FYP Final Report

Cathay Pacific - Powerplant storage and logistics strategy

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1 Introduction

1.1 Overview

Aviation industry

The aviation industry is a dynamic and essential sector of the global economy, which covers a wide range of services, including commercial air travel, air cargo transportation, and airport operations. Over the past few decades, the aviation industry has undergone significant changes, with the emergence of new technologies, increased competition, and changing consumer demands resulting in digital transformation.

In Hong Kong, over the decades, the aviation industry has also experienced significant growth over the years, with the city being a major hub for international air traffic. Of all, Cathay Pacific Airways is one of the most prominent players in the Hong Kong aviation industry, with a strong brand reputation and extensive global network.

Cathay Pacific Airways Limited

Cathay Pacific Airways is a Hong Kong-based airline that was founded in 1946, which operates under a holding company called Swire Pacific Limited. The company's mission is to be the world's best airline by providing the highest quality of service to its customers with a commitment to safety, sustainability, and innovation.

The company operates a modern fleet of aircraft, which includes Boeing and Airbus planes while its network covers more than 80 destinations in Asia, Europe, North America, and Australia. Cathay Pacific Airways also has partnerships with other airlines, such as American Airlines and Qatar Airways, which allows it to offer its customers a wider range of destinations and services.

The Covid-19 pandemic and its influences

However, the COVID-19 pandemic has had a significant impact on the aviation industry, and Cathay Pacific Airways is no exception. In 2020, the International Air Transport Association reported a net loss of US$314 billion due to airline passenger revenues drop caused by the pandemic[1]. Asia Pacific will see the largest revenue drop of US$113 billion and a 50% drop in passenger demand. Cathay Pacific carried 13,729 passengers which dropped by 99.6% in April 2020 compared to the previous year[2].

Facing the drop in customer demand, Cathay Pacific Airways has embarked on a transformation program to reshape the company and ensure its long-term sustainability. The transformation program involves several initiatives, including reducing its workforce by around 8,500 employees, retiring older aircraft, and restructuring its business to focus on cargo operations. This will entail reducing the established headcount by 24%, as these functions have been comparatively less impacted by the pandemic than the passenger operations.[3].

The transformation program allows Cathay Pacific Airways to navigate the current crisis, embrace new technologies and digital solutions, and focus on sustainability and resilience so as to position itself for long-term success in the highly competitive aviation industry.

1.2 Literature survey

Challenges faced by airline industry

The airline industry faces various challenges that can impact their operations, financial stability, and sustainability. According to Sundaram and Das , these challenges include managing complex operations, optimizing fleet utilization, and adapting to changing market conditions[4]. Hafner and Obermaier highlight the financial challenges faced by airlines, such as volatile fuel prices, increasing competition, and rising costs[5]. Additionally, the International Air Transport Association (IATA) (2021) has published a report on the sustainability challenges that airlines face, including reducing emissions, improving fuel efficiency, and managing waste[6].

Digital transformation

Digital transformation can help airlines overcome the challenges they face and improve their operational efficiency, enhance customer experience, and increase revenue. Chatzigeorgiou et al. discuss the role of digital transformation in the airline industry and highlight the potential benefits. However, the adoption of digital transformation is not without its challenges[7]. Ettlie and Tawfik explore the barriers to digital transformation in the airline industry, including legacy systems, data silos, and resistance to change[8]. Gudmundsson et al. (2020) highlight the need for airlines to adopt digital technologies to improve their crisis management capabilities, particularly in light of the COVID-19 pandemic[9].

Technical Solutions

Technical solutions, such as big data analytics, machine learning, and predictive analytics, can be used to optimize various aspects of airline operations, such as revenue management, maintenance scheduling, and crisis management. According to Wang et al. (2019), a framework for airline operations management can be developed using big data analytics and machine learning[10]. The framework involves collecting data from various sources, such as flight data and customer feedback, and using machine learning algorithms to optimize operations and enhance customer experience.

Airline revenue management's demand forecasting models primarily rely on the airline's internal sales data, which limits their ability to capture broader market conditions and the competitive environment[11]. The approach involves predicting customer demand and optimizing pricing and inventory decisions to maximize revenue. Liu et al. (2020) propose a machine learning-based approach to aircraft maintenance scheduling, which involves predicting the remaining useful life of aircraft components and scheduling maintenance accordingly[12]. Taking into account remaining useful life prognostics studies also show that a dynamic, predictive engine maintenance scheduling framework is one of the solutions that greatly lowers the overall maintenance cost[13].

Among all the possible fields of digital transformation, the efficiency of the aircraft engine movement is the focus of this project. The expected outcome is to optimize and enhance the decision-making of engine allocation into and out of the existing warehouses, which will be explained in more detail in the objective section below.

1.3 Background

The study is based on the operation of the two fleets A350-1000 with Trent XWB 97 engines and B777-300ER with GE90 engines. The engine shops for maintenance are HAESL (Hong Kong) and TAESL (Xiamen) respectively. Below, it illustrates how an engine is arranged and transported in the maintenance cycle.

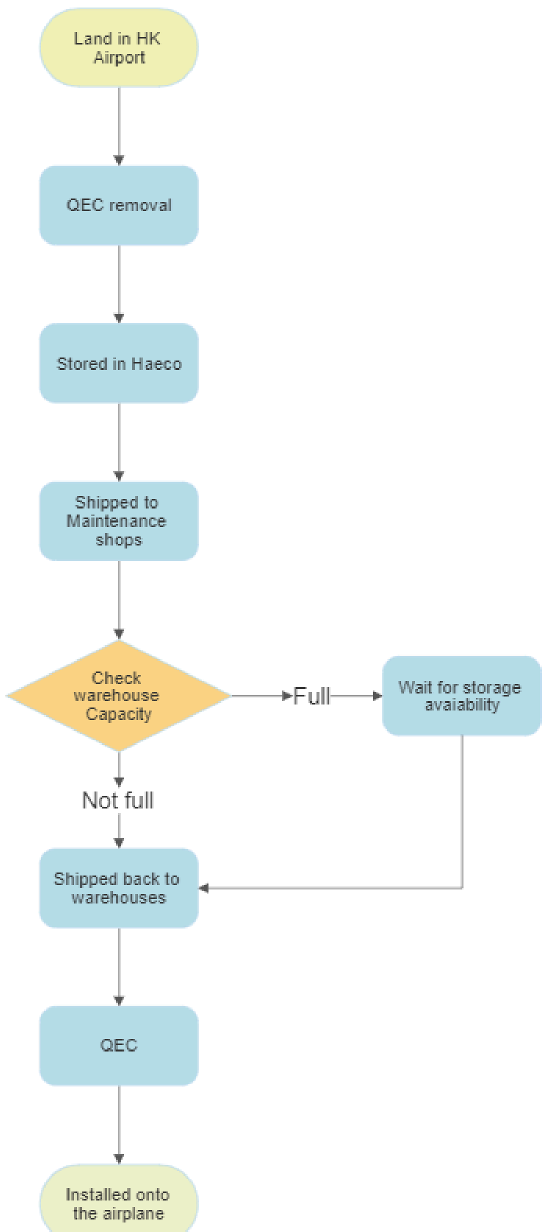

Fig.1 show the flowchart of a to-be-repaired engine from uninstallation to installation

The process of aircraft engine maintenance involves a series of steps. It begins with the arrival of the aircraft at the airport, where the engine is inspected by the airline's maintenance team to determine if it needs maintenance. If necessary, the engine is uninstalled from the aircraft and replaced with a new engine. The new engine undergoes a Quick Engine Change (QEC) check to ensure that it meets the manufacturer's specifications.

After the QEC check, the engine is stored in Haeco warehouse and waits for shipping to the engine shop for maintenance and repairs, as per the schedule. Once it arrives at the engine shop, certified engineers perform the necessary repairs and maintenance on the engine.

After the repair work is complete, the engine is released from the engine shop and is to be shipped to either Haeco warehouse or offsite warehouse for storage. If the engine is at the offsite warehouse and close to the QEC schedule date, it will be sent to Haeco to wait for QEC check. Once the engine has undergone the QEC check and is deemed safe and reliable, it stays at the Haeco warehouse until it's time to be installed on the aircraft as per the schedule.

