and outputs like actual aerodynamic coefficients, performance parameters and decision commands for phases can be obtained which can be viewed in the output window inside the system GUI window.

3.3.1 Integration of codes specific to DHC-6

Considering high risk operations of DHC-6 Twin Otter in STOL fields, the codes were modified specific to DHC-6 after generic code was completed. The performance charts were digitized, and engine specifications, power setting variations and airframe limitations were also included. The inclusion process was integrated for both sequential and non-sequential calculations for the various flight phases. Regulations specific to STOL operation were consulted, which simplified modelling process considering the fact that rules and regulations to be adhered to were fewer.

3.3.2 Program Capabilities, Functionalities and Assumptions

The tool is built to take inputs for aircraft, departure and destination airports and their real-time meteorological conditions to determine the necessary performance parameters for takeoff, climb, cruise, turning, descent, and landing. The program can thus determine necessary fuel requirements, feasibility of aircrafts for given airports, and produce graphs of performance parameters in relation to various factors affecting flight.

The calculations for the phases could be done sequentially, such that outputs for one phase can be stored as well as utilized as the inputs for the next phase and finally achieve a complete flight path. Whereas, the phase calculations could also be called in a non-sequential manner where the user has a choice to take inputs from user or pull predefined inputs form database.

The physical and numerical assumptions set for tool are:

- All calculations are based on 2 Degrees of Freedom (DOF) point mass equations.
- Analytical simplifications and linearization are used.
- Generic calculations for the aircraft are done with specialization limited to DHC-6 series 300.

The important capabilities and functionalities of the tool would include:

- Computation of aircraft point and mission performance
- Detailed takeoff, cruise, turning and landing performance calculations
- Basic Graphical User Interface
- Relevant plots for phases with proper indication of performance parameters
- Decision aids for multiple phases of flight assisting pre-flight tests

3.3.3 Code Development

The program was coded in MATLAB using functions computing for different phases of flight. These key script files determine the necessary parameters and graphs supported by decision aids for the user. The program code is categorized into code blocks in terms of functions as; conversion functions, preliminary aircraft characteristics calculation, and functions specific to computation for phases of flight.

The code blocks, as shown in the Figure 3.3 are tied along with the main block which acts as the interface for taking user inputs, calling specific phase functions (sequentially or non-sequentially) as well as storing the output generated through each block. The code blocks for the phases have the control over calling preliminary functions, which includes calculations for aerodynamic coefficients as well as other parameters utilized repeatedly, and conversion functions when required.

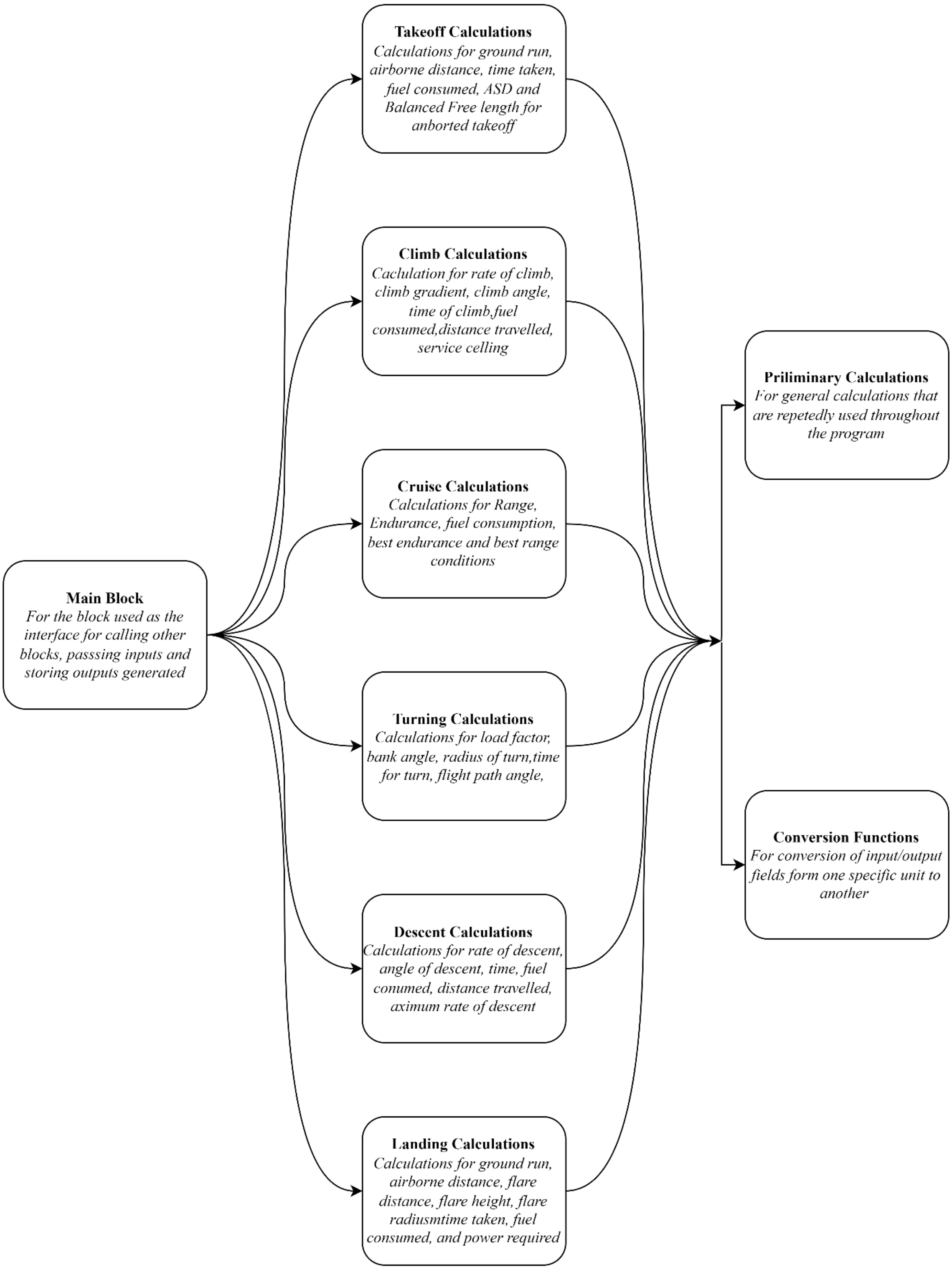

Figure 3.3: Control Flow Diagram for the Code Blocks

The code blocks and the functions they incorporate can be further explored as below:

3.3.3.1 Conversion Functions

The conversion functions include basic unit conversions for input as well as output fields. The list of conversion function used to convert the units of input/output to other required units are listed below:

Table 3.2: Conversion Functions List

MATLAB Functions	Functions
f2m	Converts distance in feet to meter
m2f	Converts distance in meter to feet
rad2deg	Converts angle from degree to radian
m2kt	Converts velocity from m/s to knots
kt2m	Converts velocity from knots to m/s
kg2lb	Converts mass from kg to lbs.
lb2kg	Converts mass from kg to lbs.
m2Nm	Converts distance from meter to nautical mile.
Nm2m	Converts distance from nautical mile to meter.

These functions are defined under the class named **unitconv** and can be assessed throughout any code blocks when called as:

$$unitconv.< Function\_Name > (Conversion\_Variable);$$

3.3.3.2 Preliminary Functions

This code block includes functions for calculation of aerodynamic parameters like lift coefficient (C_L), drag coefficient (C_D), stall speed (V_{stall}), etc. as well as other parameters utilized repeatedly including the effect of runway slope, incremental lift and drag due to flaps, wind effect, etc. The functions utilized for preliminary calculations block are listed below along with their functions:

Table 3.3: Preliminary Functions List

MATLAB Functions	**Functions**
angle_and_climb	Calculates rate of climb and gradient
cd_air	Calculates drag coefficient while on air
cd_flap	Calculates drag coefficient due to flap
cd_ground	Calculates max drag coefficient on ground
cl	Calculates lift coefficient while on air
cl_max	Calculates max lift coefficient on ground
d_get	Generates distance for a route from database
dCd_ground	Calculates for increase in C_{D_0} considering ground effect
flap_drag	Calculates the flap effect on drag
land_Ground	Calculates time and distance for landing ground roll
metar_data	Loads meteorological data for the aerodrome chosen
plott	Generates plots for various phases of flight
power_available	Determines the power available from power/thrust setting used
power_required	Calculates for power required
ro	Calculates density on the basis of height AMSL and temperature
rwy_slope	Calculates the effect of runway slope on thrust
specific_power	Determines the specific power
specific_thrust	Determines the specific thrust
stall	Calculates stall speed
take_ground	Calculates time and distance for takeoff ground roll
TAS	Converts calibrated speed to true speed
thrust_available	Determines the power available from power/thrust setting used
thrust_required	Calculates for the thrust required

3.3.3.3 Takeoff Calculations

This code block incorporates calculations specific to takeoff including ground run, airborne distance, time for takeoff, fuel consumed, etc. at conditions for both engines operating as well as critical engine failure condition. Moreover, it computes for maximum permissible weight for the given TORA, generates the 2D path for the takeoff climb segments and generates the takeoff phase plot before storing and saves the generated outputs in a mat file.

The functions included in this code block are as follows:

Table 3.4: Takeoff Calculation Functions List

MATLAB Functions	**Functions**
basic_takeoff	Calculates for stall speeds, aerodynamic coefficients repeatedly used for entire takeoff phase
both_engine	Computes for takeoff at both engine operating condition
OEI	Computes for takeoff at critical engine failure condition
reverse_take_weight	Computes for takeoff weight limitation for the available runway
to_seg_jet	Computes for takeoff climb segments for jet aircraft

For the decision support action, the outputs are tested against the airport, aircraft and regulatory limitations with suggestive remedial action, if possible, for which the logical sequence can be represented in Figure 3.4 . The figure below represents a general logical sequence for takeoff phase, which for DHC-6 is altered for STOL operations. The flags are then evaluated for remedial action if possible and later checked for feasibility for the phase to be proceeded.

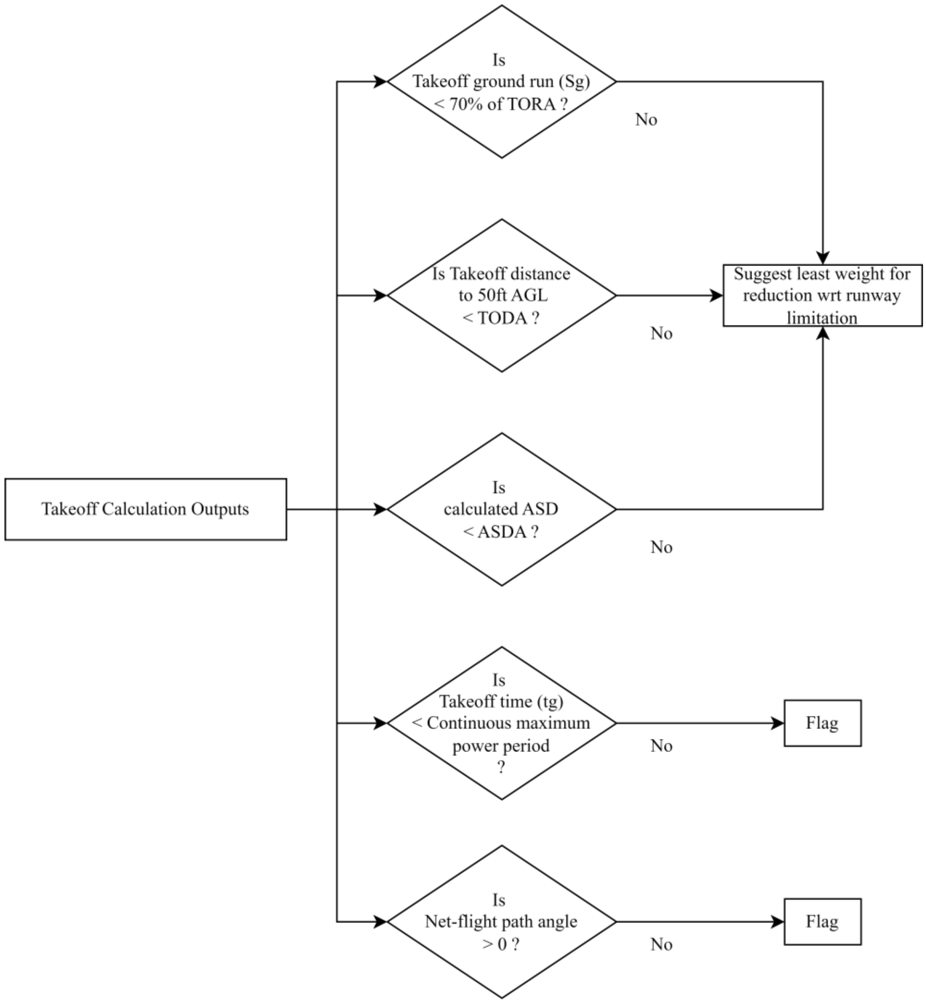

Figure 3.4: Takeoff Decision Logical Sequence

3.3.3.4 Climb Calculations

This code block incorporates calculations specific to climb in two different ways: climb considered for specific point and climb phase taken in sequence with other phases. The point specific climb includes the calculation of rate of climb, maximum rate of climb, angle of climb, maximum angle of climb. It also calculates the altitude at which ROC exceeds the max ROC (i.e., operational ceiling) for a given range of altitude.

Sequence specific climb includes the calculation of distance covered, time required for climb, fuel consumed at the end of climb and weight reduction at normal operating condition. In addition to this, it retrieves the data from the mat file that was saved after take-off phase as input data, generates the plot for the climb phase and saves the generated output in a mat file again.

The functions included in this code block are as follows:

Table 3.5: Climb Calculation Functions List

MATLAB Functions	Functions
clb	Computes for climb phase as sequence to take-off phase at normal operating condition.
climb_point	Computes for climb at specific point at normal operating condition.
climb_pointvaralt	Computes for climb at specific point for a range of altitude
maxjet	Calculate maximum ROC and AOC for jet aircraft
maxprop	Calculate maximum ROC for propeller aircraft
takeoff_pass	Passes on the variables from takeoff required for climb calculation.

