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Development of Electronic Flight Bag Application for Small Turboprop Aircraft Weight and Balance Calculation

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Abstract

Nowadays, many airlines in modern aviation utilize an Electronic Flight Bag (EFB) during flight to replace traditional paper-based systems. Considering the importance of aircraft weight and balance calculation to flight operations, the flight mission of X-123 (a small turboprop aircraft) and the current EFB market, research on weight and balance application development of X-123 on EFB in Indonesia is conducted. The research aimed to develop the application according to Indonesian regulations and to examine the weight and balance characteristics of X-123 through several simulations in a programming language, Python. Furthermore, Staff Instruction 8900 - 3.3 is analyzed to identify the factors that should be considered in EFB development. The global architecture design and substantial features are, then, proposed as an initial EFB development. In the global architecture design, the utilization of a gateway becomes important as a connection between the EFB developer and the client, providing aircraft data changes flexibility to the client. Moreover, the calculation formula is completely discussed in the calculation modules as a substantial feature and implemented in the simulation. According to simulation results, the payload weight and payload distribution changes can affect significantly the CG location. It is recommended to weigh and assign the payload before flight to ensure flight operation safety. In addition, the proposal of the architecture design and substantial features can be used as a reference and further developed by the Indonesian aviation companies.

Keywords: EFB Development, Weight and Balance Calculation, Weight and Balance Characteristics, Small Turboprop Aircraft

Abstrak

Pengembangan Aplikasi EFB untuk Perhitungan Berat dan Kesetimbangan Pesawat pada Pesawat Kecil Bermesin Turboprop: *Saat ini banyak maskapai penerbangan modern yang menggunakan Electronic Flight Bag (EFB) selama penerbangan untuk menggantikan sistem tradisional berbasis kertas. Dengan mempertimbangkan pentingnya perhitungan berat dan keseimbangan pesawat terhadap operasi penerbangan, misi penerbangan X-123 (pesawat turboprop kecil), dan pasar EFB saat ini, maka penelitian tentang pengembangan aplikasi berat dan kesetimbangan pada pesawat X-123 pada EFB di Indonesia dilakukan. Penelitian ini bertujuan untuk mengembangkan aplikasi tersebut sesuai dengan peraturan di Indonesia dan menguji karakteristik berat dan keseimbangan X-123 melalui beberapa simulasi dalam bahasa pemrograman, Python. Selanjutnya, Staff Instruction 8900 - 3.3 dianalisis untuk mengidentifikasi faktor-faktor yang harus dipertimbangkan dalam pengembangan EFB. Rancangan arsitektur global dan fitur-fitur penting kemudian diusulkan sebagai pengembangan awal EFB. Pada rancangan arsitektur global, pemanfaatan gateway menjadi penting sebagai penghubung antara pengembang EFB dengan klien sehingga memberikan fleksibilitas perubahan data pesawat kepada klien. Selain itu, formula perhitungan dibahas secara lengkap dalam modul perhitungan sebagai fitur penting dan diimplementasikan dalam simulasi. Berdasarkan hasil simulasi, perubahan berat muatan dan distribusi muatan dapat memengaruhi lokasi CG secara signifikan. Operator pesawat X-123 disarankan untuk menimbang dan mengatur posisi penumpang dan kargo sebelum penerbangan untuk memastikan keselamatan operasi penerbangan. Selain itu, proposal desain arsitektur dan fitur-fitur yang substansial dapat digunakan sebagai referensi dan dikembangkan lebih lanjut oleh perusahaan penerbangan Indonesia.*

Kata Kunci: *Pengembangan EFB, Perhitungan Berat dan Kesetimbangan Pesawat, Karakteristik Berat dan Kesetimbangan Pesawat, Pesawat Kecil Bermesin Turboprop*

1. Introduction

Weight and balance (WAB) calculation is critical for flight operation safety since it can affect the performance and handling, particularly stall speed, take-off, and landing distance, climb performance, and cruise performance. Improper weight and balance calculation may lead to serious safety problems, such as tail strikes, run-way overruns, and reduced handling characteristics [1]. A remarkable accident due to weight and balance errors was that of Fine Air Flight 101 in 1997. The aircraft encountered a tail-heavy attitude during take-off and stalled shortly after. It crashed into the ground, resulting in a casualty of five people. According to the NTSB investigation, the changing of cargo position produced a more aft CG and consequently resulted in an incorrect stabilizer trim setting [2].

A similar accident also occurred on Air Midwest Flight 5481 in 2003. A Raytheon (Beechcraft) 1900D, doing business as US Airways Express, crashed into US Airways' maintenance hangar a few minutes after take-off from runway 18R at Charlotte-Douglas International Airport (CLT), Charlotte,

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North Carolina. Impact forces and a post-crash fire destroyed the aircraft. Among the accident victims, there were 21 casualties on board, while a person on the ground received minor injuries. According to the investigation, two primary factors contribute to the accident cause. Firstly, a wrong assumption of the average payload weight causes an incorrect weight calculation, resulting in overweight at take-off. Moreover, it also changed the CG position, which exceeded a certified aft limit. Secondly, incorrect elevator rigging from maintenance activity rendered a reduction of downward elevator movement, causing uncontrollable in the pitch axis [3].

According to both accidents, the payload weight shall be calculated accurately, ensuring the aircraft weight is below its maximum allowable weight. Weight calculation errors can change CG position and cause unbalanced payload distribution. Furthermore, the CG position from the balance calculation should be within the certified CG envelope. If the CG is too far forward (nose-heavy), an increase in the downward tail load is required to maintain flight level, resulting in a higher angle of attack of flight and drag increases. On the contrary, the farther aft CG position causes aircraft instability and difficulty in recovering from a stall [4].

In addition, a study revealed that 22.3% of passenger flights have incorrect load sheets, according to aircraft accident data from 1997-2004 [5]. It is followed by CG exceeding the aft limit by 19.4%. The third weight and balanced error is overweight at take-off, which accounts for 18.4%.

Nowadays, many airlines exercise manually or heavily depend on the experiential knowledge of ramp leaders with some ambiguous guidelines in the load planning process, causing a bottleneck to the operational efficiency of airlines on the ground [6]. Furthermore, the manual processing method requires a lot of time and may still cause a calculation error due to misread graphs or tables. A software-based method for calculating the aircraft weight and CG is a solution to tackle those problems.

Following load planning, the procedures of aircraft loading are different between freight aircraft and passenger aircraft. For instance, the aircraft loading of passenger aircraft consists of boarding passengers, loading and unloading baggage, loading and unloading cargo, catering supplies, and cleaning of aircraft [7]. In practice, flight operators estimate the passenger weight and use the actual weight for baggage during aircraft loading [8]. However, assuming passenger weight according to the average passenger weight stipulated by regulators consequentially compromises the safety margins of aircraft performance, due to growing passenger weight [9].

On the other hand, aircraft X-123, a small turboprop aircraft, has entered the commercialization stage in 2021. It is designed to carry 19 passengers and fulfill various mission requirements such as flying to isolated areas, troop transportation, medical evacuation, and cargo transportation. Considering the flight mission, the WAB calculation might be handled directly by the pilot as part of the responsibility in the aircraft operation as required in CASR Part 91, article 91.3 [10], demanding a complete understanding of the WAB characteristics of the aircraft. Regarding the aircraft loading, a challenge arises in determining the procedure for loading the payload into the aircraft while respecting the WAB restrictions.