1.3 Objectives

The goal of this project is to optimize engine movement across multiple sites in and out of HK, taking into account engine removal plan, shop visit planning, shipping and storage considerations etc. Fleet coverage includes 747-400, 747-8, A330, A350, A320, 777, and with respective engines GE90, GEnx, PW4000, Trent 700, 800, XWB, Leap and V2500 engines. Our project mainly focus on the following objectives:

1. To decide a specific engine transfer to the offsite warehouse or stay HAECO(Hong Kong warehouse)
2. To build a “To-do list” to show when and how to move engines between locations
3. To design a user-friendly interface for data input and for displaying results

2. Methodology

2.1 Test case (Phase I)

2.1.1 Overview

This preliminary test case (Phase I) is based on the operation of the two fleets A350-1000 with Trent XWB 97 engines and B777-300ER with GE90 engines. The engine shops for maintenance of XWB 97 and GE90 are HAESL (Hong Kong) and TAESL (Xiamen) respectively. Regarding the engine storage area, only 4 storage areas are available in HAECO while storage areas in Xiamen are unlimited. Also, subject to space availability, the engine maintenance shop may postpone the release days within 7 days.

In addition, several constraints are set up for the optimisation model based on the scenario given. Firstly,Trent XWB 97 & GE90 engines need QEC build-up in HAECO GES before installation (which takes 3 days) and QEC removal (which takes another 3 days) in HAECO GES before being shipped out for engine shop visit.Second, Secondly, QEC is to be transferred from one engine to another engine due to the limited QEC set available. Third, there exists only one single line of QEC build-up/removal by HAECO GES.Lastly, Trent XWB 97 cannot be shipped to Xiamen due to size limitations.

2.1.2 Design

With reference to the given engine status of Trent XWB 97 and GE90 engines, a table describing the engine status and event plans is constructed so that the data recorded can be transferred into the optimisation model.

ESN	Engine type	work_progress	release_date	QEC_date	engine_change_date
26001	Trent XWB 97	remove	5/11/2021	9/11/2021	
26002	Trent XWB 97	hot	5/11/2021		5/11/2021
26003	Trent XWB 97	release	24/20/2021	6/11/2021	2/12/2021
26004	Trent XWB 97	release	8/11/2021		
959001	GE90	remove	1/11/2021	16/11/2021	
959002	GE90	hot	1/11/2021		1/11/2021
959003	GE90	release	1/11/2021	13/11/2021	10/12/2021
959004	GE90	release	5/11/2021		

Table 1 shows the overview of working progress for two types of engine

After consolidating the constraints and scenario into an excel table, the result table is shown above. Under the work_progress column, “remove” refers to removing the engine from an airplane, “hot” refers to a hot engine and “release” means the engine is released from the engine shop. Based on the table above, we can know that the deadline or end date for the Trent XWB - 26003 and GE90 - 959003 are 06/11/2021 and 13/11/2021 respectively.

	engine	status	date	engine_type	engine_location
0	26001	REMOVED	2022-11-05	Trent XWB 97	HKG
1	26001	QEC - REMOVE	2022-11-06	Trent XWB 97	HKG
2	26001	TRANSFER - ENGINE SHOP	2022-11-09	Trent XWB 97	HKG
3	26001	ARRIVAL - ENGINE SHOP	2022-11-10	Trent XWB 97	engine shop
4	26002	HOT	2022-10-24	Trent XWB 97	HKG
5	26002	INSTALL	2022-11-05	Trent XWB 97	HKG
6	26003	RFS	2022-10-24	Trent XWB 97	engine shop
7	26003	TRANSFER - HAECO	2022-10-24	Trent XWB 97	engine shop
8	26003	ARRIVAL - HAECO	2022-10-25	Trent XWB 97	HKG
9	26003	QEC - INSTALL	2022-11-06	Trent XWB 97	HKG
10	26003	HOT	2022-11-12	Trent XWB 97	HKG
11	26003	INSTALL	2022-12-02	Trent XWB 97	HKG
12	26004	RFS	2022-11-08	Trent XWB 97	engine shop

Fig. 2 show the to-do list for Phase I

The to-do-list shown after running the program is based on the logic of prioritization, which is the earliest the QEC schedule date of an engine is, the higher the priority of the engine to be moved to Haeco warehouse. The results show the engine, status, date, engine type and location in one excel format.

2.1.3 Evaluation

During the initial testing phase (Phase I), our primary focus was on the movement of two types of engines (XWB 97 and GE90) from the engine shop after repair. However, the transfer of engines from HAECO to an offsite warehouse is not considered in this case. Additionally, cost-saving comparison between each engine movement is not undergone, which is raised as one of the factors that potentially improve the efficiency of the engine transfer process.

Moving forward, we aim to address these limitations by refining our program to include all relevant engine transfer scenarios and incorporate cost-saving measures to maximize the accuracy and efficiency of the process.

2.2 Real case (Phase II)

2.2.1 Overview

Project Scope

After the evaluation of Phase I, the project has transit into Phase II given that more real-case data and constraints are provided. The project scope of Phase II is defined as follows. Seven aircraft engine types, namely XWB-84, XWB-97, T700, T800, GENX, GE90, PW4000, approximately with a total of 46 engines, are the target engines while the engines are serviced by five engine shops, including HAESL (Hong Kong), GEEVES (Taipei), TEXL (Xiamen), and MHI (Nagoya), which is illustrated by the table below.

Engine Type	ESN	Igloo required	Engine Shop
XWB-84	21XXX	Large	HAESL (Hong Kong)
XWB-97	26XXX	Large	HAESL (Hong Kong)
T700	4XXXX	Large	HAESL (Hong Kong)
T800	5XXXX	Large	HAESL (Hong Kong)
GENX	90XXXX	Large	GEEVES (Taipei)
GE90	95XXXX	Large	TEXL (Xiamen)
PW4000	P7XXXXX	Small	MHI (Nagoya)

Table 2 shows the overview of engine types and its corresponding ESN and engine shops.

For the scope of storage and transportation, the on-site storage location, i.e. Haeco warehouse in Hong Kong charges a higher monthly fee compared to the off-site location in Xiamen. The table also indicates that unlimited igloo reservations are allowed at the Xiamen off-site location. The following tables show the locations where Cathay Pacific Airways stores their engines and the corresponding monthly fees per igloo, as well as the corresponding transportation fees.

Location	Monthly Fee (HK$) - per igloo	Reserved Igloo
HKG On-site (Large)	$42,640	15
HKG On-site (Small)	$31,200	2
XMN Off-site	$6,850	Unlimited

Table 3 shows the Monthly Fee and the number of Reserved Igloo of each warehouse location

From	To	Total Fee (HK$) - (1 way)
HKG	XMN	$44,490
XMN	HKG	$44,490
XMN (shop)	XMN (off-site store)	$14,930
XMN (off-site store)	XMN (shop)	$14,930

Table 4 shows the transportation fee for corresponding path

About the time scope, since the engine schedules for QEC/Installation are less flexible and most of them are predetermined, the period for the decision-making process of engine movement is set to be from the date of engines released from engine shop to the QEC scheduled date for engines. Hence, an action plan of engine movement between the period above mentioned is expected.

Logic Consideration

Regarding the operation logic, 2 priorities must be fulfilled before deciding the movement of the incoming engine released from the engine shop.

Priority 1a: At least one serviceable "S" engine of each engine type is present in Haeco warehouse

Priority 1b: Engines must be on-time at the on-site (HKG) location to support QEC/Installation

If both priorities are met and the igloo space in Haeco is full, the engine can either be moved to an offsite warehouse or an engine can be moved out of Haeco in advance to create space for the newly released engine. In contrast, if there is space available in Haeco, the total storage and transportation costs of moving the engine to Haeco versus an offsite warehouse are considered, and the option with the lowest cost is chosen.

Cost Calculation

Cost-saving is a crucial objective in this project, and it plays a significant role in determining the engine shipment process in two scenarios- engines in Haeco and engines released from the shop. The calculation methodology is the same in both scenarios because all engine movements in and out of the shop must be via Hong Kong.

Measurement	Calculation	Explanation
Cost spent in Haeco (Large igloo)	DateDiff * Daily large igloo cost	The monthly storage cost for a large Haeco igloo is $42,640 (i.e. $1,421 per day)
Cost spent in Haeco (Small igloo)	DateDiff * Daily small igloo cost	The monthly storage cost for a small Haeco igloo is $31,200 (i.e. $1,040 per day).
Cost Spent in XMN offsite (For engine not repair in XMN)	DateDiff * Daily storage cost + 2 * HKG_XMN Transportation fee	The monthly storage cost is $6,850 (i.e. $228 per day) Since the engine is needed to be traveled back to HKG, this incurs 2 transportation fee between HKG and XMN
Cost Spent in XMN offsite (For engine repair in XMN)	DateDiff * Daily storage cost + HKG_XMN Transportation fee + XMN_XMN Transportation fee	Some engine needed to be repair in XMN engine shop The first transportation fee is from HKG to XMN offsite The second transportation fee is from XMN offsite to XMN engine shop

Table 5 shows the calculation methodology variables with explanation

Scenario 1: Engine in Haeco

In the case of engines in Haeco, there are two types of engines - serviceable and unserviceable. Serviceable engines require QEC and wait for installation, while unserviceable engines wait for the shop visit. Since different engines have different activities, the time spent in Haeco differs for each engine. To achieve the cost-saving strategy, we must calculate the number of days each engine spends in Haeco, which we refer to as "DateDiff" for simplicity. Based on the DateDiff, we can calculate the cost of storing the engine in Haeco (Haeco Cost) and the cost of transferring it from Haeco to offsite storage (XMN Cost). If the XMN Cost is lower than the Haeco Cost, transferring the engine to offsite storage can help us achieve the objective of cost-saving.