For the decision support action, the outputs are tested against the aircraft and regulatory limitations, for which the logical sequence can be represented as follows:

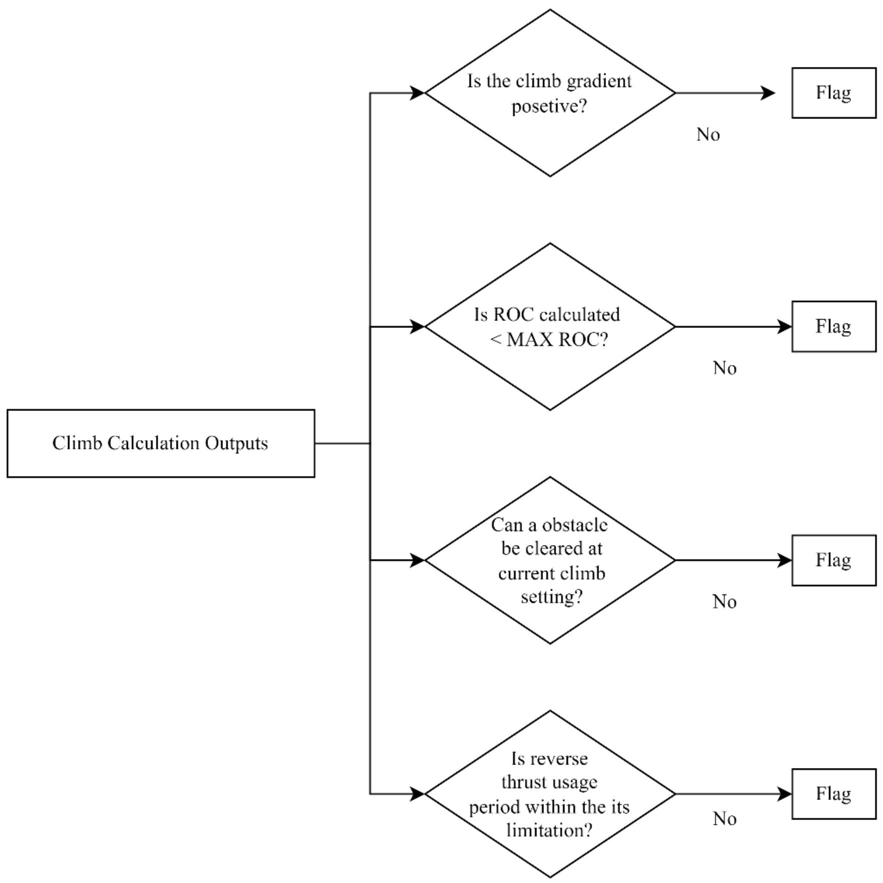

Figure 3.5: Climb Decision Logical Sequence

3.3.3.5 Cruise Calculations

This code block incorporates calculations specific to cruise including horizontal distance covered, time required, fuel consumed and weight reduction at normal operating condition. In addition, it loads the required data from the climb for the completion of calculation, generates the plot for cruise phase and saves the generated output in a mat file.

The functions included in this code block are as follows:

Table 3.6: Cruise Calculation Functions List

MATLAB Functions	Functions
climb_pass	Passes the variables from climb required for cruise.
cruisef	Computes for cruise at normal operating condition.

For the decision support, the outputs are tested against the aircraft and regulatory limitations, for which the logical sequence can be represented as follows;

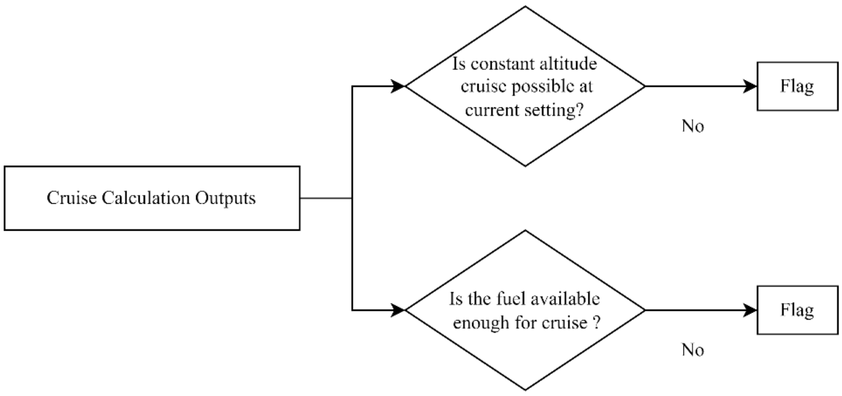

Figure 3.6: Cruise Decision Logical Sequence

3.3.3.6 Descent Calculations

This code block incorporates calculations specific to descent including distance covered, time required, fuel consumed, etc. at normal operating condition. In addition, it loads the required data from the cruise for the completion of calculation, generates the plot for descent phase and saves the generated output in a mat file.

The functions included in this code block are as follows:

Table 3.7: Descent Calculation Functions List

MATLAB Functions	**Functions**
cruise_pass	Passes the variables from cruise required for descent
des	Computes for descent at normal operating condition.
glide	Calculates for engine failure glide calculations.
max_end_glide	Computes for maximum endurance at both engine failure.
max_range_glide	Computes for max range condition at both engine failure.

The outputs are tested against the aircraft and regulatory limitations for decision support, for which the logical sequence is similar to that of the climb phase.

3.3.3.7 Landing Calculations

This code block incorporates calculations specific to landing including ground run, airborne distance, time for landing, fuel consumed, etc. Moreover, it computes for maximum permissible weight for the given LDA, generates the path for the approach and generates the landing phase plot before storing.

The functions included in this code block are as follows:

Table 3.8: Landing Calculation Functions List

MATLAB Functions	**Functions**
descent_pass	Passes the variables from descent required for landing
LDG	Computes for landing at normal operating condition.
reverse_land_weight	Computes for landing weight limitation for the available runway

For the decision support action, the outputs are tested against the airport, aircraft and regulatory limitations with suggestive remedial action, if possible, for which the logical sequence can be represented as follows:

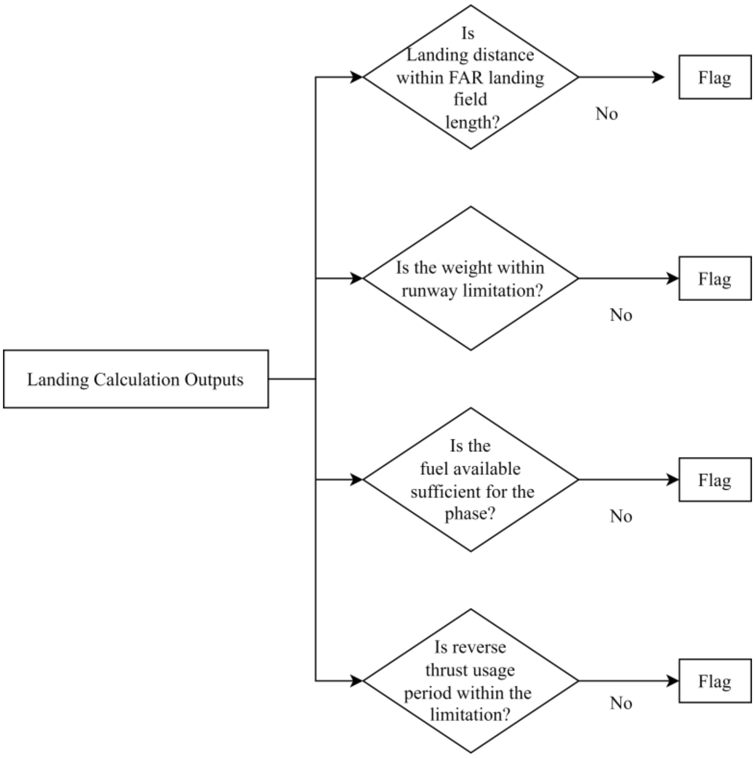

Figure 3.7: Landing Decision Logical Sequence

3.3.3.8 Turning Calculations

Turning calculations are required when prescheduled/sudden maneuvering is necessary. Turning maneuver can be done in two ways: coordinated turning and general turning. Thus, this code block incorporates calculations specific to turn for both types. Coordinated turning includes functions where either bank angle or radius of turn is a known variable along with current aircraft velocity, weight, altitude, etc. Accordingly, it computes radius of turn/ bank angle (for known bank angle/radius of turn respectively), corresponding load factor, time of turn and coefficient of lift.

Similarly, for general turning, it computes flight path angle, load factor, time of turn, coefficient of lift and height gained/lost per unit turn.

The functions include in this code block are as follows:

Table 3.9: Turning Calculation Functions List

MATLAB Functions	Functions
Coordinated turn	
loadfactor	Computes load factor for coordinated turn (with assumption of no excess specific power)
cordturn_mu	Computes for coordinated turn with bank angle (μ) known
cordturn_rot	Computes for coordinated turn with radius of turn (R) known
General turn	
genturn	Computes for general turn with radius of turn (R) and bank angle(μ) known

For decision support actions, the bank angle obtained/used as input is checked against the maximum allowable bank angle which in case of DHC-6 Twin otter is 30° at normal operating conditions. Similarly, obstacle clearance check using turning calculations is also included if maximum climb angle doesn't allow obstacle clearance.

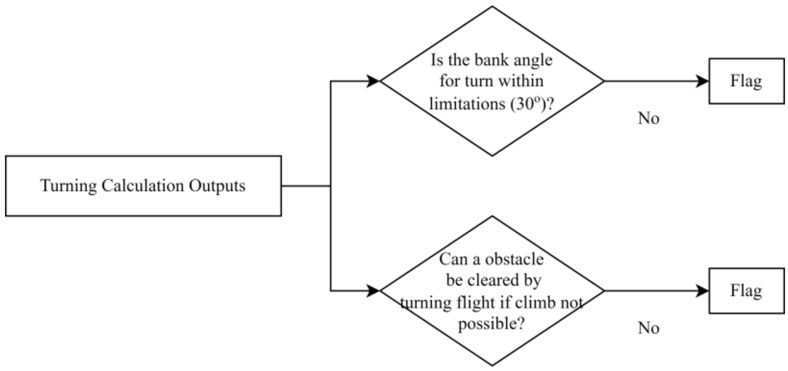

Figure 3.8: Turning Decision Logical Sequence

3.3.4 Working Sequence

The basic working sequence is as follows:

Step 1: Input the departure and destination airports with current meteorological conditions along with en-route conditions optionally as a user input or loaded through the predefined database.

Step 2: Calculate aforementioned performance parameters of a phase of flight called through the **code_main** function.

Step 3: Generate necessary phase plots with variables affecting performance parameters indicated.

Step 4: Store the output generated to specified files and pass on the parameters required for input in the succeeding phase calculations.

Step 5: Generate decision aids using the calculated performance parameters to support aircraft operators and flight operations engineers in decision making before and during flight.

Apart from the sequential operation, the functions can also be called upon non-sequentially if required, where the inputs initially passed through the previous phases are to be provided as user inputs.

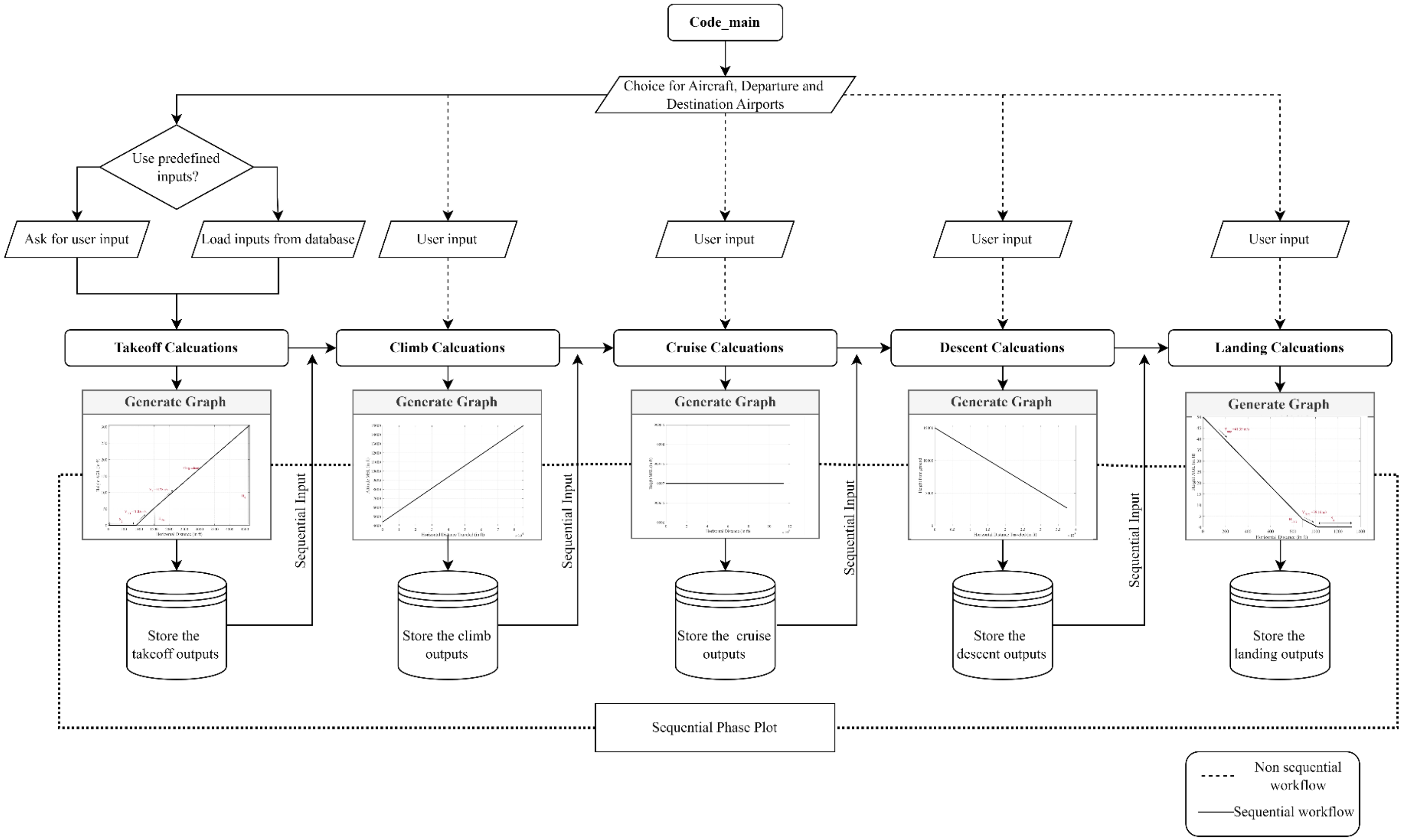

Figure 3.9: Schematic for Program Code Operation

3.4 Result Validation

The results obtained from the program specific to DHC-6 were validated against the data and performance charts available in AFM. Additionally, for en-route (climb to descent) calculations mock test scenarios simulated in X-plane were utilized for validation along with manufacturer's supplementary charts.