Along with the advanced technology development in the aviation industry, the utilization of Electronic Flight Bags (EFBs) by airlines has become prominent during flights. An EFB is a device, or combination of devices, that generally replaces the paper-based system in the conventional pilot’s flight bag by actively displaying EFB applications [11]. It provides several advantages such as improving access to necessary information, increasing efficiency by eliminating reliance on printed paper, and automating aircraft performance calculations to reduce fuel costs [12]. Although many EFB applications are available in the market, the applications exist for most types of foreign aircraft. Reprogramming the application is required to change data for new types of aircraft [13]. Furthermore, there are no such EFB solutions developed by Indonesian companies. Considering the massive usage of EFB in the future, a study of EFB development in Indonesia becomes necessary for the Indonesian aviation industry.

In conjunction with the importance of WAB, the advantages of EFB, and the current EFB market condition, research on WAB application development of X-123 on EFB in Indonesia is conducted. The research aims to develop the application of WAB calculation on EFB according to Indonesian regulations. Furthermore, several simulations are undertaken, in a programming language, Python to implement the

WAB calculation formula and examine the WAB characteristics of X-123. The contribution of this research is to provide the global architecture design and essential features of the application as an EFB initial development that can be further developed by an Indonesian company. In addition, the simulation results can be used as a reference in developing aircraft loading procedures for X-123.

2. Research Methodology

The flowchart of the research methodology is provided in Figure 1. The initial approach to handle the research is by studying the literature related to EFB development and the WAB calculation. Furthermore, Staff instruction 8900 - 3.3 is analyzed to establish the concept of architecture design of the WAB application and the essential features of EFB. Aircraft data such as arm balances, and WAB limitations is, then, collected from the Aircraft Flight Manual (AFM). Moreover, several variables of flight conditions are determined and modeled in a programming language, Python. The model is, then, tested to ensure that it works well according to requirements. After establishing a proper model, several flight conditions are simulated. The result of the simulation is the aircraft's take-off weight and aircraft center of gravity.

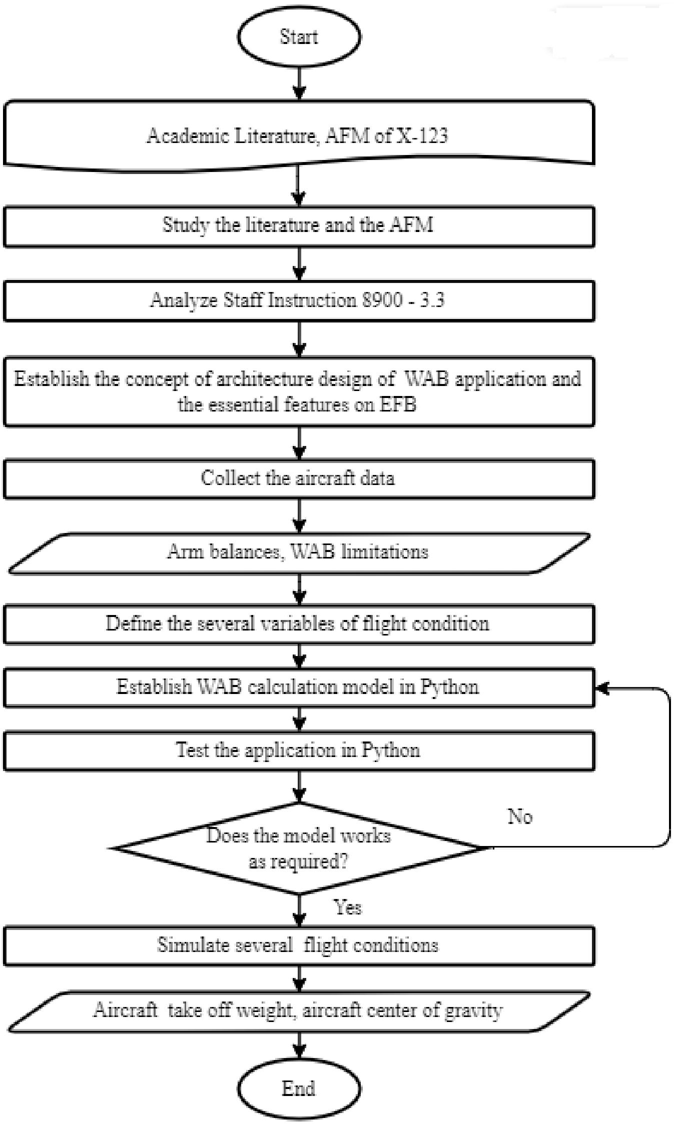

Figure 1. Flowchart of research methodology

This research is divided into two parts: the establishment of global architecture design and essential features of the application, and the WAB simulation of X-123. Before discussing those parts, the WAB calculation formula, and regulatory framework related to EFB development must be reviewed. The review is provided as follows.

2.1. WAB Calculation Formula

The theory of aircraft weight and balance is commonly discussed in various books and journals. It also has been regulated due to its importance to flight safety. However, regulatory authorities do not prescribe aircraft weight definitions used in flight operations. There are subtle differences in what is included (or excluded) in various aircraft weight definitions depending on the weight accounting procedures used by manufacturers and operators. The typical breakdown of the aircraft weight definitions is presented in Figure 2 [14].

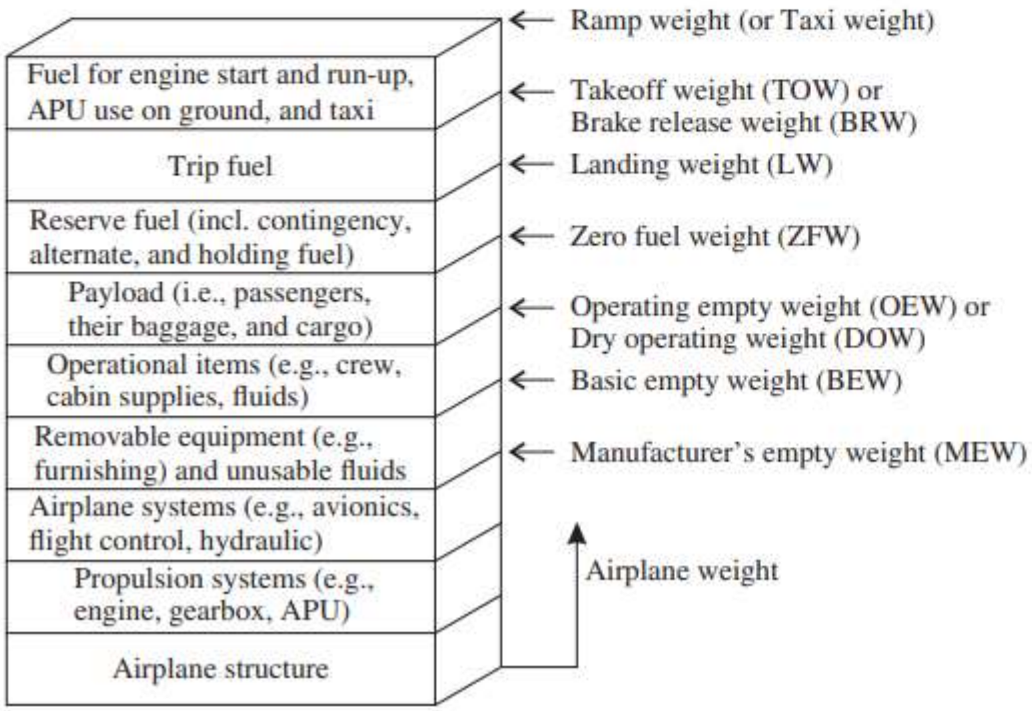

Figure 2. Typical breakdown of aircraft operational weights [14]

Zero Fuel Weight (ZFW), Landing Weight (LW), and Take Off Weight (TOW) are essential in the weight calculation for flight operation. It can be defined as an aircraft's gross weight depending on the fuel weight which can be written as [15].

$$Weight = \begin{cases} TOW & \text{if } Fuel = \text{TOF} \\ LW & \text{if } Fuel = \text{TOF} - \text{TripF} \\ ZFW & \text{if } Fuel = 0 \end{cases} \tag{1}$$

Where weight denotes aircraft gross weight, while tripf denotes trip fuel.