Below is an example:

ENGINE TYPE	ESN	Location	Current Date	QECStart	Date Diff	Haeco Cost	XMN Cost	Cost Saving
TXWB-84	21092	CLK	2023-03-01	2023-06-11	102	102 * $1421 = $144,942	102 * $228 + 2 * $44490 = $112,236	$144,942 - $112,236 = $32,706

Table 6 shows the overview calculation and cost saving of respective engine type

The "Current Date" is the date on which we run the program, and for simplicity, we set it as the default date of 2023-03-01. In the first scenario, the time that an engine spends in Haeco (i.e., "DateDiff") is calculated as the difference between "QECStart" and the "Current Date," which is 102 days. The cost of storing the engine in Haeco is $144,942, while the cost of transferring it to XMN offsite storage is $112,236. Therefore, we can save $32,706 if we transfer the engine from Haeco to offsite storage and send it back to Haeco for QEC before 2023-06-11.

Scenario 2: Engine released from shop

In the case of engines released from the shop, we must consider engines that are released from the shop and engines stored in XMN offsite that require QEC. Like the previous scenario, different engines have different release times and QEC dates, and we can use the “DateDiff” to calculate the cost of storing the engine in Haeco (Haeco Cost) and the cost of transferring it from the engine shop to offsite storage. When calculating the cost from the engine shop to offsite storage, we must consider two travel paths - from the engine shop to HKG and from HKG to XMN offsite, as all engine movements in and out of the shop must be via Hong Kong. We can exclude the cost in path 1 as the engine shop is responsible for it. Therefore, the cost from the engine shop to offsite storage is the same as XMN Cost.

Below is an example

ENGINE TYPE	ESN	Location	ShopReleasefromshop	QECStart	Date Diff	Haeco Cost	XMN Cost	Cost Saving
TXWB-84	21142	Shop	2023-04-27	2023-08-25	118	118 * $1421 = $167,678	118 * $228 + 2 * $44490 = $115,884	$167,678 - $115,884 = $51,794

Table 7 shows the overview calculation and cost saving of respective engine type

In the second scenario, an engine is released from the shop on "2023-04-27" and undergoes QEC on "2023-08-25," resulting in a “DateDiff” of 118. If we store the engine in Haeco for 118 days, it will cost $167,678. However, if we transfer the engine to XMN offsite storage and store it for 118 days, it will cost only $115,884, resulting in a cost-saving of $51,794 in this case.

The same calculation methodology is used in both scenarios to calculate the "Haeco Cost" and "XMN Cost." The only difference is the "DateDiff," which affects the cost-saving criteria.

Project workflow

The project workflow in the following comprises three stages, namely data consolidation, programming execution, and visualization. In the first stage, data is entered in Excel format to consolidate it. The data is then fed into the Programming stage, where the cost is calculated to generate a to-do list. Finally, the results are presented in the Visualization stage in a user-friendly format for end-users to comprehend.

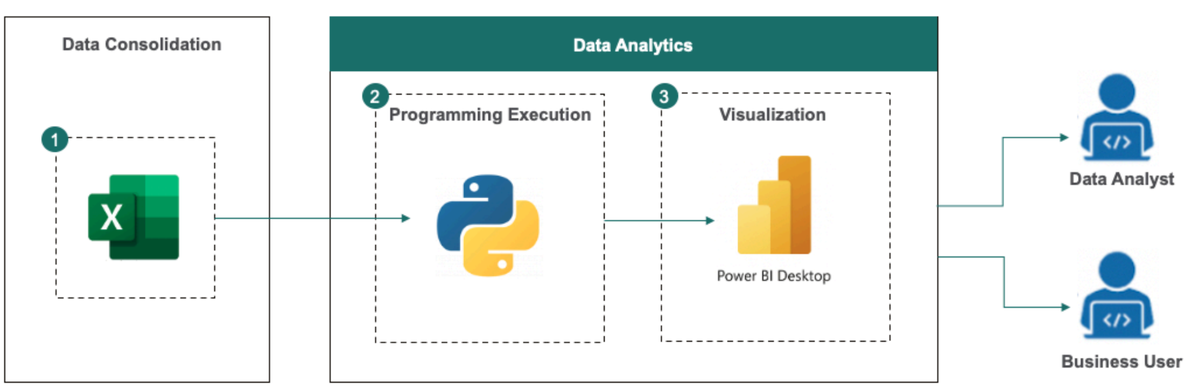

Fig. 3 show the overview of project workflow

2.2.2 Data Consolidation

The first stage of the project flow is data consolidation, which involves the reading of data from an excel file. This stage is crucial as it ensures that all the necessary information required for the project is available and ready for analysis. The data is expected to be in a structured format, and the data consolidation process aims to standardize the data for further analysis.

The dataset consists of two parts. The first part is the engine overview, which consists of the engine data in different locations, namely Hong Kong International Airport in Chek Lap Kok (CLK), offsite store in Xiamen (XMNTY), and the engine repair shop (shop). More information about the engine data is provided further below.

Variable name	Description	Example
ENGINE TYPE	The name of different engine type	7 engine type - T700, T800, XWB-84, XWB-97, GENX, GE90, PW4000
ESN	Engine series number. Different engine has its own ESN	42126, 21092, 959687
Status	The current status of the engine	US - unserviceable, S - serviceable, Repair - engine repair
Location	The current location of the engine	CLK - Hong Kong International Airport in Chek Lap Kok, XMNTY - offsite store in Xiamen, shop - engine repair shop
Shop Release from shop	The date that the engine is released from shop	27/4/2023
QEC Start	The start date of the QEC	11/5/2023
QEC Complete	The end date of the QEC	15/5/2023
Engine Installation	The installation date of the	17/5/2023

	engine to the aircraft	
Ready for pick-up (From CLK)	The date that the engine is ready to pick up from CLK	28/4/2023
Shop Visit Induction	The date that the engine visit the engine shop for repairment	1/5/2023
Remark	Any remark for the engine	No SV plan in 2023

Table 8 shows the first part information about the engine data

The second part of the data consists of some basic information for the programming execution. Cathay Pacific can modify the data of this part for future updates. Further details regarding this section are provided below.

Variable name	Description	Example
large_reserved_igloo	The reserved space for large igloo	15
small_reserved_igloo	The reserved space for small igloo	2
large_daily_hkg_onsite_fee	The daily fee for large onsite storage (i.e. Haeco)	Monthly fee/ 30 = $42,640/ 30 = $1,421
small_daily_hkg_onsite_fee	The daily fee for small onsite storage (i.e. Haeco)	Monthly fee/ 30 = $31,200/ 30 = $1,040
daily_xmn_offsite_fee	The daily fee for offsite storage (i.e. XMN)	Monthly fee/ 30 = $6,850/ 30 = $228
hkg_xmn_transportation_fee	The transportation fee between HKG to XMN	$44,490
xmn_transportation_fee	The transportation fee between XMN engine shop and XMN offsite store	$14,930
small_engine_type	The engine type that is stored in small igloo	PW4062A-3
xmn_engine_type	The engine type that is shipped to XMN engine shop for repairment	GE90-115B
engine_type	All the available engine type	T700, T800, TXWB-84, TXWB-97, GEnx-2B, GE90-115B, PW4062A-3
delay_day	The number of day allow to delay from the shop	3

Table 9 shows the second part information about the engine data

2.1.2 Programming

The second stage of the project flow is programming execution, which involves ingesting the data from excel to python and writing python code to decide engine movement based on cost-saving strategies. This stage requires programming skills and knowledge of the python programming language. The code helps in deciding which engine to move from Haeco to offsite and which engine that is released from the shop should be shipped to Haeco or offsite. The output of this stage is a decision on the engine movement, which is based on the cost-saving strategy.

Logic behind - Engine Management Process

Effective engine management is essential for airlines to maintain their fleets and ensure that their aircraft are operating safely and efficiently. The process of managing engines at Haeco is a complex one that involves careful planning and coordination to optimize space utilization and minimize costs. To ensure the efficient management of engines at Haeco, there are several steps that need to be followed.