The influence of several parameters such as altitude, gross weight of aircraft, deviation from ISA temperature (dT), and wind conditions in take-off distance were considered for validation. To evaluate the effect of each parameter, keeping one parameter as a variable at a time, the other influencing parameters were held constant. Once the calculation was verified for every parameter set as variable, the entire calculation was marked validated. While, additional effects like runway slope effect, braking forces, ground friction of coefficients though integrated onto the system haven't been validated.

For instance, when pressure altitude was taken as variable, the range was changed from 0 to 10,000 feet in steps of 2000. The take-off distance was calculated and cross verified at each altitude. A similar procedure was carried out for the weight, wind, and ISA+ temperature conditions. Gross weight ranged from 9000 pounds to 12500 pounds (MTOW) and the ISA+ temperature ranged from -20 °C to +20 °C. Similarly, wind effects to the take-off performance were examined with the variation within -10 to 20 kts (-ve tailwind, +ve headwind).

In ground operations, aerodrome declared distance becomes the limiting factor such that variations are brought to weight configuration to meet such requirements. So, a reverse calculation method was used to calculate the maximum permissible take-off weight at limited runway cases for a given input. This weight obtained was validated against performance charts provided in the AFM by tracing declared distances back to obtain maximum permissible take-off weight for given pressure altitude, ISA+ and wind condition.

While validating for climb phase calculation, altitude was set as a variable, with initial and final altitudes provided as input. The calculation for time, distance, and fuel consumed was performed based on the given input. The results were cross-checked against the supplementary charts and data obtained from mock test flight scenarios simulated in X-Plane. This procedure was repeated with variations in weight and ISA+ temperature conditions. The validation of the decent phase was done in similar manner.

For constant altitude cruise, the time and fuel consumed were calculated using the formulation for given horizontal distance. These calculations were carried out at different weights, altitudes, and ISA+ temperatures. The results thus obtained were then compared against data obtained from mock flight scenarios and supplementary chart for validation.

The landing phase validation approach was similar to that for take-off phase where, airborne distance, flare and ground run were validated with altitude, gross weight of aircraft, deviation from ISA temperature conditions, and wind conditions taken as variables. Similarly, a reverse calculation method was used to calculate the maximum permissible landing weight for given landing distance limitation which was again validated against the performance charts included in DHC-6's AFM.

For validation, the deviations within 2 to 3% from the validation case are considered adequate on comparison with performance charts included in the AFM while the errors exceeding the margin are considered for validation if justifiable trends or results are obtained. Additionally, some charts were digitized when no analytical trends were observed in the curves, for which interpolation of values for curve fitting was necessary. Validation against these interpolated values might have added to the error tendencies of the results.

3.5 GUI Development

The GUI for the program was developed using App Designer of MATLAB, designed to provide a user-friendly interface for the user to input data and interact with the calculations being performed by the tool. The GUI is divided into several sections that guide the user through the different phases of the calculation.

The initialization page presents the user with choices for selecting the aircraft and routes that they want to analyze. The user can make their selections using dropdown menus, and checkboxes, depending on the specific design of the GUI.

Once the user has made their selections on the initialization page, the tool proceeds to the calculation section. Here, the user can input specific data for the analysis, such as the aircraft weight, altitude, and temperature, as well as other parameters relevant to the analysis. The GUI provides input fields for the user to enter this data, and the tool calculates the important performance parameters based on the input data. It then displays performance parameters, phase plots and decision aids as output, that help the user understand the data being presented.

The GUI designed allows for both sequential and non-sequential actions. Sequential actions allow flight plan performed in a specific order of flight, while non-sequential actions can be performed for phase called at random. A sample sequence for the calculation performed including screen grabs of the GUI are mentioned in section 4.2. as well as APPENDIX B: GUI FOR DSS .

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Program Results

The calculations for the phases could be done both in a sequential and a non-sequential manner such that for sequential calculation, with initial input, while outputs of one phase are stored as well as utilized as the inputs for the next phase to finally compute a complete flight phase. While in non-sequential calculations, inputs are user based and output is generated accordingly.

Starting from the Departure Airport (Airport 1) to the Destination Airport (Airport 2), outputs were generated for each phase of flight. Here, for output demonstration, Airport 1 chosen is Kathmandu (VNKT) and Airport 2 is Pokhara (VNPK).

4.1.1 Takeoff

Take off phase outputs can be classified for two cases viz. normal procedures (both engine operative) and engine failure/ emergency procedures (one engine inoperative).

For normal procedures, outputs are listed as below:

- Distances: Ground run, airborne distance, total take off distance
- Time taken for: Ground run, airborne and total take off
- Velocity: Lift-off velocity (V_{LO}), Velocity at obstacle height (V_2)
- Gradients during airborne and take-off climb phase
- Fuel: Fuel consumed, Fuel remaining
- Flight path
- Maximum permissible take-off weight for TORA limitations

For one engine failure/ emergency procedures, outputs are listed as below:

- Distances: Take off distance (TOD), ASD
- Time taken for: Ground run, airborne, total take off, ASD
- Net flight path

The results obtained for takeoff ground run and takeoff total distance for normal takeoff procedures as well as accelerated stop distance while one engine inoperative, specific to DHC-6 were generated for the study of trends as well as validation against the AFM.

The considerations made during calculations for validation are as listed below

- 10° flap configuration
- Both engines set to takeoff power setting of 96% propeller speed
- Dry, hard, level aerodrome surface.
- C_{Lmax} = 2.075 (calculated from V_{stall})
- Ground friction coefficient 0.05 while brakes off.

4.1.1.1 Takeoff Ground Run

For takeoff ground run, the results obtained plotted against variation of loading condition and altitude with atmospheric parameters set at 15 °C OAT and 0 kts wind is shown in Figure 4.1 .

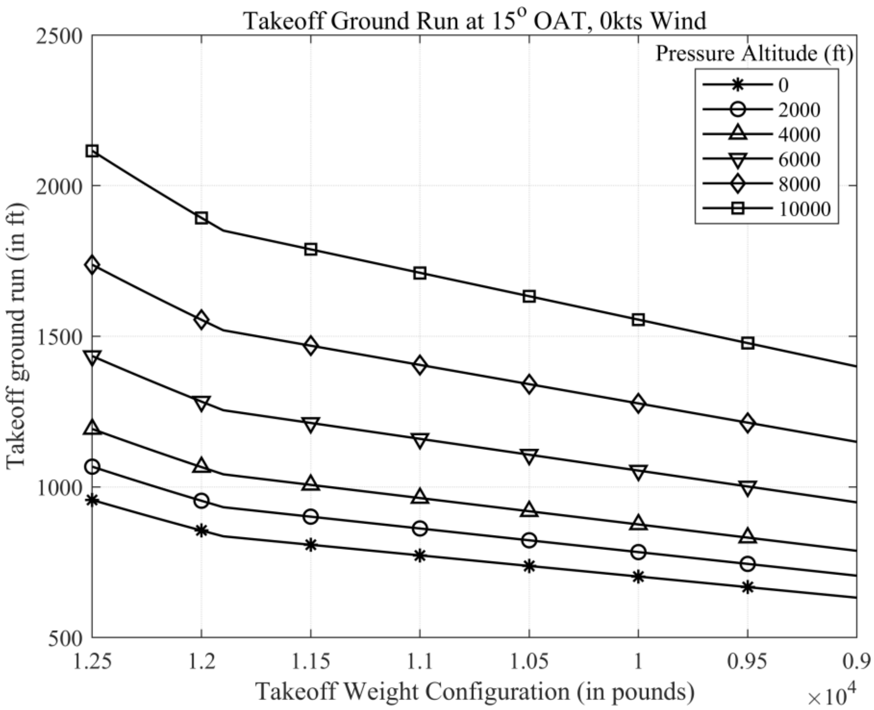

Figure 4.1: Takeoff Ground Run Variation at 15 °C OAT, 0 kts Wind

The variation of takeoff distance obtained is directly proportional to both variation of weight as well as altitude as can be seen in the figure above. The increment in altitude, ground run shows increasing trend due to the density effect i.e., inverse relationship of air density (which decreases with increasing altitude) with ground run. These results are then validated against the AFM at corresponding varying conditions.

For altitude taken as variable, the take-off ground run calculated and value obtained from AFM at similar variation are as shown in Table 4.1. The parameters held constant for the validation case are as listed below:

- Weight = 12500 lbs.
- Wind velocity = 0 kts
- dT = 0 °C

Table 4.1: Takeoff Ground Run Validation with Altitude Variation

S. N	Altitude (ft)	AFM (graph) (ft)	Calculated (ft)	Error (ft)	Error (%)
1.	0	950	956.78	-6.781	-0.71
2.	2000	1040	1045.31	-5.306	-0.51
3.	4000	1145	1143.42	1.577	0.137
4.	6000	1270	1252.33	17.673	1.39
5.	8000	1450	1446.36	3.638	0.25
6.	10000	1675	1684.85	-9.84	-0.588

The results obtained have values of error under 2 % which validates the tool for takeoff phase with the variation in attitude.

For weight taken as variable, the take-off ground run calculated and actual value obtained from AFM are tabulated as shown in Table 4.2. The parameters held constant for the validation case are as listed below:

- Altitude = 4000 ft
- Wind velocity = 0 kts
- dT = 0 °C

Table 4.2 : Takeoff Ground Run Validation with Weight Variation

S. N	Weight (lbs.)	AFM (graph) (ft)	Calculated (ft)	Error (ft)	Error (%)
1.	12,500	1,145.00	1,143.42	1.58	0.14
2.	11,000	940.00	923.63	16.37	1.74
3.	10,000	825.00	839.66	14.66	1.78
4.	9,000	770.00	755.70	-14.30	-1.86

With the variation in aircraft weight, the deviation of the results obtained when compared against the AFM were below 2%, advocating for its validity in this case as well.

For wind condition taken as variable, take-off ground run calculated and actual value obtained from AFM are tabulated as shown in Table 4.3. The parameters held constant for the validation case are as listed below:

- Altitude = 6000 ft
- Weight = 12,500 lbs.
- dT = 0 °C

Table 4.3: Takeoff Ground Run Validation with Variation in Wind Condition

S. N	Wind velocity (kts)	AFM (graph) (ft)	Calculated (ft)	Error (ft)	Error (%)
1.	-10	1,500.00	1,471.20	28.80	1.92
2.	0	1,270.00	1,252.33	17.67	1.39
3.	10	1,065.00	1,046.27	18.73	1.76
4.	20	880.00	872.00	8.00	0.91

Similarly, it can be seen that the results from the tool may be considered acceptable for too since the errors are not more than 2%.

For ISA + temperature taken as variable, the take-off ground run calculated and actual value obtained from AFM are tabulated as shown in Table 4.4. The parameters held constant for the validation case are as listed below:

- Altitude = 8000 ft
- Weight = 11,000 lbs.
- Wind velocity = 0 kts

Table 4.4: Takeoff Ground Run Validation with Temperature Variation

S. N	**dT (°C)**	**AFM (graph) (ft)**	**Calculated (ft)**	**Error (ft)**	**Error (%)**
1.	-10	1075	1048.804124	26.19587571	2.44
2.	0	1175	1169.339875	5.660125124	0.48
3.	10	1350	1312.226691	37.77330905	2.80

The errors obtained are bounded within the limit for the calculations with variation in ISA+ temperature.

Taking runway available taken as limitation and altitude taken as variable, the take-off gross weight calculated and actual value obtained from AFM are tabulated as shown in Table 4.5. The parameters held constant for the validation case are as listed below:

- dT = 0 °C
- Wind velocity = 0 kts

Table 4.5: Runway Limitation Validation for Takeoff Ground Run

S. N	**Altitude (ft)**	**Runway limit(ft)**	**AFM (graph) (lbs.)**	**Calculated (lbs.)**	**Error (lbs.)**	**Error (%)**
1.	0.00	750.00	10,700.00	10,675.00	-25.00	-0.23
2.	4,000.00	1,000.00	11,900.00	11,904.00	4.00	0.03
3.	8,000.00	1,400.00	12,350.00	12,352.00	2.00	0.02

The results generated from the takeoff ground run module has minimal deviation from the data extrapolated from the AFM for various conditions. Thus, the module can be considered successfully validated.

4.1.1.2 Takeoff Total Distance

The total takeoff distance at normal operating procedure plotted against loading condition and altitude with ambient conditions set to 15 °C OAT and 0 kts wind is as shown in Figure 4.2.

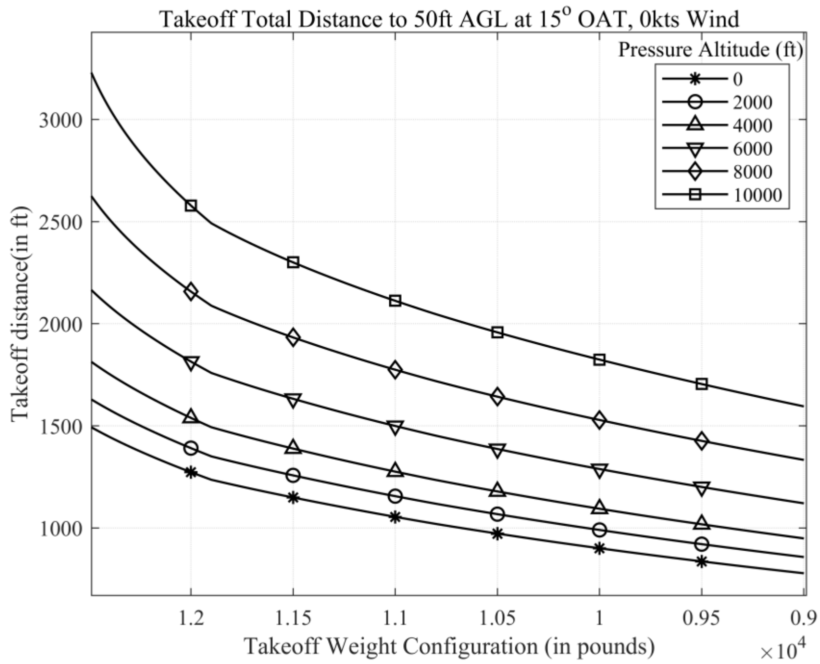

Figure 4.2: Takeoff Distance to 50ft AGL Variation at 15 °C OAT, 0kts Wind

For altitude taken as a variable, the take-off distance calculated compared with the value obtained from AFM at corresponding conditions are tabulated as shown in Table 4.6 . The parameters held constant for the validation case are as listed below:

- Weight = 125000 lbs.
- Wind velocity = 0 kts
- dT = 0 °C

Table 4.6 : Takeoff Distance Validation with Altitude Variation

S. N	Altitude (ft)	AFM (graph) (ft)	Calculated (ft)	Error (ft)	Error (%)
1.	0	1,480	1,500.23	20.23	1.37
2.	2,000	1,590	1,610.1	20.1	1.26
3.	4,000	1,720	1,731.53	11.53	0.67
4.	6,000	1,900	1,900	0	0
5.	8,000	2,180	2,207.89	27.89	1.28
6.	10,000	2,550	2,560.13	10.13	0.39

The results obtained are under the error of 2 % which validates the tool for takeoff phase with variation in attitude.