The operator shall refer to the maximum weights recorded in the Airplane Flight Manual (AFM). It is known as certified weights, which can be less than the design structural limit weights for operational or financial reasons. These weights are specific to individual aircraft and can be increased to the corresponding structural limit weights. Furthermore, the TOW cannot exceed the allowable take-off weight, a limiting weight caused by the aircraft's performance under a particular operating condition (which includes altitude, ambient temperature, wind, and runway surface conditions). It also applies to LW, in which LW cannot exceed the allowable landing weight imposed by aircraft performance [14].

In the balance calculation, the CG position can be expressed as *X*, an accurate measure from the reference datum in inches or meters. It can be calculated using Equation 2.

$$X_{CG} = \frac{\sum_h W_h X_h + W_{OE} X_{OE}}{\sum_h W_h + W_{OE}} \tag{2}$$

Where:
X_{CG} = the distance to the aircraft's CG

X_h = the distance to the CG of the h^{th} component
X_{OE} = the distance to the airplane's CG in the operating empty condition
W_H = the weight of h^{th} component (e.g., fuel, passengers, baggage, cargo)
W_{OE} = the operating empty weight

%MAC, on the other hand, is a more common term to express an aircraft's CG than X which is defined as.

$$\%MAC = \frac{(X_{CG} - X_{emac})}{\bar{\bar{c}}} \times 100 \tag{3}$$

Where:
%MAC = the percentage of CG location from the leading edge of the MAC
X_{emac} = the distance measured from the datum to the leading edge of the MAC
$\bar{\bar{c}}$ = the length of MAC

The illustration of X and %MAC is provided in Figure 3.

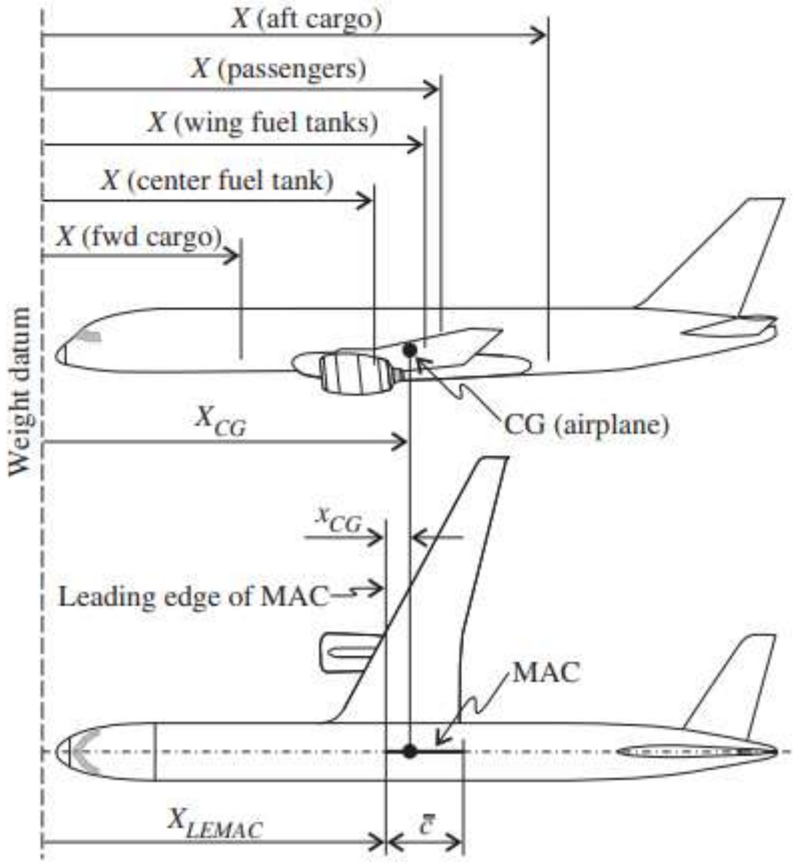

Figure 3. Illustration of X and %MAC [14]

2.2. Regulatory Framework

Before developing the application, a regulation review must be conducted to understand all important factors that should be considered by the EFB developer. Since the application will be most likely used in Indonesia, an Indonesian regulation, Staff Instruction (SI) 8900 – 3.3 subject Manual on Electronic Flight Bags (EFBs) is analyzed [16]. In addition to the SI regulations, several regulations related to aviation safety are also discussed.

2.2.1. Software Considerations

An assessment of the human-machine interface (HMI) should be conducted in the EFB development. Some factors that should be considered are summarized below.

1. A consistent user interface should be provided in the EFB system, including, but not limited to, data entry methods, color-coding philosophies, and symbology
2. Ease of access to common functions, consistency of symbols, terms, and abbreviations, legibility of text, methods of interaction, and management of multiple applications should be addressed
3. “Red” color should be used only to indicate a warning level condition. “Amber” should be used to indicate a caution-level condition. Other colors may be used for items not intended as warnings or cautions, provided the colors used differ sufficiently from those prescribed to avoid confusion.
4. The EFB user should be able to obtain information about an application's status when it is fully or partially disabled, or not visible or accessible to them. Prioritizing these EFB faults and status may be desirable.
5. The EFB application should not accept incorrect user-entered data format or type required by the application. An error message should be provided that indicates the incorrect entry and the expected type of data.
6. The system should provide feedback to the user when user input is accepted. If the system is occupied and cannot process inputs immediately that preclude immediate processing of user input (e.g., calculations, self-test, or data refresh), the EFB should display a “system busy” indicator (e.g., clock icon).
7. If the document segment cannot be viewed in its entirety in the available display area, such as during zooming or panning, off-screen content should be indicated. It should be evaluated based on the application and intended operational function.
8. Software applications must have adequate security measures to ensure data integrity, preventing unauthorized data manipulation.
9. The validity and updatability of the software application and the database installed on EFB must be easily determined by the user.

2.2.2. Paper Removal

According to Chapter 8 of SI 8900 – 3.3, an operator can choose to start a paperless flight deck operation without any paper backup or a combination of solutions with limited paper backup depending on the intention of the operation. The EFB approval may be issued if the EFB is reliable and/or functions to be acceptable based on validation data. The detailed EFB evaluation is discussed in Chapter 3.

According to CASR 121.697, three copy documents shall be in the cockpit: load manifest, dispatch release, and flight plan [17]. Among those documents, the load manifest is the document related to the aircraft weight and balance calculation. According to CASR 121.693, the load manifest must contain some information as follows:

1. The weight of the aircraft, fuel and oil, cargo and baggage, passengers, and crewmembers.
2. The maximum allowable weight for that flight.
3. The total weight is computed under approved procedures.
4. Evidence that the aircraft is loaded according to an approved schedule that ensures that the center of gravity is within approved limits.
5. Names of passengers, unless such information is maintained by other means by the certificate holder.

Furthermore, the load manifest must be prepared and signed for each flight by employees who have the duty of supervising the loading of aircraft and preparing the load manifest forms or by other qualified persons authorized by the certificate holder as required in CASR 121.665.