Definition for special term

The term "RFS Engine" refers to an engine that has been released from the shop. The "RFS date" is the date on which this engine is released from the shop, while the "QEC date" is the date on which the engine is expected to undergo Quick Engine Change, and it's necessary for the engine to arrive at Haeco before this date. The "Available date" is the date on which space becomes available in Haeco, and the "Date difference" refers to the number of days between the “RFS date” and the “Available date”.

Logic Flow

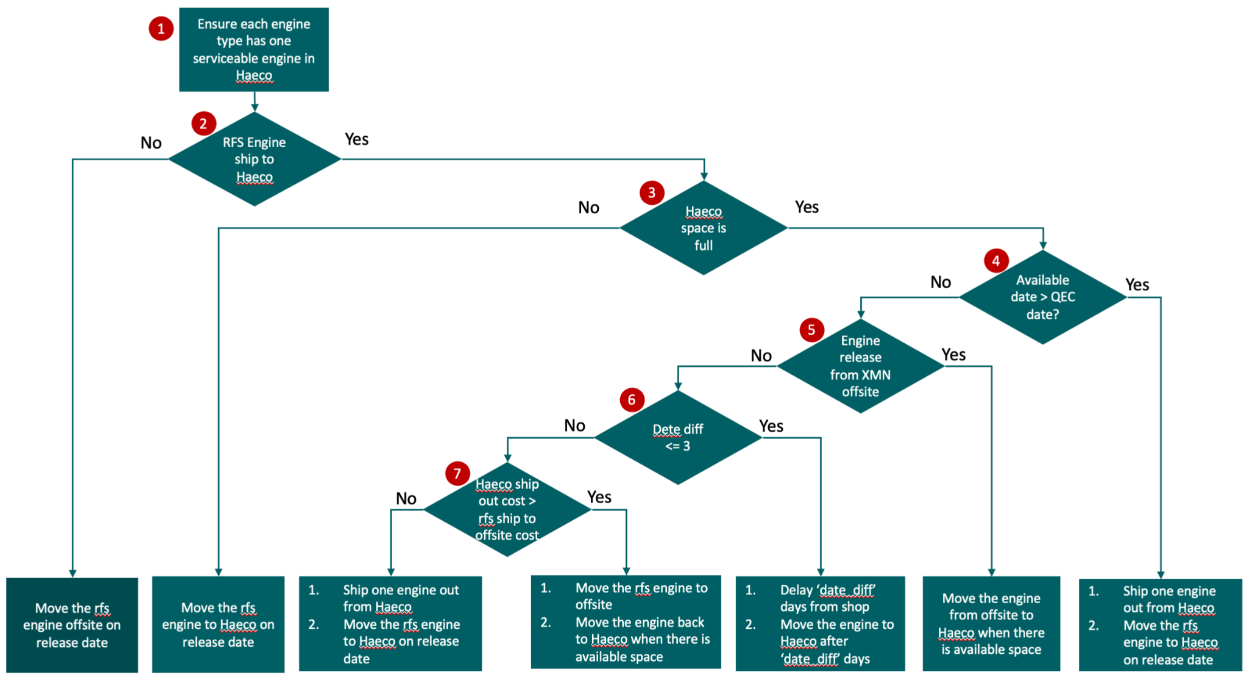

Fig. 4 show the logic flow of programming execution

Step 1: Ensure that there is a serviceable engine available for each engine type at Haeco.

To accomplish this, it is necessary to ensure that there is at least one operational engine accessible for every engine type at Haeco. This is critical to ensure that adequate engines are available to support aircraft maintenance and repairs. Airlines must have enough engines accessible to replace any engines that require maintenance or repairs and need to be taken out of service.

Step 2: Determine whether "RFS Engine" needs to be transported to Haeco or not.

This step involves assessing whether the engine that has been released from the shop requires shipment to Haeco or not. If the engine does not need to be transported, it should be moved to an offsite location on the release date to reduce costs. However, if the engine needs to be shipped to Haeco, we proceed to the next step of the engine management process. This step is crucial in optimizing the engine management process and minimizing costs for the airline.

Step 3: Evaluate whether there is enough space available at Haeco to accommodate the "RFS Engine".

In this step, it is essential to determine if there is enough space available at Haeco to store the engine that has been released from the shop. If there is enough space, the engine can be moved to Haeco on the release date for storage. However, if there is no space available, we proceed to the next step of the engine management process. This step is critical in ensuring that there is adequate storage capacity at Haeco for the engines that require maintenance or repair.

Step 4: Assess whether the “Available date” is greater than the “QEC date”.

In this step, we need to determine whether Haeco has available space to store the engine that has been released from the shop before the QEC (Quick Engine Change) date. If there is no available space before the QEC date, we must ship one engine out from Haeco to make room for the newly released engine.

ENGINE TYPE	ESN	Location	ShopRelease fromshop (RFS date)	QECStart (QEC date)	Available Date
TXWB-97	26058	Shop	2023-04-23	2023-04-24	2023-04-26

Table 10 shows the RFS, QEC and Available Date for TXWB-97

For example, Haeco only has available space on 2023-04-26 and this engine requires QEC on 2023-04-24. In this case, “Available date” is greater than “QEC date”, we must ship one engine out from Haeco to ensure this RFS engine can arrive Haeco for QEC on 2023-04-24. This also ensures that there is enough storage capacity for the engines that require maintenance or repair. However, if there is available space before the QEC date, we can proceed to the next step of the engine management process. This step is critical to optimizing the storage capacity of Haeco and reducing overhead costs for the airline.

Step 5: Check if the engine is released from XMN offsite.

In this step, we need to determine if the engine is released from XMN offsite. If it is, we can hold the engine on offsite until there is available space at Haeco without incurring any additional costs. This is because this engine is not released from the engine shop but stored on offsite. However, if the engine has not been released from XMN offsite, we move on to the next step of the engine management process. This step is critical in reducing transportation and storage costs associated with managing engines for maintenance or repair.

Step 6: Check the "date difference" between the "RFS date" from the shop and the “Available date” at Haeco.

In this step, we evaluate whether the "date difference" between the engine release from the shop and the available date at Haeco is less than 3 days. If it is, we delay the engine's move to Haeco by the "date difference" number of days. This is because delaying the move can optimize space utilization by ensuring that the engine arrives at Haeco when there is available space for storage.

ENGINE TYPE	ESN	Location	ShopRelease fromshop (RFS date)	QECStart (QEC date)	Available Date
GEnx-2B	959687	Shop	2023-05-17	2023-06-08	2023-05-19

Table 11 shows the RFS, QEC and Available Date for GEnx-2B

For example, Haeco has available space on 2023-05-19 and this engine releases from the shop on 2023-05-17. The “date difference” is 2 in this case, which is smaller than 3 days, and also the “Available date” is smaller than the “QEC date”. This means that there is available space at Haeco before the QEC starts. This engine can be delayed 2 days at the engine shop and shipped back to Haeco on 2023-05-19 when there is available space. By doing so, airlines can minimize the storage and transportation costs associated with managing their engines. This step is critical in ensuring that the engine management process is optimized and that the airline's fleet remains operational and safe for passengers.

Step 7: Compare the cost of shipping an engine out from Haeco to the cost of moving the engine that was released from the shop to an offsite location.

In this step, if moving the engine that was released from the shop to an offsite location is cheaper, it should be moved there until there is available space in Haeco. This is because it is more cost-effective to move the engine to an offsite location than to ship an extra engine out from Haeco. However, if shipping an extra engine out from Haeco to an offsite location is cheaper, one engine should be shipped out to create available space in Haeco for the engine that was released from the shop. Then, the newly released engine should be moved to Haeco on the release date. This step is crucial in optimizing the engine management process and reducing costs for the airline.

cost of shipping an engine out from Haeco:

ENGINE TYPE	ESN	Location	Engine Ship Out Date	QECStart	Date Diff	Haeco Cost	XMN Cost	ExtraMoneySpend
TXWB-84	21092	CLK	2023-03-03	2023-05-09	67	67 * $1421 = $95,207	67 * $228 + 2 * $44490 = $104,256	$104,256 - $95,207 = $9,049

Table 12 shows the overview and cost of shipping for TXWB-84

Cost of moving the engine that was released from the shop to an offsite location:

ENGINE TYPE	ESN	Location	ShopRelease fromshop	QECStart	Date Diff	Haeco Cost	XMN Cost	ExtraMoneySpend
T700	42658	Shop	2023-03-05	2023-04-10	36	36 * $1421 = $51,156	36 * $228 + 2 * $44490 = $97,188	$97,188 - $51,156 = $46,032

Table 13 shows the overview and cost of shipping for T700

To illustrate, let's consider the cost of shipping an engine out from Haeco. In this case, the "Engine Ship Out Date" is the date that assumes the engine needs to be shipped out to offsite storage to create available space in Haeco. However, there is an additional cost incurred, referred to as "ExtraMoneySpend," as the cost of transferring the engine to XMN offsite (i.e., XMN Cost) is much higher than storing it in Haeco (i.e., Haeco Cost). Similarly, when moving an engine released from the shop to an offsite location, there is also an "ExtraMoneySpend." We must incur additional expenses to ensure that the engine arrives before the QEC date, which is a fundamental requirement. Therefore, we need to compare the two "ExtraMoneySpend" amounts and determine which one is lower. In this case, shipping an engine out from Haeco is the better option because it incurs lower additional expenses.