For weight taken as variable, the take-off distance calculated and actual value obtained from AFM are tabulated as shown in Table 4.7. The parameters held constant for the validation case are as listed below:

- Altitude = 4000 ft
- Wind velocity = 0 kts
- dT = 0 °C

Table 4.7 : Takeoff Distance Validation with Weight Variation

S. N	Weight(lbs.)	AFM (graph)(ft)	Calculated(ft)	Error(ft)	Error (%)
1.	12,500	1,720	1,731.53	11.53	0.67
2.	11,000	1,250	1,225.31	-24.69	-1.98
3.	10,000	1,050	1,051.78	1.78	0.17
4.	9,000	900	912.22	12.22	1.36

With the variation in weight configuration the deviation of the results obtained when compared against the AFM were always below 2 % advocating for its validity in this case as well.

For wind taken as variable, the take-off distance calculated and actual value obtained from AFM are tabulated as shown in Table 4.8. The parameters held constant for the validation case are as listed below:

- Altitude = 6000 ft
- Weight = 12, 500 lbs.
- dT = 0 °C

Table 4.8: Takeoff Distance Validation with Variation in Wind Condition

S. N	Wind velocity (kts)	AFM (graph)(ft)	Calculated(ft)	Error (ft)	Error (%)
1.	-10	2,200	2,196.66	-3.34	-0.15
2.	0	1,900	1,900	0	0
3.	10	1,610	1,616.24	6.24	0.39
4.	20	1,360	1,364.45	4.45	0.33

Similarly, it can be seen that the results from the tool may be considered acceptable for the tool, since the errors are not more than 1%.

For ISA + temperature taken as variable, the take-off distance calculated and actual value obtained from AFM are tabulated as shown in Table 4.9 . The parameters held constant for the validation case are as listed below:

- Altitude = 6000 ft
- Weight = 9500 lbs.
- Wind velocity = 0 kts

Table 4.9: Takeoff Distance Validation with Temperature Variation

S. N	dT (°C)	AFM (graph) (ft)	Calculated(ft)	Error (ft)	Error (%)
1.	-10	810	800.7	-9.3	-1.15
2.	0	850	841.909	-8.091	-0.95
3.	10	890	881.814	-8.186	-0.92

Additionally, the errors are bounded within the limit for calculations with variation in ISA+ temperature.

For weight limitation determination with bounded runway lengths, altitude taken as variable, the maximum permissible weight calculated and actual value obtained from AFM are tabulated as shown in Table 4.10. The parameters held constant for the validation case are as listed below:

- Outside Air Temperature (OAT) = -10 °C
- Wind velocity = 0 kts

Table 4.10 : Weight Limitation Validation for Takeoff Distance

S. N	**Altitude (ft)**	**Runway Limit(ft)**	**AFM (graph)(lbs.)**	**Calculated (lbs.)**	**Error(lbs.)**	**Error (%)**
1.	0	1,000	11,400	11,382.5	-17.5	-0.15
2.	4000	1,500	12,300	12,315	15	0.12
3.	8000	2,000	12,500	12,500	0	0

The results for the calculation at varying altitudes and runway limitation shows coincidence with the data extrapolated from DHC-6's AFM [20] as well.

4.1.1.3 Accelerated Stop Distance

For rejected takeoff at one engine operating case, the variation for accelerated stop distance required with altitude and loading condition is shown in the Figure 4.3 .

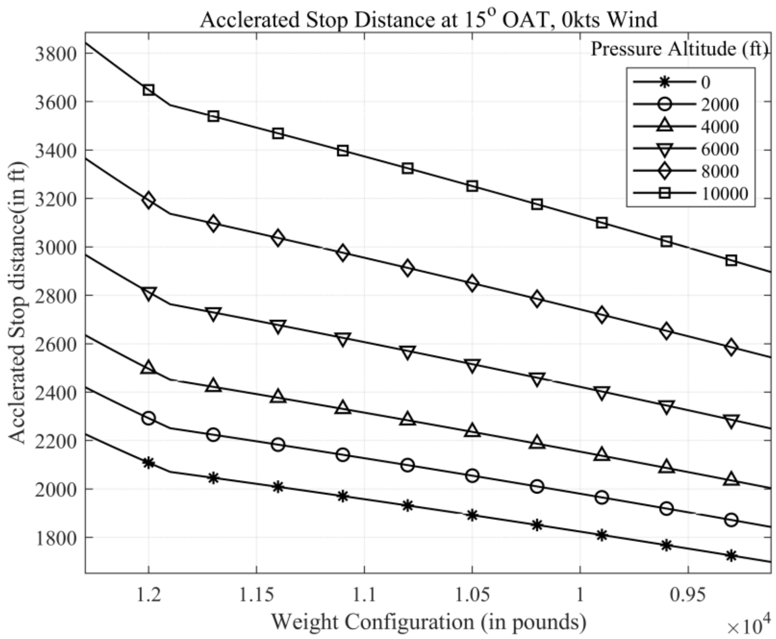

Figure 4.3: Accelerated Stop Distance Variation at 15 °C OAT, 0 kts Wind

For altitude taken as variable, the accelerated stop distance calculated compared with the corresponding values obtained from AFM are tabulated as shown in Table 4.11. The parameters held constant for the validation case are as listed below:

- Weight =12,500 lbs.
- Wind velocity = 0 kts
- dT = -10 °C

Table 4.11: Accelerated Stop Distance Validation with Altitude Variation

S. N	Altitude (ft)	AFM (graph) (ft)	Calculated (ft)	Error (ft)	Error (%)
1.	0	1020.513	1016.583	-3.929	-0.385
2.	2,000	1079.966	1077.819	-2.147	-0.199
3.	4,000	1135.176	1143.66	8.484	0.747
4.	6,000	1194.999	1214.526	19.527	1.634
5.	8,000	1303.167	1290.878	-12.289	-0.943
6.	10,000	1385.063	1373.228	-11.835	-0.854

For wind taken as variable, the accelerated distance calculated and actual value obtained from AFM are tabulated as shown in Table 4.12. The parameters held constant for the validation case are as listed below:

- Altitude = 2000 ft
- Weight = 12,500 lbs.
- dT = 0 °C

Table 4.12 : Accelerated Stop Distance Validation with Variation in Wind Condition

S. N	Wind (kts)	AFM (graph) (ft)	Calculated (ft)	Error (ft)	Error (%)
1.	-10	715.305	699.680	-15.625	-2.184
2.	-6	908.978	894.054	-14.924	-1.642
3.	0	976.254	973.679	-2.574	-0.264
4.	6	1095.653	1108.166	12.513	1.142
5.	10	1235.734	1252.159	16.426	1.329
6.	20	1290.891	1327.984	37.092	2.873

For ISA + temperature taken as a variable, the accelerated stop distance calculated and the actual value obtained from AFM are tabulated as shown in Table 4.13. The parameters held constant for the validation case are as listed below:

- Altitude = 2000 ft
- Weight = 12,500 lbs.
- Wind velocity = 0 kts

Table 4.13: Accelerated Stop Distance Validation with Temperature Variation

S. N	dT (°C)	AFM (graph) (ft)	Calculated (ft)	Error (ft)	Error (%)
1.	-20	1043.379	1052.989	9.611	0.921
2.	-10	1079.966	1077.818	-2.147	-0.199
3.	0	1095.653	1108.167	12.513	1.142
4.	10	1135.449	1129.506	-5.943	-0.523
5.	20	1163.876	1161.44	-2.438	-0.209

As the results generated through the takeoff module has minimal deviation from the data extrapolated from the AFM at varying weight, altitudes, wind condition as well as runway limitation calculation, the module can be considered successfully validated.

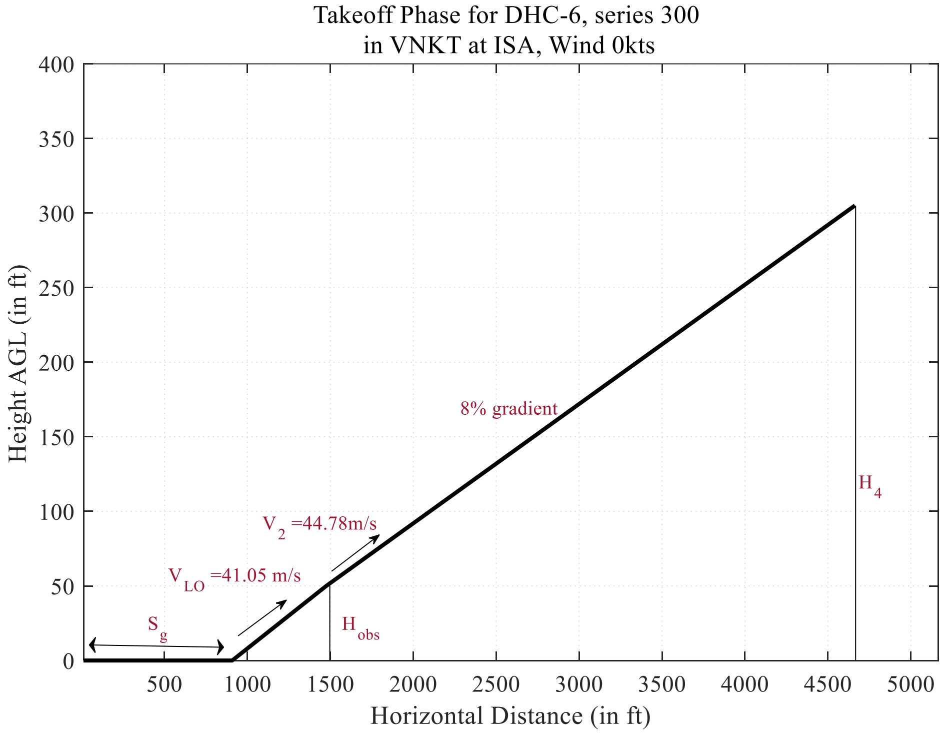

Figure 4.4: Takeoff Phase Plot for DHC-6 from VNKT

The flight path thus obtained for normal take-off procedure from the module is shown in Figure 4.4. Here, S_g denotes ground run, at the end of which, aircraft takes off with lift-off speed (V_{LO}) of 41.05 m/s. It clears screen height of 50 ft (AGL) with speed (V_2) 44.75 m/s. This marks the beginning of takeoff climb phase with 8% gradient which meets the airport published Procedure Design Gradient (PDG), ending at 305 ft AGL (4700 ft MSL). The additional conditions considered for the phase calculation includes the 0.807% average runway slope of VNKT while taking off from runway 02.

4.1.2 Climb

As mentioned earlier, calculations specific to climb are done in two different ways, for a specific point and for the climb phase taken in sequence with other phases.

For climb taken in sequence to other phase, the outputs are listed as below:

- Distance: Horizontal distance, height gained
- Time taken
- Fuel: Fuel consumed, fuel remaining
- Weight reduced at normal operating condition

For ISA + temperature taken as a variable, the time required to climb from sea level to 10,000 ft were calculated compared against the value obtained from supplementary charts, which are tabulated in Table 4.14. For the case, the parameters listed below were held constant.

- Weight = 12,000 lbs.
- Wind velocity = 0 kts

Table 4.14: Validation for Flight Time When Aircraft Climbs from MSL to 10,000ft

S. N	**dT (°C)**	**AFM Supp. (sec)**	**Calculated (sec)**	**Error (sec)**	**Error (%)**
1.	-20	360	368.03	8.03	2.23
2.	0	420	406.59	-13.40	-3.19
3.	10	426	427.21	1.21	0.28
4.	20	492	448.82	-43.18	-8.78

For the same case, there results for horizontal distance travelled compared against the supplementary chart are as shown in Table 4.15.

Table 4.15: Validation for Distance when Aircraft Climbs form MSL to 10,000ft

S. N	**dT (°C)**	**AFM Supp. (NM)**	**Calculated (NM)**	**Error (NM)**	**Error (%)**
1.	-20	10	9.46	-0.54	-5.4
2.	0	11	10.89	-0.11	-1
3.	10	12	11.67	-0.33	-2.75
4.	20	13.5	12.49	-1.01	-7.48

The flight path for climb phase taken in sequence to take-off phase (i.e., from 4700 MSL, where take-off ended) is shown in Figure 4.5. As shown in figure, climb phase ends at 15000 ft (MSL).