In general, a load sheet is attached to meet the requirement of CASR 121.693. The load sheet also known as the load and trim sheet has a function to ensure the CG is within the operational envelope [18]. The load control unit has the responsibility to calculate the aircraft weight and balance based on load weight distribution on the load sheet referring to the airline’s standard operational procedure [19].

2.2.3. EFB Management

The operator must appoint at least one person as an EFB manager (e.g., ops director), that have a comprehensive understanding of the overall EFB system and responsibilities within the operator’s management structure according to Chapter 7.3 of SI 8900 – 3.3. However, it may require more than one person to support the EFB management system for complex EFB systems. Furthermore, EFB management is the key link between the operator, the EFB systems, and the EFB developers. It has several duties related to hardware and software configuration management. Firstly, it should be ensured that no unauthorized software is installed. Secondly, a valid version of the application software and current data packages must be installed on the EFB system. The operator must provide a procedure to check the data content before releasing it for operational use. Thirdly, it should be ensured that software applications supporting functions(s) not directly related to flight operations (e.g., web browser, e-mail) do not adversely impact the EFB operation.

2.2.4. Electronic Signatures

According to Chapter 7.2 Article B, a signature may be required to signify acceptance or to confirm the authority. To be accepted as an equivalent to a handwritten signature, electronic signatures should have the same degree of security as a handwritten one.

2.2.5. Software Evaluation

There are two primary considerations in evaluating the application: the performance of the Graphical User Interface (GUI) and the performance of the application. The GUI must be well-designed to reduce the risk of data entry errors by the user. The design should follow the guidelines as described in section III.1. However, some supplemental guidelines may follow the guidelines in Appendix A of SI 8900 – 3.3. Furthermore, the calculation performance of weight and balance must be tested. The results provided by the application must be consistent with the approved data in AFM. Moreover, the system behavior must be sensible in case incorrect values have been entered. Finally, the integration test must be conducted, ensuring the application runs in the EFB environment without any issues.

3. Results and Discussion

3.1. The Concept of Application Architecture Design

To establish the application, architectural design must be established first. It is defined as the process of describing a collection of hardware and software components and the interfaces to establish the framework for the application system development. It is proposed to have a global architectural design that describes the connection between the developer's environment and the airline's environment. The global architecture of the application is presented in Figure 4.

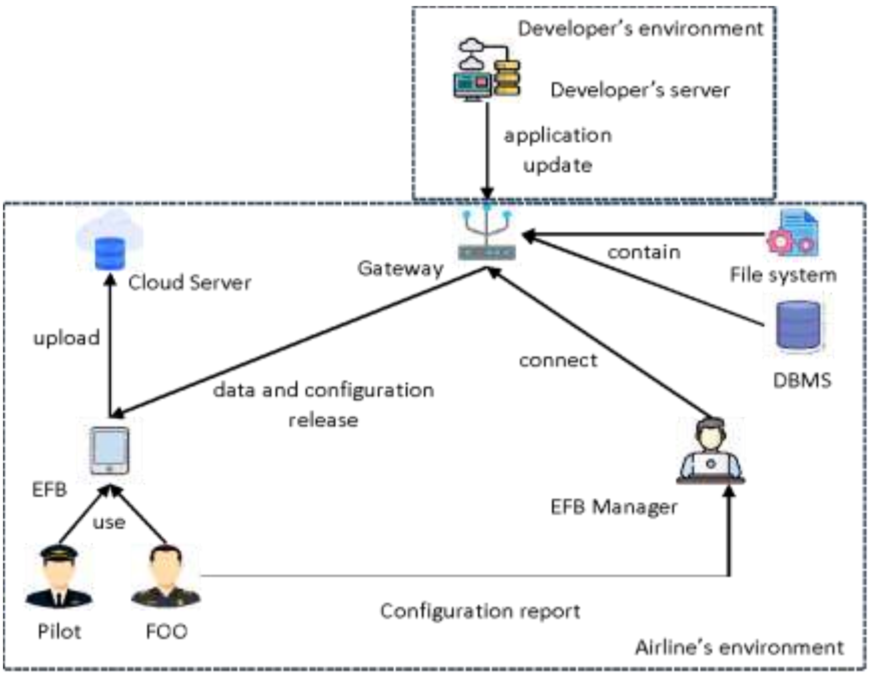

Figure 4. The Global Architecture Design of the Application

The software and roles of each actor can be described below.

1. Developer's server. This server connects to the gateway of each customer (airline company). It contains the data of each airline such as the general information of the company and its EFB subscription. The developer should appoint its delegation (can be from the customer support division) to manage the server, application update, and the EFB subscription requested by the customers.
2. Gateway. Each customer has its gateway. This gateway has a function to connect the server with the database system of the customers. It contains the file system (e.g., configuration of the gateway and database management system (DBMS). The DBMS can contain several data related to the customer which is used in the EFB configuration such as fleet management (registration number, type, and model of aircraft), list of pilot's names, and special configuration of the EFB.
3. EFB Manager. A person or more must be appointed by the airline company as an EFB manager. The duties are to assign the EFB application to the PED, manage the subscription, configure the EFB setting, update the application, and release the data needed by the application. This concept aligns with the regulation SI 8900 – 3.3, Chapter 7.3 as aforementioned.
4. Pilot and FOO. The pilot is the main user of the EFB. However, FOO can prepare and set up the EFB before the flight. In the case of the WAB application, FOO can prepare the calculation of weight and balance and sign it. The calculation is, then, verified and approved by the pilot. After signing the calculation document, it will be uploaded to the cloud server of the airline.
5. Cloud server. The server is dedicated to filing all flight documents from the EFB application. It is necessary to reduce the use of the paper at the station. All files can be saved securely in the cloud if there is a Wi-Fi or 3G/4G connection.

The present conceptual network may not represent a novel paradigm within the EFB industry. For instance, Airbus employs a gateway to establish a connection between its server to the client's server. However, Airbus has more advanced features where its EFB can be also integrated with the ground software. Nevertheless, the concept is sufficient for initial development since the aircraft performance calculation or WAB calculation can be undertaken in the EFB. In the future, the developer may expand its application features by integrating the application into the ground software.

In addition, this concept offers several benefits for the developer and the client. Firstly, the developer only needs to focus on the EFB development, adding more features or enhancing its reliability function. Secondly, the client can manage the aircraft data independently. In case of aircraft modification, the data on EFB can be changed directly by the client without asking the software developer. However, a procedure for data changes must be established to ensure only authorized changes take place to EFB functions as required in Chapter 7.3 of SI 8900 – 3.3.

3.2. Substantial Features

There might be several features in the application depending on the system design. However, it is important to discover the substantial features that should exist in the application. In this section, only features directly related to WAB calculation and paper removal on the cockpit are discussed.

3.2.1. Application and Database Update

It has a function to ensure the application and the database is up-to-date. In this case, the user must have an internet connection. The oldest version of the application and the database may affect the function of the application, especially the calculation function. Therefore, there should be information about the version of the application and database in use. Moreover, an "update" button must exist to update the current version.

3.2.2. Filling General Flight Information

This feature contains a dialog box that asks the user to input the general flight information. The information may vary depending on the airline's request. However, at least it should contain the pilot's name, departure airport, arrival airport, and aircraft registration number. The information is important to describe the basic flight information and to provide easy documentation while saving the calculation result. Moreover, it is recommended to have a user interface design like a load sheet in a paper-based system since it is more familiar to use.

In addition, the selection of aircraft registration numbers is necessary since an airline may have several fleets. After the selection, the aircraft version including the family, the type, the model, and the modification must be indicated in the application. It has a function to check whether the aircraft in use is correct or not. Furthermore, the calculation table including the balance arm data, weight limitation, basic empty weight, and aircraft layout must appear adjusted to the selection.