By efficiently managing the transportation and storage of engines, airlines can improve their overall operational efficiency and profitability.

2.1.3 Visualization

The third stage of the project flow is visualization, which involves presenting the results of the project in a meaningful and understandable format. The output data taken from the programming are saved in an excel file format, and then they are uploaded to a software, PowerBI, for data visualization. Two main dashboards are generated, including an interactive map showing the engine type, engine status and engine location, and a to-do list showing the reason for engine movement and the cost-saving. This stage is essential in visualizing all the findings of the project to stakeholders and enhancing their understanding of current engine status and future plans.

The first part of the dashboards is an interactive map which displays all the current engines, in the Asia-Pacific region, i.e. Hong Kong, Xiamen, Taiwan and Japan. Filters of engine location, engine type and engine status are available for instant sorting and selection.

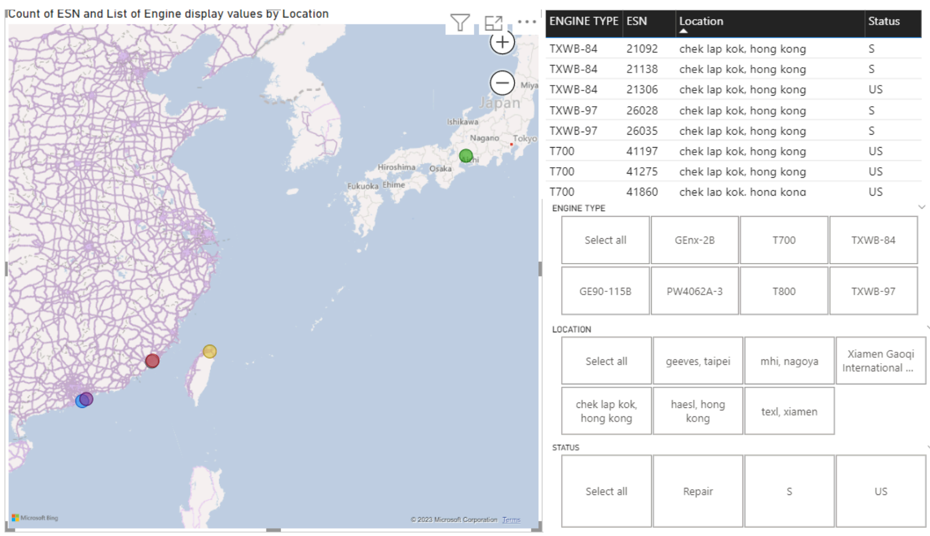

Fig. 5 shows the interactive map that records all the current engines

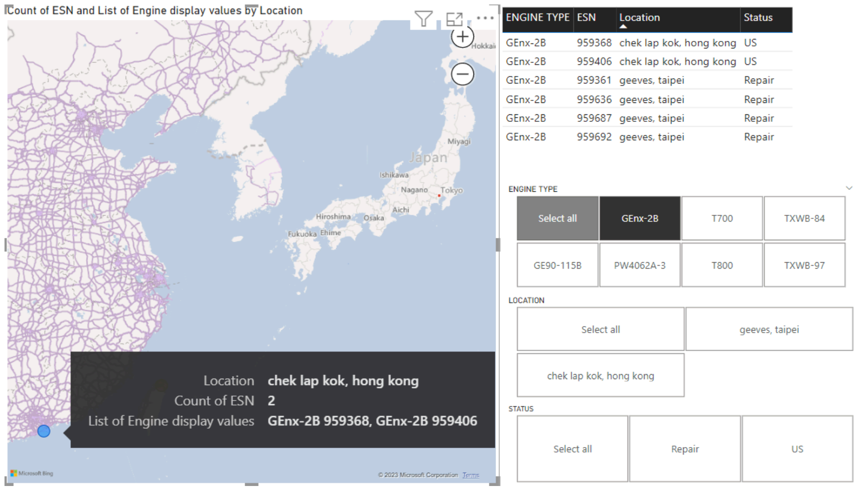

Fig. 6 shows the interactive map that sorts out a certain engine type, in this case, the GEnx-2B

The second part of the dashboards is the action plan in a calendar format, which lists out all the future engine movements that are required. The engine movement action plans consist of four types - moving the engine

i) from Engine shop to Haeco warehouse

ii) from Engine shop to Offsite warehouse

iii) from Haeco warehouse to Offsite warehouse

iv) from Offsite warehouse to Haeco warehouse.

In addition to the engine type, engine serial number and the action plans, the reasons behind each movement are also clearly stated, for example, the cost-saving purpose, for QEC check and the full capacity in Haeco warehouse. On the other hand, engine type and engine serial number can be selected in the filter sections. Along with different options available for calendar view, it enhances the flexibility of viewing the engine action plan for the future.

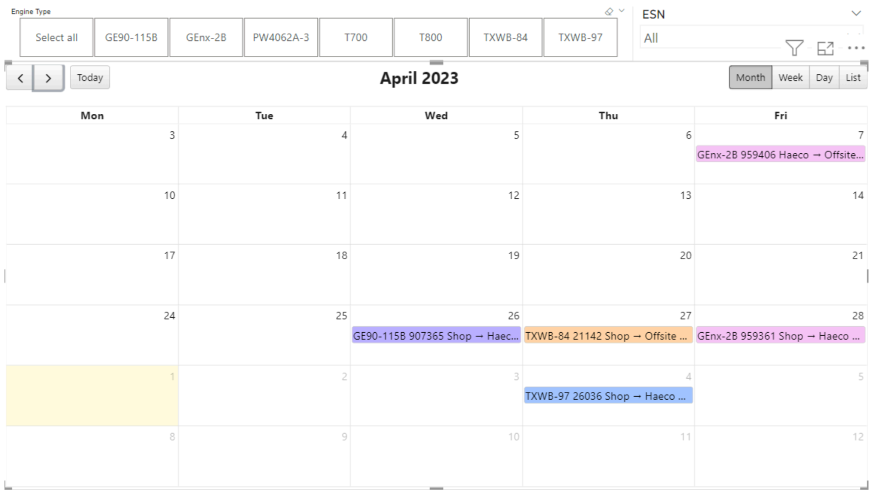

Fig. 7 shows the action plan in a monthly view for April 2023

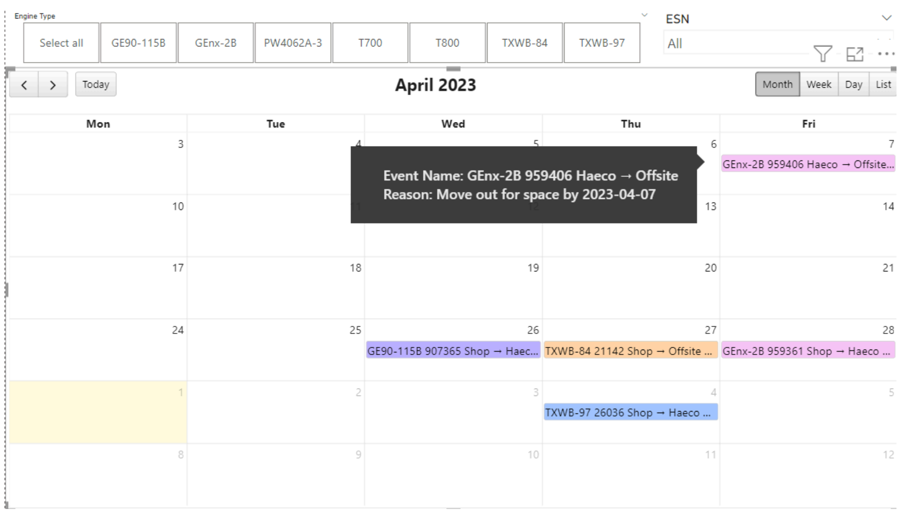

Fig. 8 shows the action plan where an event is hovered against to show more action details