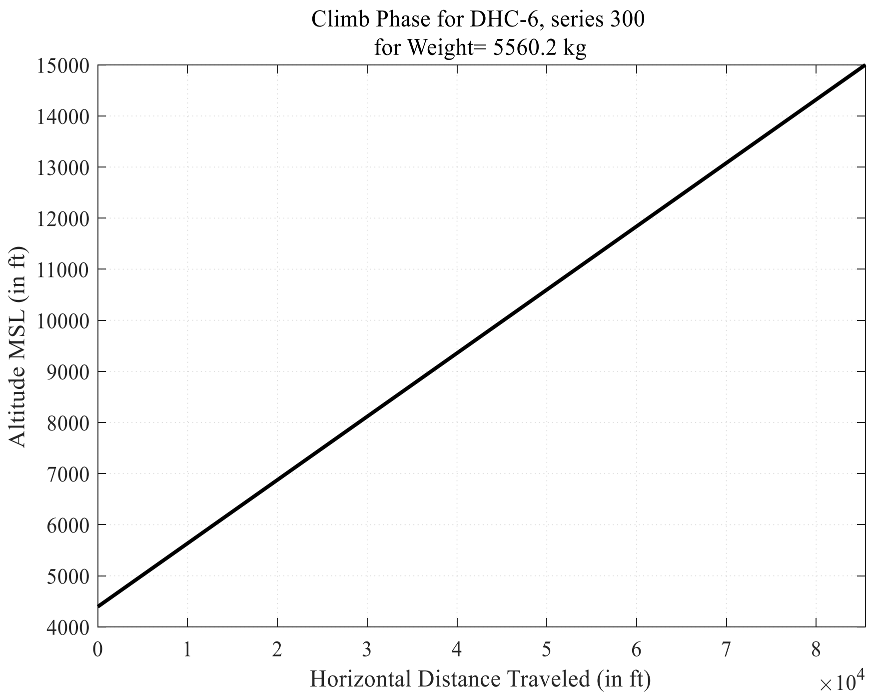

Figure 4.5: Climb Altitude v/s Distance Travelled Plot

For climb calculation taken at a specific point in flight, the outputs are listed as below:

- ROC, maximum ROC for given altitude, AOC for maximum ROC
- AOC, maximum AOC for given obstacle, ROC for maximum AOC
- Operational ceiling
- Hodograph

For service ceiling validation, keeping weight constant at 12000 lbs. with varying altitude and temperature, the quantitative comparison in between the value obtained from supplementary charts of the AFM and the calculated values for service ceiling are tabulated as shown in Figure 4.16.

Table 4.16: Climb Point Validation for service ceiling with Constant Weight

S. N	dT (°C)	AFM Supp.(ft)	Calculated(ft)	Error (%)
1.	20	24700	24263.2335	-1.768
2.	25	23800	23622.048	-0.748
3.	30	22800	23622.048	3.606

Similarly, when ISA + temperature was maintained constant at 25 °C, the actual value obtained from AFM and the calculated value of service ceiling with varying altitude and weight, compared against each other are tabulated as shown in Table 4.17 .

Table 4.17: Climb Point Validation for service ceiling with Constant Temperature

S. N	Weight (lbs)	AFM Supp. (ft)	Calculated(ft)	Error (%)
1.	12500	22590	22965.88	1.66
2.	12000	23800	23622.048	-0.75
3.	11000	25000	24753.19	-0.98

In case of point validation of ROC with weight taken as a variable, the calculated and the obtained values from supplementary charts included in the AFM are tabulated as shown in Table 4.18. The parameters held constant for the validation case are as listed below:

- OAT = 10 °C
- Altitude = 4000 ft
- Engine Torque Pressure = 49.2 psi

Table 4.18: Climb Point Validation for ROC with Weight Variation

S. N	Weight (lbs.)	Velocity (kts)	AFM Supp. (ft/min)	Calculated (ft/min)	Error %
1.	12500	93	1425	1433.65	0.607
2.	12200	92	1475	1498.25	1.567
3.	11000	88	1700	1783.89	4.93
4.	10000	84	1925	2073.35	7.71

Similarly, when altitude was taken as a variable, the value obtained from supplementary charts compared against calculated value of ROC are tabulated as shown in Table 4.19. For this validation case, parameters listed below were held constant.

- OAT = 10 °C
- Weight = 12500
- Velocity = 93 kts

Table 4.19: Climb Point Validation for ROC with Altitude Variation

S. N	**Torque (psi)**	**Altitude (ft)**	**AFM Supp. (ft/min)**	**Calculated (ft/min)**	**Error %**
1.	50	2000	1425	1585.086	7.46
2.	49.2	4000	1475	1433.652	0.607
3.	46.2	6000	1260	1283.389	1.86

The large error obtained for the climbing flight starting from 2000 ft corresponds to a difference of 160 ft/min in ROC which is an extra few seconds of flight time to compensate for the overestimation. At the same time, this error is lower at high altitudes so the rate of compensation required will be lower.

For determination of maximum angle of climb and rate of climbs for propeller aircrafts corresponding hodographs are referred to, such that, the hodograph plotted for DHC-6 at MTOW and 2000ft altitude is as shown in the Figure 4.6. The maximum ROC obtained for the case is 8.178 m/s while the maximum AOC corresponds to an angle of 17.9 °.

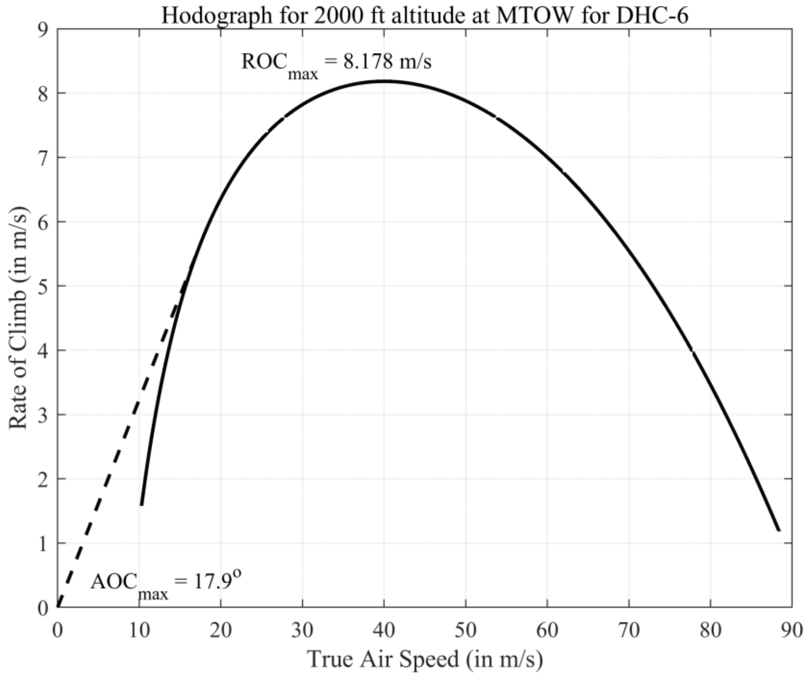

Figure 4.6: Hodograph for 2000 ft Altitude at MTOW for DHC-6

4.1.3 Cruise

The outputs for cruise phase are listed as below:

- Horizontal distance
- Time taken
- Fuel: fuel consumed, fuel remaining
- Weight reduced at normal operating condition

The validation of cruise phase is done against the supplementary charts in AFM for fuel calculations while flight simulations were referred in validation for cruise period.

For validation for cruise period, the cruise distance and cruise altitude were varied such that the results obtained from calculations compared against the results from flight simulator can be as shown in Table 4.20.

Table 4.20: Cruise Phase Validation for Time

S. N	Altitude (MSL ft)	Distance (NM)	Simulation time (secs)	Calculated time (secs)	Error (secs)
1.	6000	14	263.07	264.79	1.72
2.	8000	12.8	255.06	257.67	2.61
3.	10000	18.8	353.63	351	-2.63
4.	12000	28	519.38	518.39	-0.99

The cruise period obtained from calculation has a maximum variation of about 3 seconds, which constitute around one percent of error in calculation.

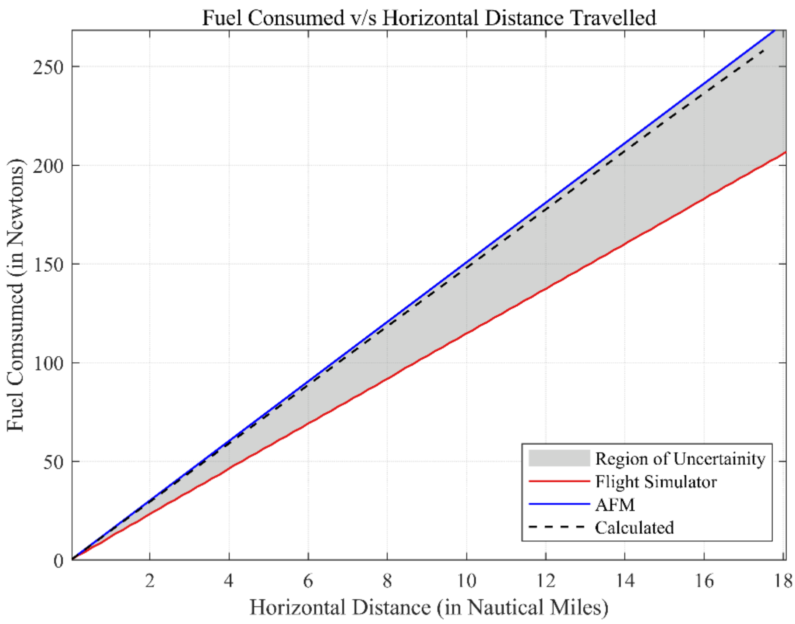

Figure 4.7: Fuel Consumption for Cruise at 10,000 ft

The fuel consumed for constant altitude cruise at 10,000 ft from MSL with distance travelled obtained from calculation is as shown in Figure 4.7, compared against the dataset obtained through AFM as well as using flight simulator at similar conditions. The shaded region signifies the measured region of uncertainty for the fuel consumption obtained through the two sources, the fuel consumption data obtained through calculation lie within the region skewed towards the AFM results. For cruise of 18 nautical miles, the fuel consumed obtained through calculation and AFM were 283.4 Newtons and 277.24 Newtons respectively, corresponding to a 2.17% error in calculation.

4.1.4 Descent

The calculations for descent are based on similar working sequence as for climb with the only change of final altitude being less that the initial altitude, such that descent calculation too hold similar level of accuracy as that for climb. The outputs generated for descent phase are listed as below:

- Distance: Horizontal distance, Height lost
- Time taken
- Fuel: Fuel consumed, Fuel remaining
- Weight reduced at normal operating condition

Similarly, for descent at both engine failure integrates outputs for:

- Range and Endurance for given glide angle
- Range, Endurance, Velocity, Rate of descent and Angle of descent for maximum range
- Range, Endurance, Velocity, Rate of descent and Angle of descent for maximum endurance

For power off glide while flaps retracted, the maximum range per 1000 feet of altitude loss for DHC-6 is found within two nautical miles at a glide gradient of - 8%.
Figure 4.8 shows the glide speeds (for maximum range, and for maximum endurance) obtained through the program compared with the values obtained through AFM.

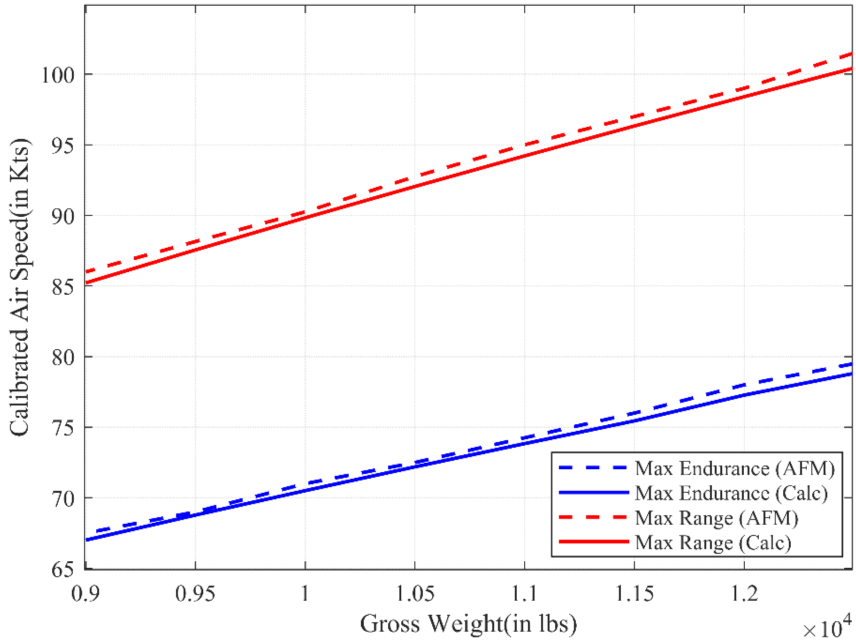

Figure 4.8: Glide Speed for Maximum Range and Endurance

An example for descent phase where descent from an altitude of 15000 ft (MSL) to an altitude of 2734 ft (MSL) at an indicated air speed of 100 Kts at 50% throttle setting along with the corresponding travel in horizontal distance is shown in Figure 4.9. It is plotted against varied throttle setting at 91% and 0% (i.e. power off glide) condition for which the variation in horizontal distance travelled can be seen as show below:

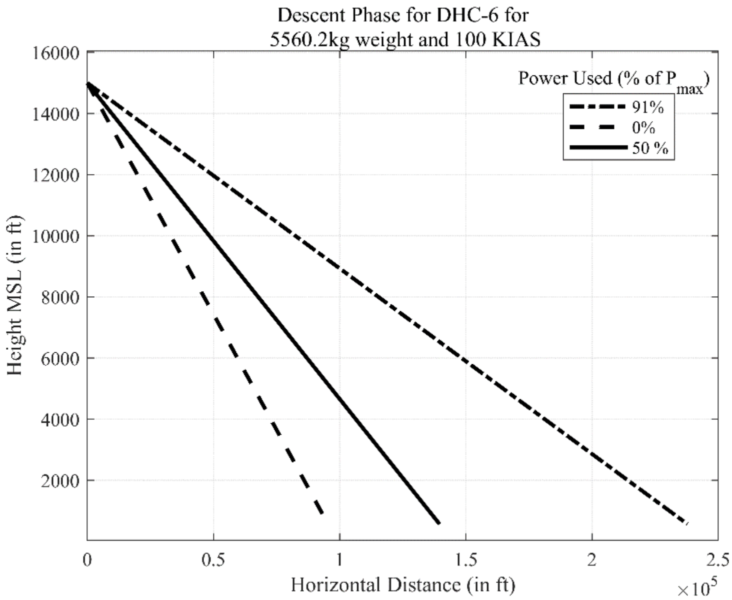

Figure 4.9: Descent Altitude v/s Distance Travelled Plot

4.1.5 Landing

The outputs for landing phase are listed below:

- Distances: Ground run distance, flare distance, total landing distance
- Time taken: Ground run, flare, total landing distance
- Velocity: Approach velocity (V_{app}), Flare velocity (V_{flare})
- Fuel: Fuel consumed, Fuel remaining
- Flight path
- Maximum permissible landing weight for LDA limitations

For validation of results, calculations were done under the consideration of constant configuration with flaps fully extended to 37.5°, approach speed at 3° and power promptly reduced to idle at 50 feet AGL. For the landing configuration the C_{Lmax} is assumed to be 2.8 while a dry, hard, level airfield is considered with ground friction coefficient of 0.5 while on maximum brake effort.