3.2.3. Calculation Modules

There are two modules proposed in this paper: allowable traffic load (ATL) calculation and WAB calculation. The first module aims to ensure that ATL does not exceed the weight limitations, either imposed by the aircraft's performance or maximum structural weight limitations.

To calculate the ATL, several inputs by the user are required: fuel weight in the left and right tank, trip fuel, maximum take-off weight imposed by the aircraft performance, and weight of the cabin crew. A warning message must appear if the total fuel weight exceeds the tank capacity or the weight difference between the left tank and the right tank exceeds the limit according to the aircraft data. Since small turboprop aircraft are very sensitive to weight changes, every item’s weight must be considered including aircraft manual and safety equipment. The data is retrieved from the database.

$$OEW = BEW + cabin\ crew's\ weight + fixed\ item's\ weight \quad (4)$$

Where:
BEW= Basic Empty Weight
BEW and Fixed item’s weight are retrieved from the aircraft database

Furthermore, the system must decide the regulated take-off weight (RTOW) and landing weight (RLW), which can be expressed as follows.

$$RTOW = minimum \begin{cases} TOW\ imposed\ by\ the\ aircraft\ performance \\ MSTOW \end{cases} \quad (5)$$

$$RLW = minimum \begin{cases} LW\ imposed\ by\ the\ aircraft\ performance \\ MSLW \end{cases} \quad (6)$$

After the decision, the system must choose the lowest value of allowable take-off weight imposed by MZFW, RTOW, and RLW to calculate allowable traffic load (ATL). It can be written as follows.

$$Allowable\ TOW = minimum \begin{cases} MZFW + TOF \\ RTOW \\ RLW + TripF \end{cases} \quad (7)$$

The ATL is formulated as.

$$OM = OEW + TOF \quad (8)$$

$$ATL = Allowable\ TOW - OM \quad (9)$$

Where OM denotes the operating mass of the aircraft.

To calculate the TOW, the user needs to input the weight and the distribution of the passenger. The TOW formula can be written as follows.

$$TOW = OM + \sum_{h} W_h \quad (10)$$

$$TOW \leq Allowable\ TOW \quad (11)$$

Where W_h is the weight of h^{th} component (e.g., fuel, passengers, baggage, cargo). The system must also provide a warning message if the TOW exceeds the allowable TOW as expressed by formula III.8. In addition, the system must calculate the aircraft CG with formulas (2) and (3). In the end, the visual illustration of the CG changes during the flight must be presented.

3.2.4. Signing the Load Sheet

There must be two signature columns in the application. The first one is for the flight operations officer (FOO) as the person who prepares the calculation (load sheet). The second one is for the pilot who approves the calculation.

Handwritten signatures are not recommended since it is cumbersome to use in the tablet even though many tablets support it along with the use of a stylus. Thus, it is proposed to use a QR code which requires a password to sign the load sheet. This method ensures that only the authorized person signs the document. After entering the password successfully, the QR code with the name of the person is generated. Furthermore, The QR code can be scanned by a person. Upon scanning, it will be redirected to a webpage. The webpage contains some information related to the signing document, for instance, the general flight information, the person who signed it, and the date and time of signing.

3.2.5. Saving, Reviewing, and Uploading the Load Sheet

Since the load sheet is attached to a load manifest document which should be carried out in the cockpit, a “save” feature must exist to store the load sheet in the PED’s memory. A “review” feature has a function to load the sheet during the flight if it is required. The last feature, is the “upload” feature, allowing the user to upload the load sheet in the airline’s cloud. The last feature is essential since the copy of the load manifest must be kept by the operator for at least three months as required in CASR 121.695.

3.3. Computational Test

A simple programming model was established for aircraft X-123 using the programming language, Python version 3.10 on a portable computer with an Intel(R) Core (TM) i5-9300H CPU processor (CPU @ 2.40GHz / 2.60 GHz and 8 GB RAM), on the Windows 11 operating system. Several simulations were conducted to demonstrate the calculation modules and analyze the WAB characteristics of the aircraft. In the programming model, the formulas of (1) – (11) were implemented. In addition, several assumptions must be determined before running some simulations. For instance, fuel consumption during flight affects the fuel carried on board. However, it is a function of aircraft speed, altitude, and wind conditions during flight. Thus, assuming fuel consumption is more straightforward instead of calculating it. Several assumptions and parameters related to the simulation are described in the following subchapters.

3.3.1. Aircraft Characteristics

In general, X-123 has the same WAB calculation as the aforementioned in the previous chapters. Nevertheless, the CG envelope of the aircraft uses an index unit to represent the moment relative to 25% MAC as the x-axis and the aircraft gross weight as the y-axis according to AFM. Since the CG results must be within the CG envelope, the index unit must be calculated. Thus, the formula II.1 can be modified as follows.

$$X_{CG} = \frac{\sum_h W_h (X_h - X_n) + W_{OE} (X_{OE} - X_n)}{\sum_h W_h + W_{OE}} \quad (12)$$

Where X_n is the distance to the CG of the 25% MAC. As a consequence of the formula, the value of X_{cg} is negative if the value of X_h or X_{oe} is in front of X_n. Additional weight limitations for the aircraft are provided in Table 1. In addition, an aircraft layout is presented in Figure 5 to provide the location of the seat and the cargo compartment.

Table 1. Weight limitations for the aircraft X-123

Limitation	Weight (kg)
MSTOW	6,700
MSLW	6,600
MSZFW	6,270
Fuel capacity in left/right tank	800
Maximum fuel imbalance weight	75
Maximum cargo weight	235

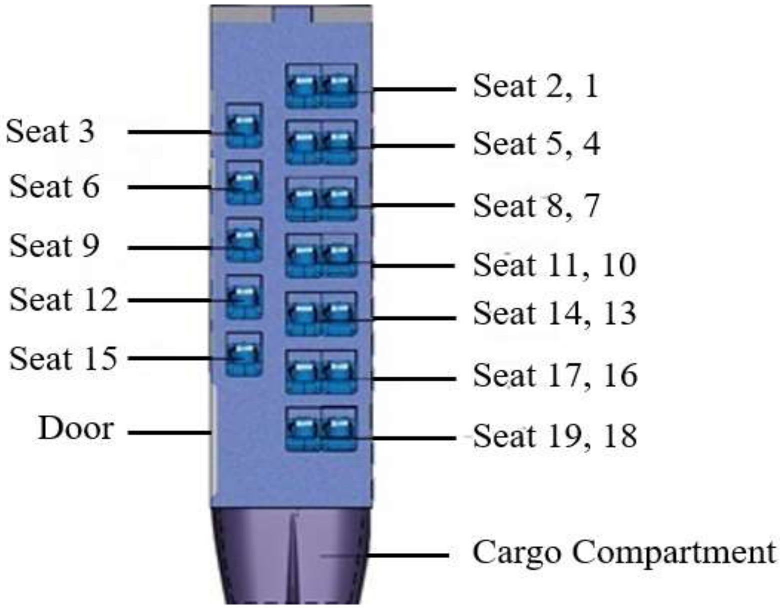

Figure 5. Aircraft Layout of X-123

3.3.2. Parameter Assumptions

In the simulation, the weight of each cabin crew is retrieved from AFM. The weight limitations are not imposed by aircraft performance, resulting in RTOW = MSTOW and RLW = MSLW. Moreover, the average passenger weight (including carry-on bags of 7.3 kg) refers to Staff Instruction 8900 – 3.4 [20]. The overall assumptions used in the simulation are outlined in Table 2.