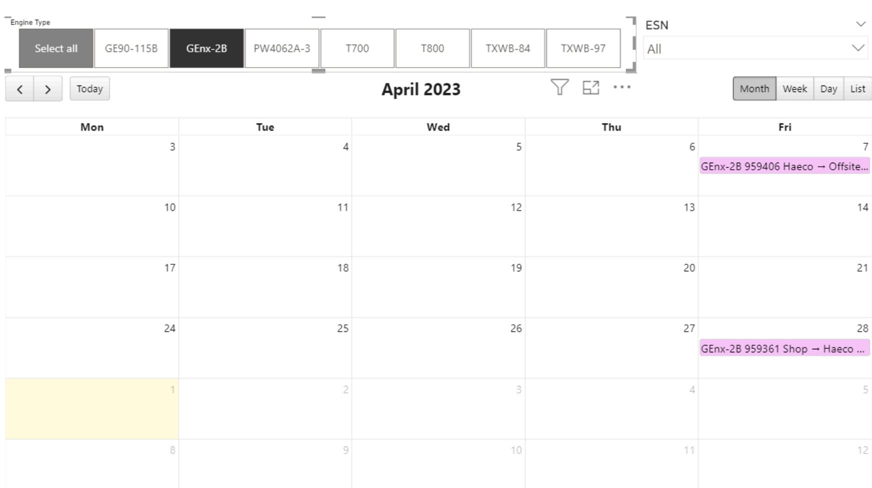

Fig. 9 shows the action plan where a particular engine type, i.e. GEnx-2B, is selected for filtering

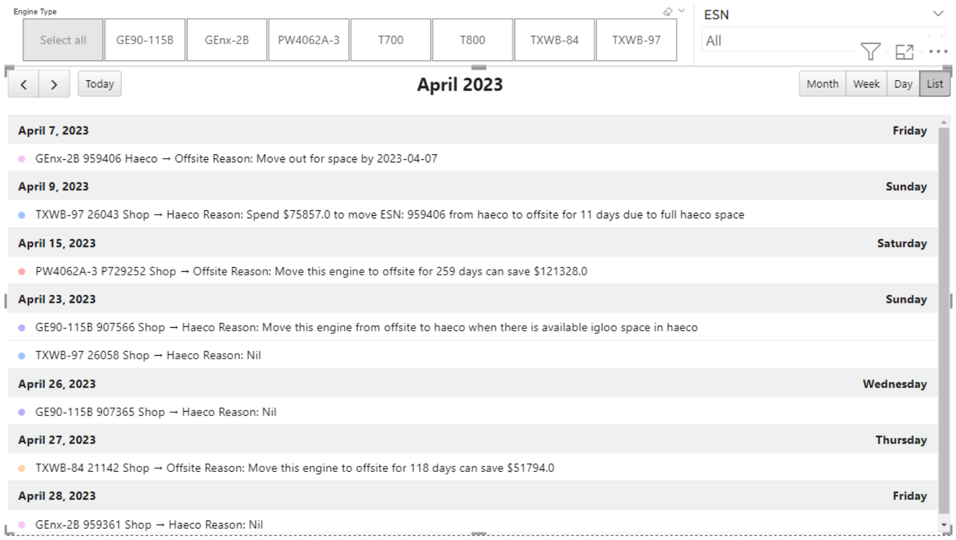

Fig. 10 shows the action plan in a list view for April 2023

2.2 Process flow

With the integration between excel data, python coding scripts, and Power BI dashboards, the following process flow elucidates the complete workflow to execute day-to-day engine arrangements.

Step 1: Update current engine location and status and confirm with the consolidated engine information in the excel file format and save.

Step 2: Run the python program to generate an updated engine movement action plan in excel format

Step 3: Refresh Power BI dashboards (which read the excel data) to show the latest interactive map and action plan calendar.

Step 4: Review the action plan calendar and arrange engine movements accordingly.

Step 5: If necessary, adjust and update the consolidated excel form again, save it, run the python program and refresh the power BI dashboard again for further review.

3. Evaluation

3.1 Conclusion

To address our primary objectives in a precise manner, a python program based on igloo capacity and storage and transportation cost is created to decide a specific engine transfer to the offsite warehouse or stay HAECO (Hong Kong warehouse) and a user-friendly interface (Power BI dashboards and an excel form) for data input and for displaying results respectively is launched. The displayed results include an interactive map and an action plan calendar, which clearly illustrates current engine status and its corresponding movement plan.

Along with the solution, a number of expected benefits are anticipated. Firstly, with the implementation of this project, users are able to capture the entire engine status on the map via visualized real-time engine data. This information can be useful in several ways, such as identifying the location of a particular engine and its status (e.g., in the engine shop for maintenance, in the on-site location for QEC/Installation), which can help in scheduling and coordinating the necessary activities, hence making informed operational decisions.

Secondly, the solution allows users to follow an action plan and make engine movement decisions based on the list. The action plan contributes to prioritizing the engine movement activities and ensures that the most critical tasks are addressed first so that all necessary engine movements are executed on time, which can help in avoiding delays and operational disruptions.

Thirdly, the project can help save costs. By calculating the operational costs including storage and transportation costs, the program can identify and optimize the engine movements. The program also states the cost implications while making engine movement decisions for further review. With the implementation, it is expected that the operational cost can be reduced by over HKD 0.6 million annually.

Lastly, manual updates and re-run for the dashboard are allowed for execution, which makes the solution flexible in nature. If any updates or changes of engine information are required, users can make updates and re-run for the dashboards to reflect the changes at any time. This flexibility empowers users to customize the dashboard according to their specific requirements and ensure that the dashboard always shows the most up-to-date information.

3.2 Future improvement

Moving forward to the adoption stage, the implementation process should also involve a thorough evaluation of the technology's functionality and compatibility as well as identifying potential risks and developing strategies to mitigate them. Additionally, it is important to consider the training required for employees to understand and effectively use the new technology so that the stability of the new system can be maintained.

To further improve the accuracy of the model, more data which might involve unplanned events and accidents can be collected and trained in the probability calculation for predictions. With AI machine learning predictions and dynamic optimisation, the degrees of the overall cost-saving and comprehensiveness can be extended further.

4. Reference

[1]COVID-19 Impact on Asia-Pacific Aviation Worsens. (2020, April 24). https://www.iata.org/en/pressroom/pressroom-archive/2020-press-releases/2020-04-24-01/

[2]Cathay Pacific Group Releases Combined Traffic Figures for April 2020. (n.d.). Cathay Pacific. https://news.cathaypacific.com/cathay-pacific-group-releases-combined-traffic-figures-for-april-2020

[3]Cathay Pacific Group announces corporate restructuring. (n.d.). Cathay Pacific. https://news.cathaypacific.com/cathay-pacific-group-announces-corporate-restructuring

[4]Ma, Wenliang & Zhang, Anming & Zhang, Yahua & Xu, Shiteng, 2021. "The growing influence of low-cost carriers in Northeast Asia and its implications for a regional single aviation market," Journal of Air Transport Management, Elsevier, vol. 91(C).

[5]Tyagi, A. K. (2022). Handbook of Research on Technical, Privacy, and Security Challenges in a Modern World. IGI Global.

[6]IATA's Annual Review. 2021 (n.d.).https://www.iata.org/en/publications/annual-review/

[7]Sukhorukov, A. P., Koryagin, N. D., Sulyagina, J., Ulitskaya, N., & Eroshkin, S. (2019). Digital Transformation of Airline Management as the Basis of Innovative Development. In Advances in intelligent systems and computing (pp. 845–854). Springer Nature. https://doi.org/10.1007/978-3-030-37916-2_83

[8]Ettlie, J. E., & Tawfik, H. (2021). Barriers to digital transformation in the airline industry. Journal of Air Transport Management, 93, 101983.

[9]Pérez-Castán, J. A., Asensio, B. A., Rodríguez-Sanz, Á., Ho-Huu, V., Sanz, L. F. A., Comendador, V. F. G., & Valdés, R. M. A. (2020). Impact of Continuous Climb Operations in ATC workload. Case-study Palma airport. *Journal of Air Transport Management*. https://doi.org/10.1016/j.jairtraman.2020.101890

[10]Wang, X., Luo, X., & Huang, Y. (2019). Development of airline operations management framework using big data analytics and machine learning. Transportation Research Part C: Emerging Technologies, 101, 83-100. https://doi.org/10.1016/j.trc.2019.02.016

[11]Gautam, N., Nayak, S., & Shebalov, S. (2021). Machine learning approach to market behavior estimation with applications in revenue management. Journal of Revenue and

Pricing Management, 20(3), 344–350.
https://link.springer.com/article/10.1057/s41272-021-00317-y

[12]Liu, Y., Wu, D., Xu, H., Yang, J., & Sun, X. (2020). A machine learning-based approach for aircraft maintenance scheduling. Journal of Air Transport Management, 84, 101729. https://doi.org/10.1016/j.jairtraman.2019.101729

[13] de Pater, Ingeborg & Reijns, Arthur & Mitici, Mihaela, 2022. "Alarm-based predictive maintenance scheduling for aircraft engines with imperfect Remaining Useful Life prognostics," Reliability Engineering and System Safety, Elsevier, vol. 221(C).