The landing distance at normal operating procedure plotted against variation of loading and altitude with atmospheric parameters set at 15 °C OAT and 0 kts headwind component is shown in Figure 4.10.

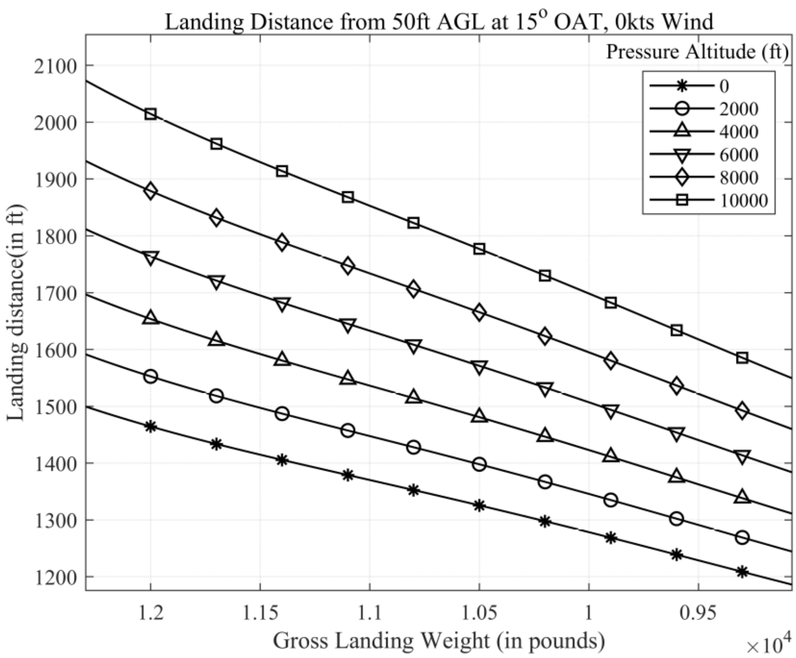

Figure 4.10: Landing Distance Variation at 15 °C OAT, 0kts Wind

- For altitude taken as variable, the landing distance calculated and actual value obtained from AFM are tabulated as shown in

Table 4.21. The parameters listed below were held constant for the case.

- Weight = 12,3000 lbs.
- Wind velocity = 0 kts
- dT = 20 °C
- dT = 20 °C

Table 4.21: Landing Distance Validation with Altitude Variation

S. N	Altitude(ft)	AFM (graph)(ft)	Calculated(ft)	Error(ft)	Error (%)
1.	0	1,600	1,599.91	-0.09	-0.005
2.	2,000	1,660	1,660.58	0.58	0.034
3.	4,000	1,750	1,748.23	-1.77	-0.101
4.	6,000	1,850	1,852.62	2.62	0.142
5.	8,000	1,960	1,958.2	-1.8	-0.092
6.	10,000	2,075	2,075.48	0.48	0.023

Similarly, with weight taken as variable, the landing distance calculated and actual value obtained from AFM are tabulated as shown in Table 4.22. The parameters held constant for the validation case are as listed below:

- Altitude = 0 ft
- Wind velocity = 0 kts
- dT = 0 °C

Table 4.22 : Landing Distance Validation with Weight Variation

S. N	Weight (lbs.)	AFM (graph)(ft)	Calculated(ft)	Error(ft)	Error (%)
1.	12,000	1460	1464.53	4.53	0.31
2.	11,000	1360	1370.34	10.34	0.76
3.	10,000	12650	1278.59	13.59	1.07
4.	9000	1160	1179.14	19.14	1.65

For wind taken as variable, the landing distance calculated and actual value obtained from AFM are tabulated as shown in Table 4.23 The parameters held constant for the validation case are as listed below:

- Altitude = 0 ft
- Weight = 12, 300 lbs.
- dT = 0 °C

Table 4.23 : Landing Distance Validation with Variation in Wind Condition

S. N	Wind (kts)	AFM (graph)(ft)	Calculated(ft)	Error(ft)	Error (%)
1.	-10	1,750	1,767.51	17.51	1
2.	-6	1,650	1,661.74	11.74	0.71
3.	0	1,500	1,500.05	0.05	0.003
4.	6	1,370	1,373.54	3.54	0.26

For ISA + temperature taken as a variable, the landing distance calculated and the actual value obtained from AFM are tabulated as shown in Table 4.24. The parameters held constant for the validation case are as listed below:

- Altitude = 10,000 ft
- Weight = 12,300 lbs.
- Wind velocity = 0 kts

Table 4.24 : Landing distance Validation with Temperature Variation

S. N	dT (°C)	AFM (graph)(ft)	Calculated(ft)	Error(ft)	Error (%)
1.	-20	1,825	1,838.28	13.28	0.73
2.	-10	1,875	1,873.9	-1.1	-0.05
3.	0	1,940	1,940.3	0.3	0.01
4.	10	2,000	2,000.6	0.6	0.03
5.	20	2,075	2,075.48	0.48	0.02

Similar to the results for takeoff module, the landing module at varying weight configuration, altitudes, wind condition as well as reverse weight calculation, has minimal deviation with the data extrapolated through the AFM, thus could be considered successfully validated.

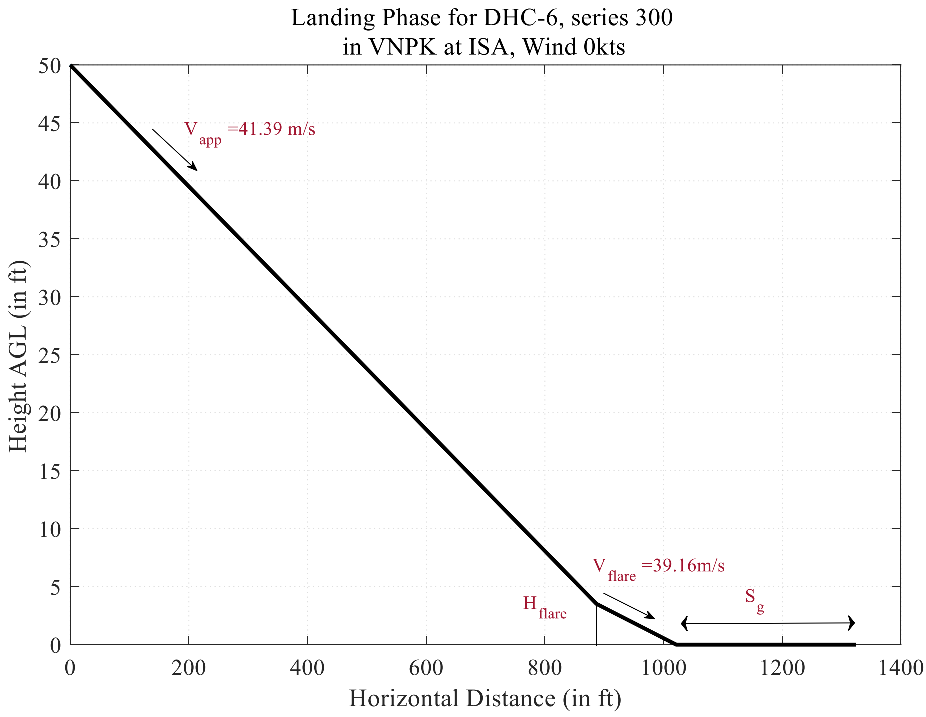

Figure 4.11: Landing Phase Plot for DHC-6 to VNPK

The flight path for normal landing procedure at VNPK generated through the program is as shown in

Figure 4.11. In the figure, approach for landing begins at the height of 50 ft (AGL) with approach speed (V_{app}) of 41.39 m/s. Flare height is crossed at velocity (V_{flare}) 39.16m/s. At this point aircraft flares with an arc before it touches the runway with touchdown velocity (V_{TD}). S_g denotes ground run for landing distance as shown in the figure.

4.1.6 Turning

The outputs of turning phase can be classified for coordinated turn and general turn. The outputs for turn phase are listed as below:

- Radius of turn and Bank angle
- Total time taken to turn
- Load factor

- Coefficient of lift
- Flight path angle (for general turn)
- Height gained per unit complete turn

The outputs are backed up by the decision support as discussed in section 3.3.

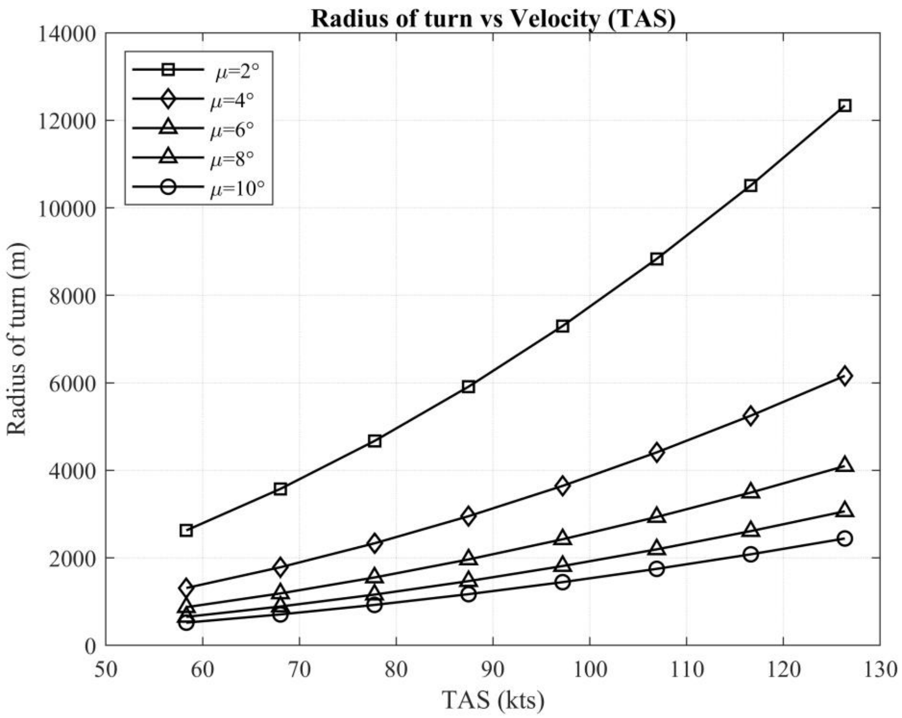

Figure 4.12 : Variation of Radius of Turn with Bank angle (μ)

When TAS was varied from 58 kts to 126 kts, the radius of turn obtained is shown in

Figure 4.12. Variation of the radius of turn with bank angle can also be seen in the figure. It is directly proportional to forward velocity (TAS) and inversely proportional to bank angle (μ).

4.2 Case Study on flight from VNPK to VNJS

For the case study, the necessary calculations were made and the path for the complete flight phase was studied utilizing the GUI developed.

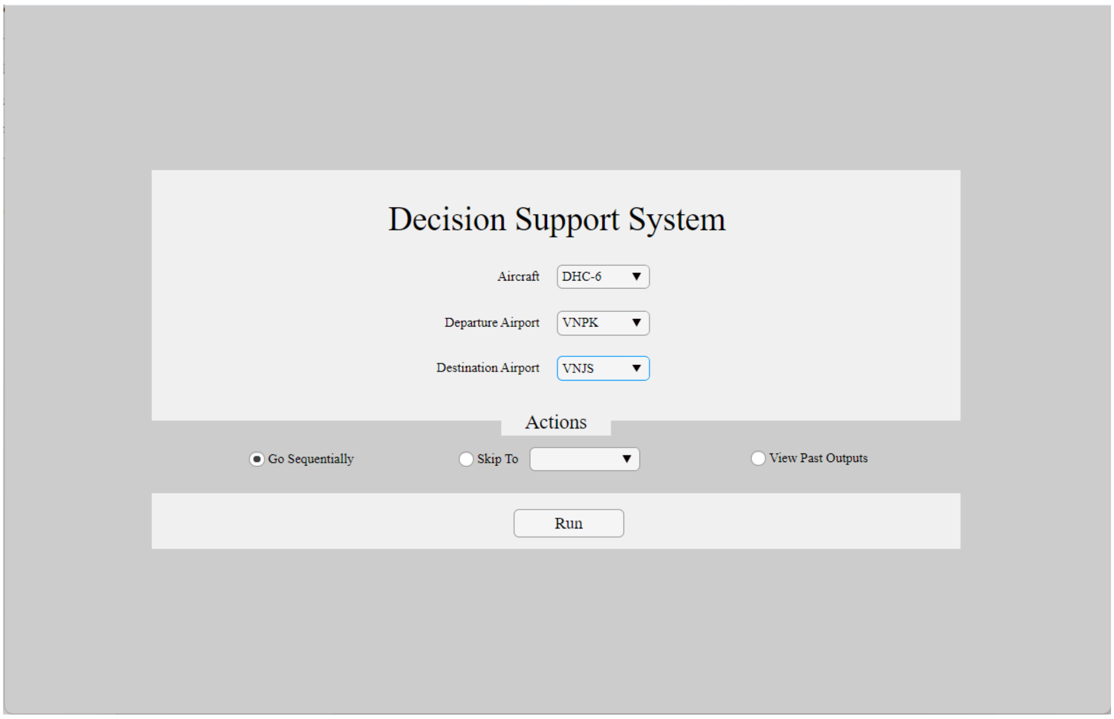

Figure 4.13: GUI for Home Page

The calculation begins with the selection of aircraft and the airports for both departure and destination. The calculation could be done sequentially or skipped to the required phase, which in current case has been run sequentially. DHC-6 was selected for the aircraft of choice, which was set to depart from VNPK and arrive at VNJS.

For takeoff, initial user inputs are asked for data such as weight, takeoff runway, throttle setting and environmental parameters. The environmental parameters input could be given manually or directly loaded from METAR.

The necessary calculation was performed and the result was obtained with decision aid messages and the graph signifying the flight phase.