Table 2. Assumptions in the simulation

Parameter	Assumption
Pilot's weight	77 kg
Second officer's weight	77 kg
Average passenger weight	71 kg
Taxi fuel	20 kg
RTOW	Equal to MSTOW
RLW	Equal to MSLW
Alternate fuel	Equal to trip fuel
Aircraft speed	160 kt
Fuel consumption	250 kg/h
Air distance	100 NM
Aircraft loading sequence	Fuel loading, cargo loading, passenger loading,

In addition, the fuel requirement is also assumed to be the same for all cases in the simulation. In general, it consists of trip fuel from the departure airport to the destination airport, fuel to land at the alternate airport (where required), and fuel to fly for 45 minutes at normal cruising fuel consumption as stated in CASR 121.639. Thus, the fuel carried on board can be formulated as follows.

$$Fuel\ on\ board = TripF + alternate\ fuel + 45\ minutes\ fuel + taxi\ fuel \tag{13}$$

The trip fuel can be calculated by the following formula.

$$TripF = \frac{air\ distance}{aircraft\ speed} \times fuel\ consumption \tag{14}$$

Using Formula III.10-III.11 and retrieving all necessary parameters in Table 2, the fuel on board is 520 kg.

3.3.3. Simulation Cases

In the simulation, six cases are examined with variables of payload weight, payload distribution, and weight combination of passenger weight and cargo weight. A set of random weight data is generated to demonstrate the actual condition before flight. The variables of the simulation are presented in Table 3.

Table 3. Variables of simulation

Variables	Simulation cases (unit: kg)					
	1	2	3	4	5	6
Seat 1	71	57	57	75	75	-
Seat 2	71	44	44	93	93	-
Seat 3	71	52	52	87	87	-
Seat 4	71	62	62	82	82	-
Seat 5	71	76	76	52	52	-
Seat 6	71	34	34	38	38	-
Seat 7	71	81	81	79	79	-
Seat 8	71	73	73	85	85	-
Seat 9	71	56	56	48	48	-
Seat 10	71	88	88	-	-	-
Seat 11	71	67	67	-	-	75
Seat 12	71	69	69	-	-	93
Seat 13	71	78	78	-	-	87
Seat 14	71	89	89	-	-	82
Seat 15	71	64	64	-	-	52
Seat 16	71	86	86	-	-	38
Seat 17	71	92	92	-	-	79
Seat 18	71	87	87	-	-	85
Seat 19	71	94	94	-	-	48
Cargo	-	-	235	-	235	-
Total payload	1,349	1,349	1,584	639	874	639

In the first case, the passenger weight refers to the standard average passenger weight according to SI 8900 – 3.4. The objective of the first case is to analyze the CG profile, starting from aircraft loading to the flight without any cargo. In the second case, a set of random passenger weight data with a mean of 71 kg and a standard deviation of 17.11 is generated to represent the actual passenger weight. The second case aims to compare the CG profile between the case with standard average passenger weight and the case with actual passenger weight. The variables of the third case are the same as the second case with an additional cargo of 235 kg, aiming to examine the effect of the additional cargo weight on the CG profile.

In addition, there are only nine passengers with a mean of 71 kg and a standard deviation of 19.74 in the fourth case. The passengers are assigned to occupy the seat from seat 1 (starting from the forward section of the aircraft). The goal is to check the effect of fewer passengers and passenger distribution on the CG profile. The fifth case has the same variables as the fourth case with 235 kg of additional cargo weight. It is purposed to test the combination of nine passengers and cargo to the CG profile. In the last case, the variables are the same as in the fourth case. However, the passenger occupation started from seat number eleven. The intention is to explore the CG profile due to the passenger distribution in the aft section of the aircraft.

3.4. Simulation Analysis

After determining the variables, several simulation cases were run. In the following tables, weight is given in kilogram and CG in % MAC. In addition, the symbols “a” and “b” are used to represent the forward and the aft CG limit due to confidentiality. The simulation results indicate that the aircraft weight is limited by RTOW with the allowable TOW of 6,700 kg for all cases. The simulation results are provided in Table 4.

Table 4. Simulation results

Case	TOW	LW	ZFW	CG TOW	CG LW	CG ZFW
1	6,648	6,491	6,147	b – 2.18	b – 2.33	b – 2.8
2	6,648	6,491	6,147	b – 0.07	b – 0.17	b + 0.51
3	6,883	6,726	6,383	b + 6.92	b + 6.55	b + 6.57
4	5,938	5,781	5,438	a – 0.28	a – 0.67	a – 1.72
5	6,173	6,016	5,673	b – 2.58	b – 2.75	b – 3.28
6	5,938	5,781	5,438	b + 2.28	b + 2.23	b + 1.99

3.4.1. Analysis of Case 1

According to the results, the TOW is less than the allowable TOW by 52 kg. It can be used to carry additional cargo such that the TOW is 6,700 kg. In the first case, it should be noted that the total payload weight is near the ATL. It demonstrates that the aircraft can carry full passengers with 520 kg of fuel. If the operator decides to add more fuel to add more air distance, some passengers must be removed from the flight to maintain the TOW below the allowable TOW. Furthermore, the problem arises when the actual average passenger weight is more than 71 kg. It may lead to overweight at the TOW. Thus, if the operator decides to use the standard average passenger weight, it is recommended to carry less than 19 passengers to provide more safety margin. In terms of aircraft CG, the profile is within the CG limit on the ground and during the flight, proving that the aircraft is safe for the intended mission. The CG profile for the first case is presented in Figure 6.

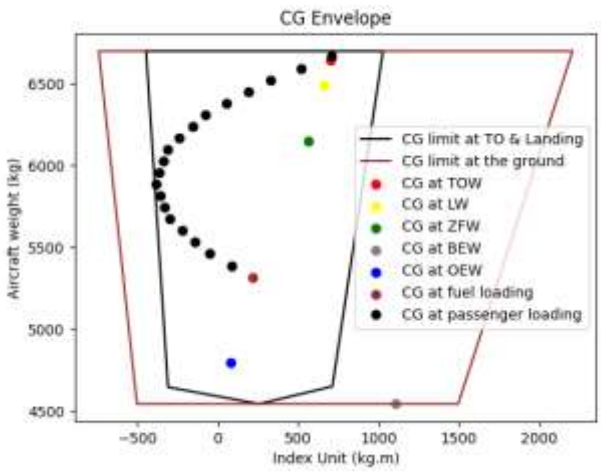

Figure 6. CG Profile for Case 1

3.4.2. Analysis of Case 2

In case 2, the results of ATL, TOW, LW, and ZFW are the same as in the first case. However, the CG results at TOW, LW, and ZFW are different, where it is moved to the aft limit. The CGTOW is near the aft CG limit during flight by 0.07% MAC. This condition is favorable for the operator since it can save more fuel. Nevertheless, the CG location near the aft limit increases the difficulty of pitch control by the pilot. Moreover, the operator should notice that the CG may exceed the aft CG limit depending on the weight and distribution of the passenger. For instance, the CGTOW exceeds by 0.09% of the aft CG limit if the passenger on seat 7 is exchanged each other with passenger 15. Considering that factor, it is recommended to weigh each passenger before a flight. A seat assignment may be required if the CG results of the initial distribution (distribution that relies on seat selection by passengers) exceed the CG limit during the flight. Setting the rigorous CG limit can be also a solution with the compensation of reducing payload weight. In terms of CG profile on the ground, the aircraft can be loaded safely without any issues. The CG profile for the second case is provided in Figure 7.