5. Appendix A

Cost-saving function

```python
def cost_calculation(df, info, type):
    df['DateDiff'] = (df['AvailableEndDate'] - df['AvailableStartDate']) / np.timedelta64(1, 'D')
    # parameter setting
    large_daily_hkg_onsite_fee = int(info[info['Measure']=='large_daily_hkg_onsite_fee']['Value'].values)
    small_daily_hkg_onsite_fee = int(info[info['Measure']=='small_daily_hkg_onsite_fee']['Value'].values)
    daily_xmn_offsite_fee = int(info[info['Measure']=='daily_xmn_offsite_fee']['Value'].values)
    hkg_xmn_transportation_fee = int(info[info['Measure']=='hkg_xmn_transportation_fee']['Value'].values)
    xmn_transportation_fee = int(info[info['Measure']=='xmn_transportation_fee']['Value'].values)
    small_engine_type, xmn_engine_type, _, _ = get_info_engine_type(info)

    df.loc[(~df['ENGINETYPE'].isin(small_engine_type)), 'HaecoCost'] = df['DateDiff']*large_daily_hkg_onsite_fee
    df.loc[(df['ENGINETYPE'].isin(small_engine_type)), 'HaecoCost'] = df['DateDiff']*small_daily_hkg_onsite_fee
    if type == 'haeco':
        # 1. engine needed to ship back to CLK for shop visit
        df['XmnCost'] = df['DateDiff']*daily_xmn_offsite_fee+2*hkg_xmn_transportation_fee
        # 2. engine needed to ship to XMN for shop visit
        if 'RequireShopVisit' in df.columns:
            df.loc[(df['RequireShopVisit']=='True') & (df['ENGINETYPE'].isin(xmn_engine_type)), 'XmnCost'] = df['DateDiff']*daily_xmn_offsite_fee+hkg_xmn_transportation_fee+xmn_transportation_fee
        # staying in XMN is cheaper than staying in haeco
        df['CostSaved'] = np.where(df['XmnCost']<df['HaecoCost'], df['HaecoCost']-df['XmnCost'], 0)
    else:
        # calculate XMN offsite cost
        # 1. consider engine release from xmn shop and ship to xmn offsite directly
        df.loc[(df['ENGINETYPE'].isin(xmn_engine_type)) & (df['Location'] == 'Shop'), 'XmnCost'] = df['DateDiff']*daily_xmn_offsite_fee+xmn_transportation_fee+hkg_xmn_transportation_fee
        # 2. consider engine not release from xmn shop
        df.loc[(~df['ENGINETYPE'].isin(xmn_engine_type)) & (df['Location'] == 'Shop'), 'XmnCost'] = df['DateDiff']*daily_xmn_offsite_fee+2*hkg_xmn_transportation_fee
        # for engine release from xmn offsite, fill the XmnCost with 0
        df['XmnCost'].fillna(0, inplace = True)
        df['CostSaved'] = np.where((df['XmnCost']<df['HaecoCost']) & (df['Location']=='Shop'),
                                   df['HaecoCost']-df['XmnCost'], 0)
    # staying in XMN is more expensive than staying in haeco (for engine needed to be shipped to XMN due to full haeco space)
    df['ExtraMoneySpend'] = np.where(df['XmnCost']>=df['HaecoCost'], df['XmnCost']-df['HaecoCost'], 0)
    df['ShipToXmnOffsite'] = np.where((df['CostSaved']>0) & (df['DateDiff']>5), True, False)
    return df
```

Fig. 10 shows the Cost-saving function Python code

Engine management process function

```python
def create_transfer_df(haeco_calendar, haeco_space, engine_release_plan, info):
    """
    use while loop-> when engine_release_plan is not null
    get the first item of release plan and transform the esm to engine_calendar
    drop the first item after finish
    sort the engine_release_plan on AvailableStartDate
    """
    release_plan_df = engine_release_plan.copy()
    current_haeco_space = haeco_space[['ENGINETYPE', 'ESN', 'Status', 'Location', 'AvailableStartDate', 'AvailableEndDate', 'StartDate', 'EndDate',\
                                       'DateDiff', 'HaecoCost', 'XmnCost', 'CostSaved', 'ExtraMoneySpend', 'ShipToXmnOffsite']].copy()
    df = haeco_calendar[['date', 'remaining_space']].copy()

    delay_day = int(info[info['Measure']=='delay_day']['Value'].values)
    engine_in_calendar = release_plan_df['ESN'].unique()
    transport_df = pd.DataFrame(engine_in_calendar, columns=['engine'])
    transport_df[['CostSaved', 'ExtraMoneySpend', 'Remaining_igloo_space']] = 0
    transport_df[['haeco_transfer_date', 'haeco_transfer_date(With_delay)', 'offsite_transfer_date', 'engine_delay_date']] = pd.to_datetime(np.nan)
    transport_df['Remark', 'ENGINETYPE'] = np.nan
    # engine_ship_out is the engine ship out from haeco to offsite due to full haeco space
    engine_ship_out = pd.DataFrame(columns=['ENGINETYPE', 'ESN', 'Status', 'AvailableStartDate', 'AvailableEndDate', 'StartDate', 'EndDate', 'DateDiff', \
                                            'HaecoCost', 'XmnCost', 'CostSaved', 'ExtraMoneySpend', 'ShipToXmnOffsite', 'TransferESN'])
    serviceable_engine_df = pd.DataFrame(engine_in_calendar, columns=['rfs_engine'])

    def rfs_to_offsite(transport_df, rfs_engine, rfs_date, available_arrival_date, release_plan_df, df):
        # transfer to offsite first and then transfer to haeco when there are available space
        transport_df.loc[transport_df['engine']==rfs_engine ,'offsite_transfer_date'] = rfs_date
        transport_df.loc[transport_df['engine']==rfs_engine, 'haeco_transfer_date'] = available_arrival_date
        transport_df.loc[transport_df['engine']==rfs_engine, 'ExtraMoneySpend'] =  release_plan_df[release_plan_df['ESN']==rfs_engine]['ExtraMoneySpend'].values[0]
        df.loc[(df['date']>=available_arrival_date) & (df['date']<=install_date) , 'remaining_space_'+rfs_engine] = df.loc[(df['date']>=available_arrival_date) & \
                                                                                                                        (df['date']<=install_date) , 'remaining_space_'+rfs_engine] - 1
        return transport_df, df

    def haeco_to_offsite(esn_ship_out, rfs_engine, rfs_date, current_haeco_space, df):
        # ship out haeco engine 2 days before rfs date
        end_date = esn_ship_out['EndDate'].values[0]
        esn_ship_out['EndDate'] = pd.to_datetime(rfs_date)-pd.Timedelta(days=2)
        esn_ship_out['TransferESN'] = rfs_engine
        esn_ship_out['ShipToXmnOffsite'] = True
        esn_ship_date = esn_ship_out['EndDate'].to_list()[0]
        current_haeco_space = current_haeco_space[~current_haeco_space['ESN'].isin(esn_ship_out['ESN'].values)]
        # add one space for remaining_space as one engine is shipped out from haeco to offsite
        df.loc[(df['date']>esn_ship_date) & (df['date']<=end_date), 'remaining_space_'+rfs_engine] = df.loc[(df['date']>esn_ship_date) & (df['date']<=end_date), 'remaining_space_'+rfs_engine] + 1
        return current_haeco_space, df, esn_ship_out
```