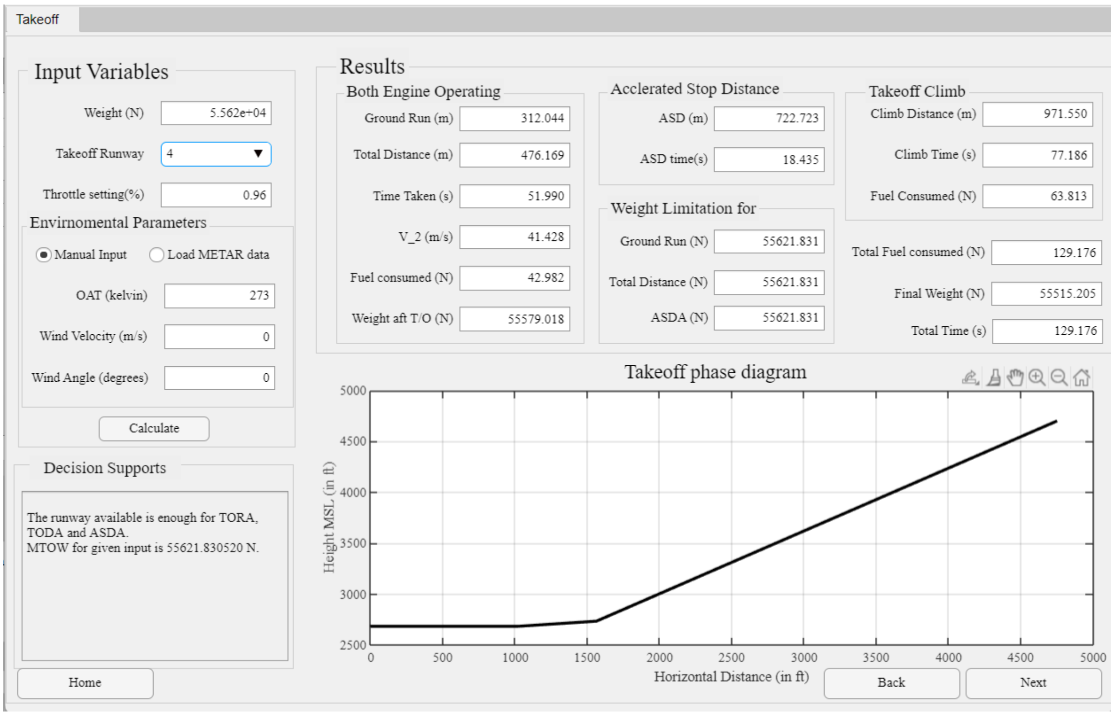

Figure 4.14: GUI for Takeoff Calculations

As shown in the Figure 4.14, with the input weight of 55621.83N, the minimum ground run required for safe take-off was 312.044 m whereas to abort the take-off procedure due to one engine failure at V_{EF}, accelerated stop distance required was 722.723 m.

With runway length as a limiting factor the aircraft weight is determined as well. The rated runway limitations were extracted form database and the maximum permissible weight for given input is calculated. For VNPK, rather than the runway available, the structure limit of the aircraft became the limiting factor and 55621.831N was the maximum permissible weight for the given inputs.

Till the airborne phase, the airplane accelerates to the speed (V2) of 41.428 m/s, traveling the total distance of 476.169 meters horizontally in 51.990 seconds while using 41.732 N of fuel to reach an altitude of 50 ft (above AGL). Next the aircraft climbs to the altitude of 1433m (above MSL) at the time period of 77.186 seconds covering a horizontal distance of 971.55 meters. This marks the completion of take-off phase.

Hence, for the entire takeoff phase the time period for completion is 129.176 seconds, while a horizontal distance of 1447.719 meter is travelled.

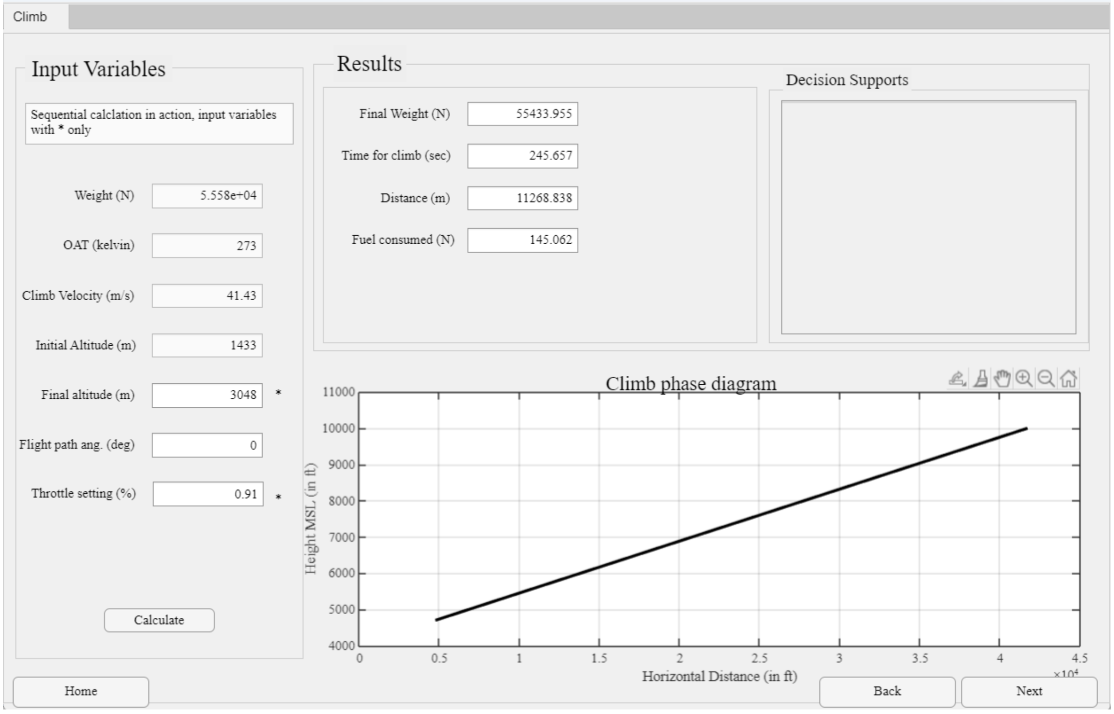

Figure 4.15: GUI for Climb Calculations

For the calculation of climb phase as shown in, the values for weight of climb, climb velocity and initial altitude passed from takeoff phase calculations and while remaining are included as user inputs. Specific input for a climb, such as the final altitude, the throttle setting, and the flap setting, can be varied but are set to default values during initialization.

At throttle setting of 0.91, the aircraft climbed from initial altitude 1433 m to final altitude of 3048 m in 245.657 sec, covering a distance of 11268.838 m horizontally, while consuming 145.062 N of fuel. This process was carried out at a constant speed of 41.43 m/s.

Similar to the climb phase, certain values were passed on from climb to the cruise phase, and few cruises specific values can be altered as per user which are initially set to default values.

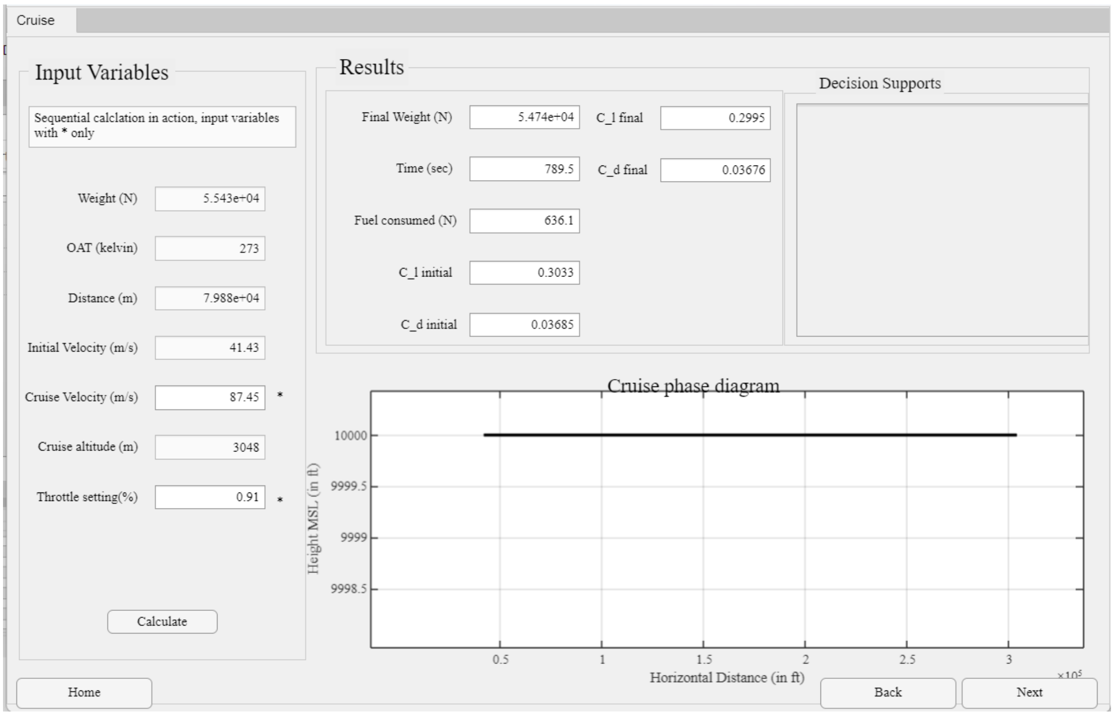

Figure 4.16: GUI for Cruise Calculations

At throttle setting of 0.91, the aircraft was accelerated from initial velocity of 39.82 m/s (velocity at the end of climb) to the cruise velocity of 87.45m/s. The aircraft cruise at a constant altitude of 3048 meters, and the distance to be traveled was 79880 meters extracted from the database for distance in between departure and destination airports. The phase had a fuel requirement of 636.1 N, while the phase was completed in 789.5 seconds to travel the required distance.

After extracting the inputs passed on from cruise phase and entering the descent specific value, the calculation proceeded as shown in Figure 4.17. At idle throttle setting (0.51), the aircraft descended from initial altitude 3048 m to final altitude of 2751 m in 42.557 sec and covering a distance of 4328.747 m horizontally. This process was carried out at a constant speed of 87.45 m/s.

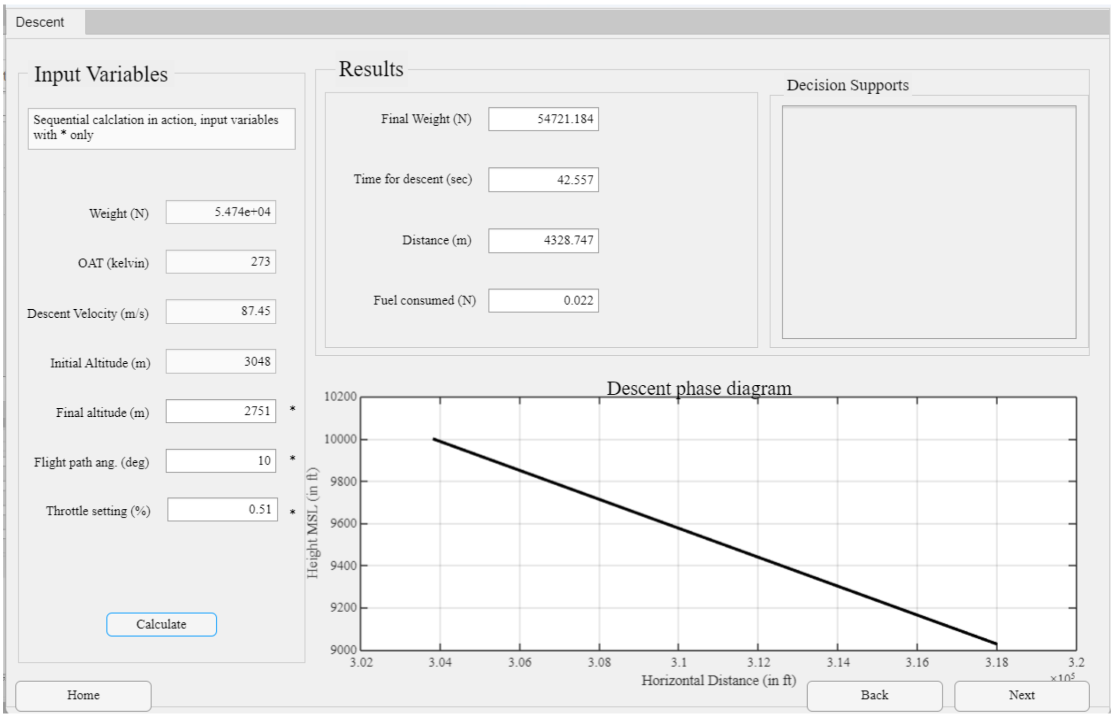

Figure 4.17: GUI for Descent Calculations

The landing phase at VNJS begins at an altitude 2751 m (i.e. 50 ft AGL) and comes to rest after covering total distance of 578.855 m in 14.347 sec. The maximum permissible weight was found to be 54731.881 N for ground run limitation.