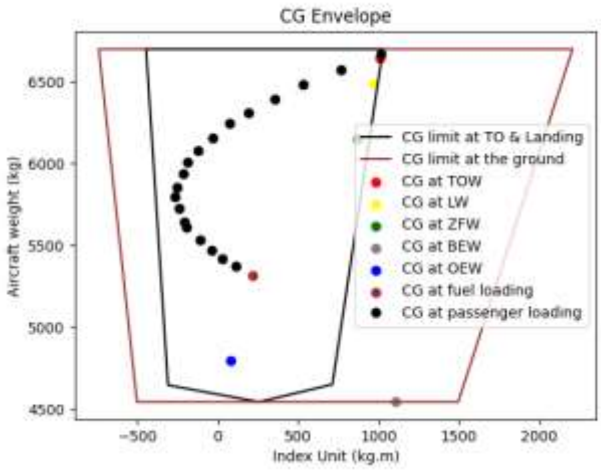

Figure 7. CG profile for case 2

3.4.3. Analysis of Case 3

In case 3, the TOW exceeds the allowable TOW by 183 kg due to an additional cargo weight of 235 kg from case 2. Furthermore, the additional cargo weight also causes the CG to exceed the aft limit by 6.92% MAC at TOW. If the cargo is a priority over the passengers, the passengers in seats 17, 18, and 19 must be removed to be within the CG envelope on the ground. However, this condition is still not satisfactory since the CGTOW is still outside the CG limit during flight. The passengers in seats 13 to 16 must also be removed to be within the CG envelope during the flight. However, this condition leads to a TOW of 6,313 kg, a decrease of 387 kg from the allowable TOW. It is not acceptable for the operator since it can reduce the income. To maximize the payload weight, several alternations must be conducted as follows.

1. The passenger is removed accordingly from the heaviest one until the weight is more than the cargo weight
2. The passenger is assigned to occupy seat 1 accordingly from the heaviest one

According to alternations, the TOW is 6,640 kg and the CG profile is within the CG envelope. However, passenger removal may not be practical since there may be passenger groups that cannot be separated. The CG profile during the flight for case 3 and the modification of case 3 are illustrated in Figures 8 and Figure 9.

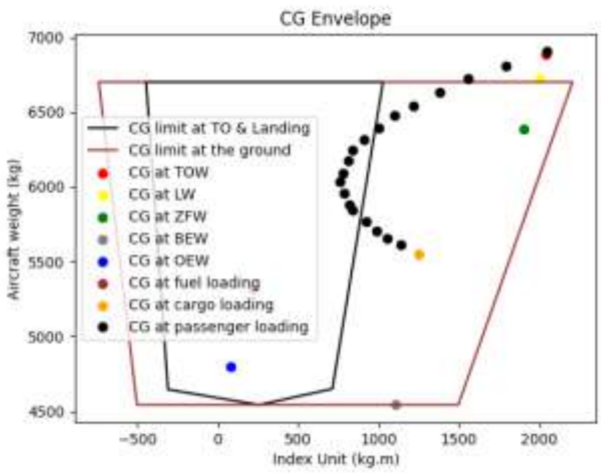

Figure 8. CG profile for case 3

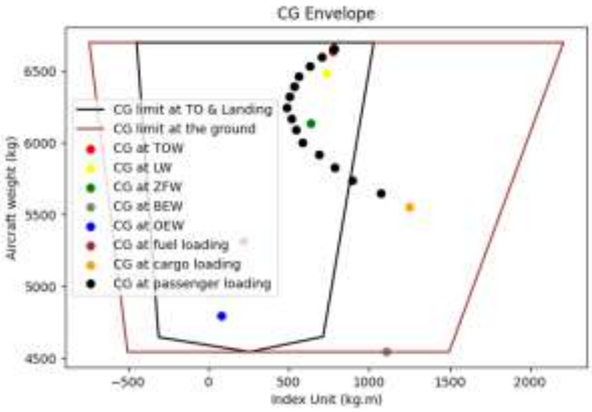

Figure 9. CG profile for the modification of case 3

3.4.4. Analysis of Case 4

In case 4, the TOW is less than the allowable TOW by 762 kg. It can be used to carry additional payload, either passenger or cargo. The result demonstrates that the CGTOW exceeds the forward CG limit by 0.28% MAC. In this case, the CGTOW will be near the forward CG limit if the passengers on seats 7, 8, and 9 are removed. Nevertheless, the CGLW and CGZFW are still outside the CG envelope according to the CG pattern in cases 1 - 4. Thus, the passenger distribution must be changed such that the CG during the flight is within the CG envelope. It is proposed to assign the passenger from seat 5 instead of from seat 1. Theoretically, the distribution causes a change of CG location to the aft CG limit. The CG results due to the distribution change are outlined in Table 5. The illustration of the CG profile without the distribution change and with the distribution change is provided in Figures 10 and Figure 11.