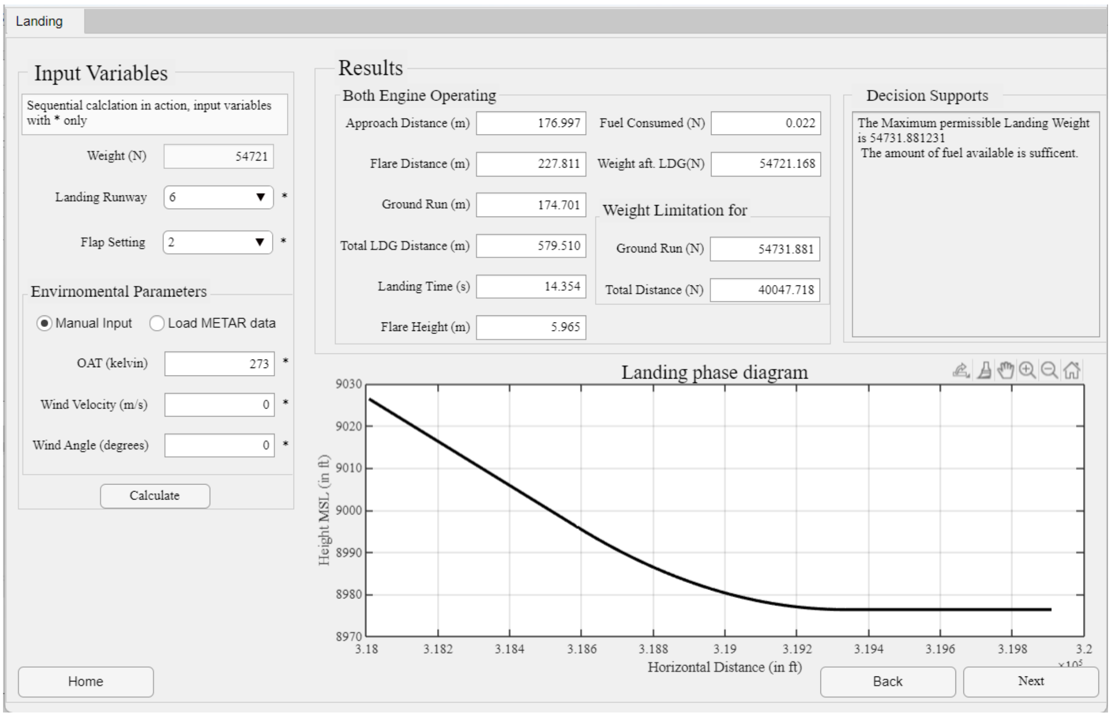

Figure 4.18: GUI for Landing Calculations

Hence, the total time required to cover the entire phase of flight was 20.35 min, consuming 931 N approx. amount of fuel. This can also be seen in the GUI output as shown in Figure B.3.

4.3 Limitations

- The program is designed for application in operations engineering within the ground calculations, but it is not currently a ready to use program/software and requires a series of refinements and validations before it can be used.
- Factors like runway slope effect, flap induced drag, ground effect for drag, etc. are taken under consideration during mathematical formulation. However, the corresponding validations are yet to be carried out.
- Data extraction from performance charts was done manually. However, the scales of the graphs were higher and slightest offset while locating the actual data could lead to larger deviation from the actual value. This might have added to the existing error tendencies in calculated values.
- The tool is based on analytical equations which again are simplified through numerous assumptions. These assumptions cause the calculated value to deviate from actual values of parameters.

4.4 Problem Faced

The problems faced during the project are as follows:

- Apart from the factors like OAT, altitude, wind conditions, etc., that we considered for our calculations, the actual flight parameters are impacted by many other factors. It is challenging to consider every one of them. Thus, the approximations are made considering the most influencing ones.
- Simulated flight scenarios were to be referred for validation of climb, cruise and descent phase of flight which are generally unreliable than manufacturers published charts.

4.5 Budget Analysis

Table 4.25: Budget Analysis

S. No.	Particulars	Cost
1	X-Plane 11 License	Rs. 8,000
2	DHC-6 X-Plane Model	Rs. 3,000
3	Transportation	Rs. 5,000
4	Documentation	Rs. 2,000
	Total	Rs. 18,000

The project was mostly based on computing and code development such that the major driving factor to the budget distribution of the project included costs involved in validation. This included charge for X-Plane 11 license (for $59.99 USD) along with additional cost for purchase of DHC-6 Series 300 aircraft compatible for the X-Plane version (for $30 USD) required for validation using mock flight scenarios. Additionally, other expenses included cost for transportation and documentation.

CHAPTER FIVE: CONCLUSION AND FUTURE ENHANCEMENT

5.1 Conclusion

The study aimed to enhance the efficiency of flight procedure management, fuel utilization, and flight feasibility assessment for specific circumstances through mathematical models for performance calculation. A tool was developed using analytical techniques for estimation of operational requirements and performance calculation for different phases of flight which includes decision-making aids that consider the constraints imposed by the airport, aircraft, and regulations to facilitate flight operations.

For the tool, a database for ten airports in Nepal was collected, based on type (international/domestic & non-STOL/STOL) and air-traffic mobility trends [22] while, data for DHC-6 and ATR-42 were collected for aircraft database [20], which can be further extended when necessary. Moreover, regulatory requirements were collected for STOL operation for generating decision aids. The tool developed integrated sequential and non-sequential execution for all phase of flight, with additional features for point performance calculations for climb, descent as well as glide at both engine failures with inclusion of decision logical sequences. A GUI was developed for the end-user, which includes the interface for every phase of flight for a specific route and the options that provide graphs and the variation of several dynamic parameters.

The results generated from the tool were validated against the performance charts included in the AFM of DHC-6, series 300 for takeoff, landing and rejected takeoff condition for which the deviations obtained were within 3%. The remaining phases of flight (i.e., climb, cruise and descent) were validated using simulated flight scenarios as well as manufacturer's supplementary charts where the discrepancies obtained were within justifiable limits. The validated performance parameters obtained through the program were then tested against imposed aircraft, airport as well as regulatory limitations to generate necessary decision aids to help make informed decisions and plan flights efficiently.

5.2 Scope for Future Enhancement

This project presented a decision support model for STOL operations based on 2-DOF point mass assumption validated for DHC-6 twin otter aircraft. There are still some limitations and shortcomings that could be addressed by future researchers which may hold scope for further enhancements.

- The tool developed is limited for STOL operations specific to DHC-6, such that the tool can be further extended for non- STOL operations with inclusion of regulatory information as well as other aircrafts besides DHC-6 Twin otter.
- One engine inoperative and other emergency failure cases could be integrated extending for other phases, which currently has only been included only for take-off phase.
- Effect of airport slope, flap induced drag, ground effect for drag, though integrated hasn't been validated for the current model. Additionally, effect of stability and control surfaces, runway surface effect could also be integrated with proper validation
- Integration of 3D terrain data for obstacle and flight path generation could be done for generating KML files as output aiding better visualization of flight paths rather than two dimensional plots.

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APPENDICES

APPENDIX A: FORMULAE FOR CLIMB CALCULATIONS

A.1 Climb mission

$$\text{Thrust Required}(T_r) = \frac{1}{2}\rho V^2 S\, C_d \quad (A.\ 1)$$

$$\text{Power Required}(P_r) = T_r V \quad (A.\ 2)$$

$$P_{max2} = 0.932825 P_{max} \sqrt[0.739667]{\frac{rho}{\rho}} \quad (A.\ 3)$$

$$\text{Power Available}(P_a) = \eta_{pr}\eta_{pu}P_{max2} \quad (A.\ 4)$$

$$\text{Thrust Available}(T_a) = \frac{P_a}{V} \quad (A.\ 5)$$

$$\text{Specific Excess Power} = \frac{(P_a - P_r)}{W} \quad (A.\ 6)$$

$$\text{Time} = \int_{\text{initial altitude}}^{\text{final altitude}} \left(\frac{\text{altitude}}{\text{specific excess power}}\right) \quad (A.\ 7)$$

$$\text{Fuel} = \text{Power available mean} * \text{Time} * \text{sfc} \quad (A.\ 8)$$

$$\text{Distance} = V * \text{Time} * \cos(\theta) \quad (A.\ 9)$$

A.2 Climb point

Calculation of ROC and AOC:

$$\text{Specific Excess Thrust} = \left(\frac{(T_a - T_r)}{W}\right) \quad (A.\ 10)$$

where,

$$AOC = \text{specific excess thrust}$$

$$ROC = \text{specific excess power}$$

For maximum ROC

$$V_{max} = \sqrt{\left(\frac{2W}{\rho S}\right)\sqrt{\frac{K}{3 * c_{d0}}}} \quad (A.\ 11)$$

$$\left(\frac{L}{D}\right)_{max} = \left(\frac{1}{\sqrt{4Kc_{d0}}}\right) \quad (A.\ 12)$$

$$ROC_{max} = \left(\left(\frac{\text{Power available}}{W}\right) - \left(\frac{1.155V_{max}}{\left(\frac{L}{D}\right)_{max}}\right)\right) \quad (A.\ 13)$$

APPENDIX B: GUI FOR DSS

GUI pages not included in the case study at section 4.2 are as shown below:

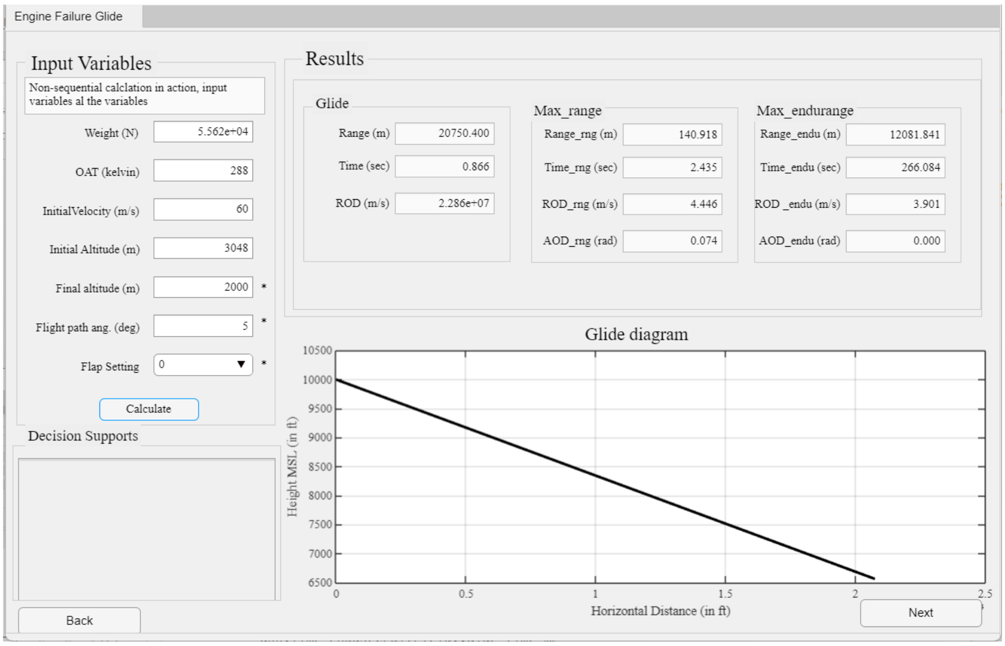

Figure B.1: GUI for Engine Failure Glide

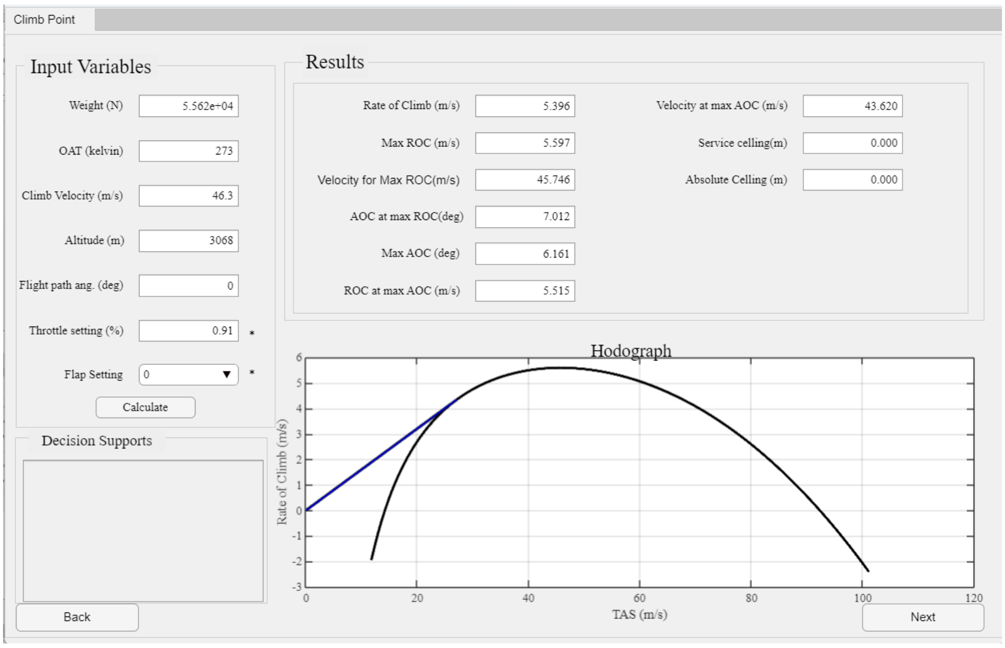

Figure B.2: GUI for Climb Point Calculation

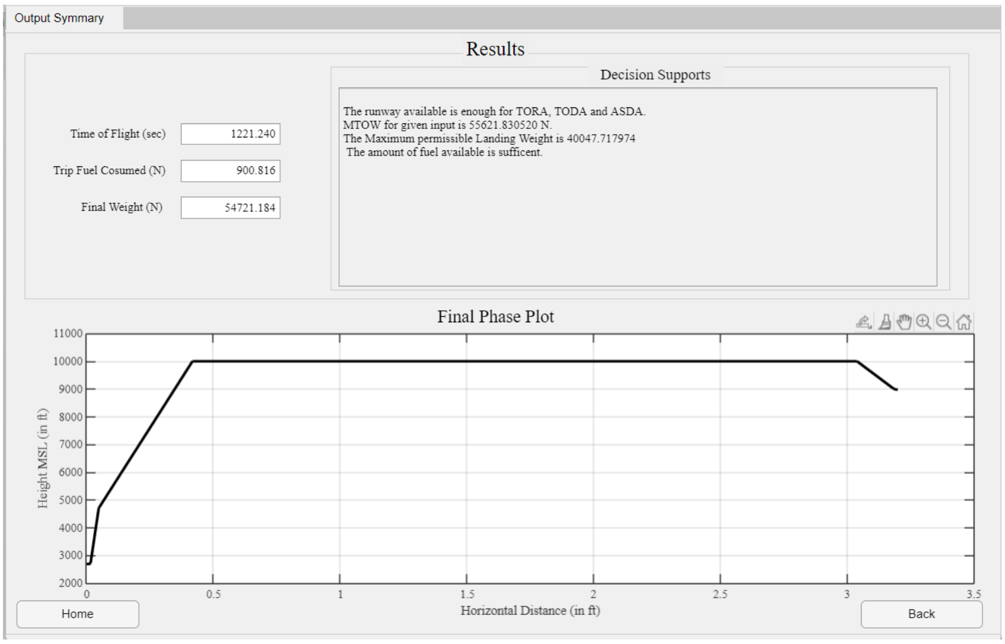

Figure B.3: GUI for Final Output Summary