Table 5. CG results due to the change in passenger distribution

Parameter	Result
CG_{TOW}	a + 4.73
CG_{LW}	a + 4.8
CG_{ZFW}	a + 3.75

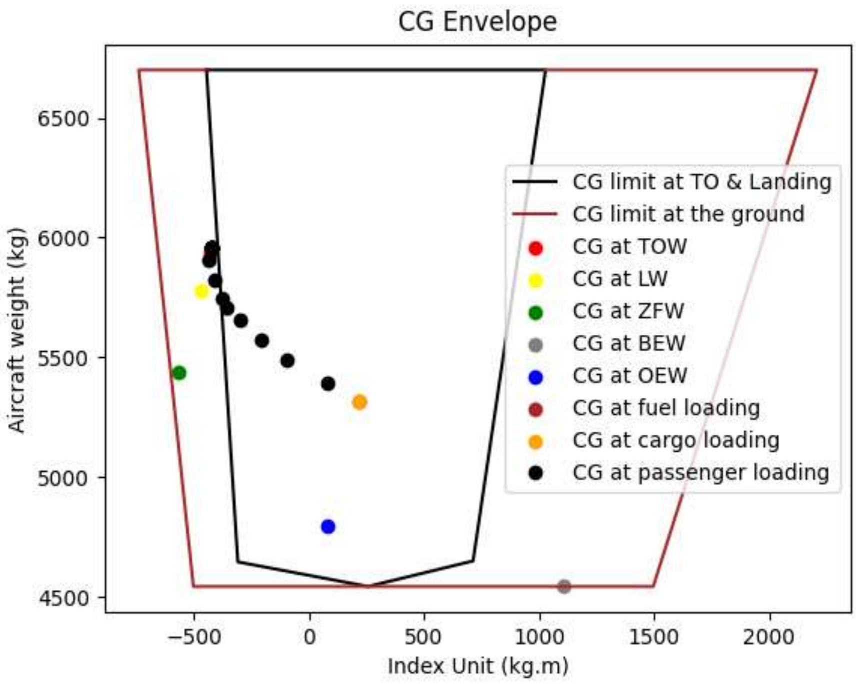

Figure 10. CG profile for case 4

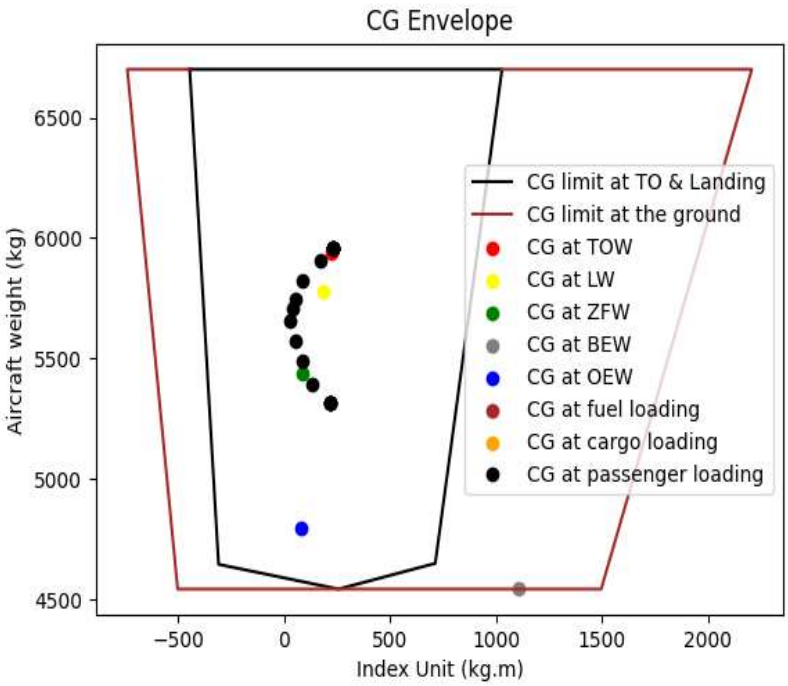

Figure 11. CG profile for the modification of case 4

3.4.5. Analysis of Case 5

In case 5, there is additional cargo of 235 kg compared to case 4. According to allowable TOW, there is still 527 kg of available weight that can be used to carry additional passengers. In this case, the additional baggage placed in the cargo compartment (in the aft section of the aircraft) overcomes the moment produced by the passenger distribution in the forward section of the aircraft. Thus, the CG profile is within the CG limit compared to case 5, as presented in Figure 12. Furthermore, there is no issue in aircraft loading since the CG profile is within the CG limit at the ground.

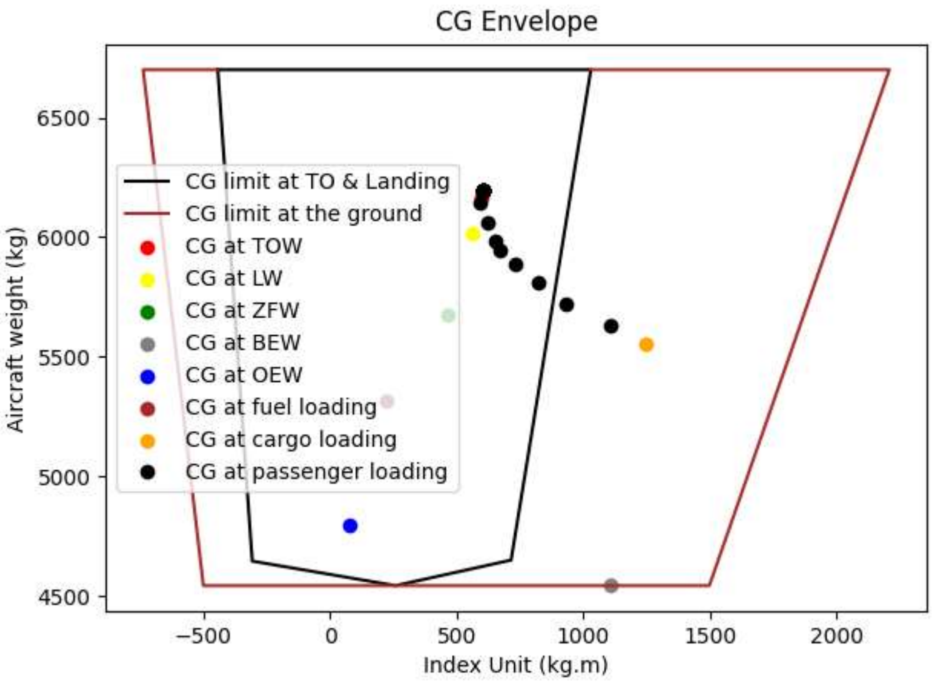

Figure 12. CG profile for case 5

3.4.6. Analysis of Case 6

In case 6, the passenger distribution in the aft section of the aircraft leads to producing more aft moments, exceeding the aft CG limit by 2.28 % MAC at TOW compared to case 4. In this case, the baggage cannot be carried in the aircraft although there is an available weight of 762 kg. According to CG's profile, the passenger in seats 18, and 19 must be removed such that the CG is within the CG envelope during the flight. According to the results of cases 1-6, X-123 is a tail-heavy aircraft. Thus, the passengers must be assigned to the front section of the aircraft if the aircraft carries baggage in the cargo compartment. The illustration of the CG profile is given in Figure 13.

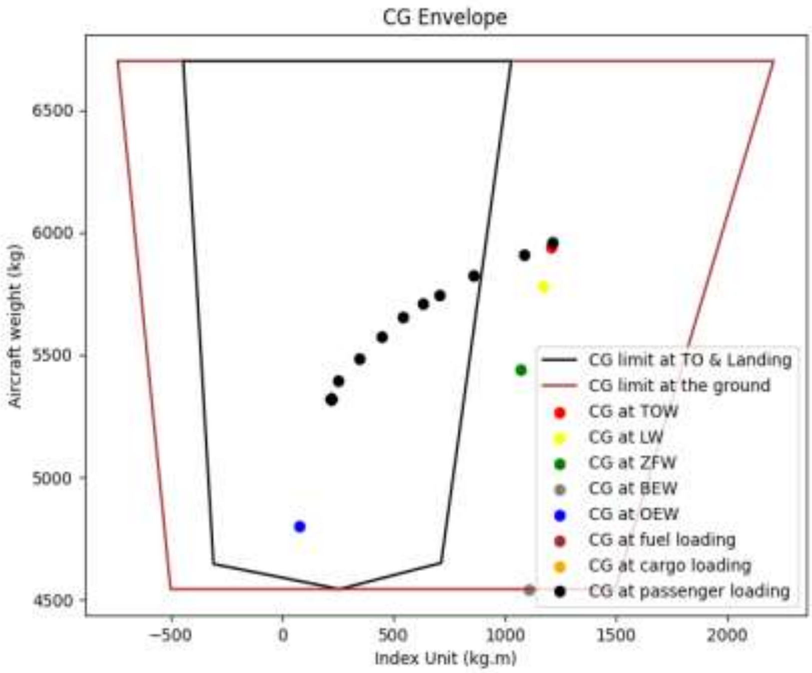

Figure 13. CG profile for case 6

4. Conclusions

This paper has addressed the application development of WAB calculation of X-123 on EFB according to Indonesian regulations. A global architecture design of the application and substantial features is proposed as an EFB initial development. The utilization of a gateway in the application is a key link between the developer and the client, offering flexibility for data changes by the client. Furthermore, the calculation modules that discuss the WAB calculation formula have been discussed as a substantial feature of the application.

Simulation results indicate that X-123 is a tail-heavy aircraft. An additional cargo weight in the aft aircraft section leads to a significant increase of CG to the aft CG limit, impacting aircraft safety during flight. In addition, the payload weight and payload distribution changes affect the CG position which may exceed the forward or aft CG limit. To ensure a safe flight operation, it is recommended to weigh and assign passengers to the seats by operators.

In the future, this research can be extended by integrating the WAB calculation with the aircraft performance calculation. The integrated application enables the aircraft weight imposed by the aircraft performance and the WAB calculation is calculated consecutively, enhancing the flight operations efficiency. Moreover, an automatic loading of the payload assignment feature is required to provide time efficiency for the operator.

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