Fig. 11 shows the Engine management process function Python code (Part 1)

```python
while len(release_plan_df.head(1)['ESN'].to_list()) != 0:
    rfs_engine = release_plan_df.head(1)['ESN'].values[0]
    rfs_date = release_plan_df[release_plan_df['ESN']==rfs_engine]['AvailableStartDate'].values[0]
    install_date = release_plan_df[release_plan_df['ESN']==rfs_engine]['EndDate'].values[0]
    require_date = release_plan_df[release_plan_df['ESN']==rfs_engine]['AvailableEndDate'].values[0]
    qec_date = release_plan_df[release_plan_df['ESN']==rfs_engine]['QECStart'].values[0]
    current_haeco_space = current_haeco_space[current_haeco_space['EndDate']>rfs_date]
    release_plan_df['temp_date'] = pd.to_datetime(rfs_date)
    # check whcih serviceable engine type needed to ship to haeco
    release_plan_df, esn_ship_from_xmn, esn_ship_from_shop = transform_release_plan(current_haeco_space, info, release_plan_df, release_plan_df['temp_date'])
    serviceable_engine_df.loc[serviceable_engine_df['rfs_engine']==rfs_engine, 'current_time_check'] = rfs_date
    serviceable_engine_df.loc[serviceable_engine_df['rfs_engine']==rfs_engine, 'engine_require_xmn'] = [np.nan if len(esn_ship_from_xmn)==0 else np.array2string(esn_ship_from_xmn)]
    serviceable_engine_df.loc[serviceable_engine_df['rfs_engine']==rfs_engine, 'engine_require_shop'] = [np.nan if len(esn_ship_from_shop)==0 else np.array2string(esn_ship_from_shop)]

    ship_to_haeco = release_plan_df[(release_plan_df['ShipToXmnOffsite']==False) & (release_plan_df['ESN']==rfs_engine) \
                                    ][['ENGINETYPE', 'ESN', 'Status', 'Location', 'AvailableStartDate', 'AvailableEndDate', 'StartDate', 'EndDate', 'DateDiff', 'HaecoCost', 'XmnCost', 'CostSaved', 'Extra
    ship_to_haeco['Status'] = 'S'
    ship_to_haeco['Location'] = 'CLK'
    ship_to_haeco = cost_calculation(ship_to_haeco, info, 'haeco')
    engine_calendar = create_calendar(release_plan_df[release_plan_df['ESN']==rfs_engine], info, 'shop', True)
    df = df.merge(engine_calendar, how = 'left', on = 'date').fillna(0)
    """
    testing
    """
    df.loc[(df['date']>='2023-03-06') & (df['date']<='2023-03-11'), 'remaining_space'] = 0
    df.loc[(df['date']=='2023-04-09'), 'remaining_space'] = 0
    df.loc[(df['date']>='2023-04-21') & (df['date']<='2023-04-22'), 'remaining_space'] = 0
    df.loc[(df['date']>='2023-05-17') & (df['date']<='2023-05-19'), 'remaining_space'] = 0
    ############################################################################################################
    # check if the engine should ship to (variable) release_plan_df: Any
    if release_plan_df.loc[release_plan_ )ffsite'].values == True:
        cost_save = release_plan_df.loc[release_plan_df['ESN']==rfs_engine, 'CostSaved'].values[0]
        transport_df.loc[transport_df['engine']==rfs_engine ,'haeco_transfer_date'] = require_date
        transport_df.loc[transport_df['engine']==rfs_engine ,'offsite_transfer_date'] = rfs_date
        transport_df.loc[transport_df['engine']==rfs_engine ,'CostSaved'] = cost_save
        remark_string = f"Move this engine to offsite for {str(int(release_plan_df.loc[release_plan_df['ESN']==rfs_engine, 'DateDiff'].values[0]))} days can save ${cost_save}"
        transport_df.loc[transport_df['engine']==rfs_engine, 'Remark'] = remark_string
    else:
        df['remaining_space_'+rfs_engine] =  df['remaining_space'] - df[rfs_engine]
        if any(df.loc[(df['date']>=rfs_date) & (df['date']<=install_date), 'remaining_space_'+rfs_engine].values<0):
            # if haeco space is fulled
            last_unavailable_date = df[(df['date']>=rfs_date) & (df['date']<=install_date) & \
                                        (df['remaining_space_'+rfs_engine]<0))]['date'].values[-1]
```

Fig. 12 shows the Engine management process function Python code (Part 2)

```python
    # check if the engine should ship to offsite
    if release_plan_df.loc[release_plan_df['ESN']==rfs_engine, 'ShipToXmnOffsite'].values == True:
        cost_save = release_plan_df.loc[release_plan_df['ESN']==rfs_engine, 'CostSaved'].values[0]
        transport_df.loc[transport_df['engine']==rfs_engine ,'haeco_transfer_date'] = require_date
        transport_df.loc[transport_df['engine']==rfs_engine ,'offsite_transfer_date'] = rfs_date
        transport_df.loc[transport_df['engine']==rfs_engine ,'CostSaved'] = cost_save
        remark_string = f"Move this engine to offsite for {str(int(release_plan_df.loc[release_plan_df['ESN']==rfs_engine, 'DateDiff'].values[0]))} days can save ${cost_save}"
        transport_df.loc[transport_df['engine']==rfs_engine, 'Remark'] = remark_string
    else:
        df['remaining_space_'+rfs_engine] =  df['remaining_space'] - df[rfs_engine]
        if any(df.loc[(df['date']>=rfs_date) & (df['date']<=install_date), 'remaining_space_'+rfs_engine].values<0):
            # if haeco space is fulled
            last_unavailable_date = df[(df['date']>=rfs_date) & (df['date']<=install_date) & \
                                          (df['remaining_space_'+rfs_engine]<0)]['date'].values[-1]
            # arrive when there are available space
            available_arrival_date = last_unavailable_date + np.timedelta64(1,'D')
            # calculate the date difference bwtween available_date and rfs_date
            date_diff = int((available_arrival_date - rfs_date) / np.timedelta64(1, 'D'))
            engine_move_num = abs(int(df.loc[(df['date']>=rfs_date) & (df['date']<=install_date), 'remaining_space_'+rfs_engine].min()))
            df['remaining_space_'+rfs_engine] =  df['remaining_space']
            # require_date is the date that the engine must arrive haeco
            if available_arrival_date>require_date or available_arrival_date==qec_date:
                # calculate the number of engine needed to be shipped out
                for num in range(engine_move_num):
                    esn_ship_out = haeco_space_checking(current_haeco_space, release_plan_df, rfs_engine, info, rfs_date)
                    current_haeco_space, df, esn_ship_out = haeco_to_offsite(esn_ship_out, rfs_engine, rfs_date, current_haeco_space, df)
                    engine_ship_out = engine_ship_out.append(esn_ship_out)
                df['remaining_space_'+rfs_engine] = df['remaining_space_'+rfs_engine] - df[rfs_engine]
                transport_df.loc[transport_df['engine']==rfs_engine, 'haeco_transfer_date'] = rfs_date
                transport_df.loc[transport_df['engine']==rfs_engine, 'ExtraMoneySpend'] =  esn_ship_out['ExtraMoneySpend'].values[0]
                remark_string = (f"Spend ${str(esn_ship_out['ExtraMoneySpend'].values[0])} to move ESN: {str(esn_ship_out['ESN'].values[0])} from haeco to offsite for "
                                 f"{str(int(esn_ship_out['DateDiff'].values[0]))} days due to full haeco space")
                transport_df.loc[transport_df['engine']==rfs_engine, 'Remark'] = remark_string
            else:
                offsite_date_diff = int(release_plan_df[release_plan_df['ESN']==rfs_engine]['DateDiff'].values[0])
                if release_plan_df[release_plan_df['ESN']==rfs_engine]['Location'].values[0] == 'XMNTY':
                    transport_df.loc[transport_df['engine']==rfs_engine, 'haeco_transfer_date'] = available_arrival_date
                    df.loc[(df['date']>=available_arrival_date) & (df['date']<=install_date) , 'remaining_space_'+rfs_engine] = df.loc[(df['date']>=available_arrival_date) & \
                                                                                                                      (df['date']<=install_date) , 'remaining_space_'+rfs_engine] - 1
                    remark_string = (f"Move this engine from offsite to haeco when there is available igloo space in haeco")
                    transport_df.loc[transport_df['engine']==rfs_engine, 'Remark'] = remark_string
```

Fig. 13 shows the Engine management process function Python code (Part 3)

```python
                # delay 'delay_day' from engine shop
                elif date_diff<=delay_day:
                    transport_df.loc[transport_df['engine']==rfs_engine, 'engine_delay_date'] = date_diff
                    transport_df.loc[transport_df['engine']==rfs_engine, 'haeco_transfer_date(With_delay)'] = available_arrival_date
                    remark_string = (f"Delay {date_diff} days from engine shop. Move this engine from shop to haeco when there is available igloo space in haeco")
                    transport_df.loc[transport_df['engine']==rfs_engine, 'Remark'] = remark_string
                    df.loc[(df['date']>=available_arrival_date) & (df['date']<=install_date) , 'remaining_space_'+rfs_engine] = df.loc[(df['date']>=available_arrival_date) & \
                                                                                                                      (df['date']<=install_date) , 'remaining_space_'+rfs_engine] - 1
                # if the engine needed to ship out from haeco is greater than 1, ship rfs engine to offsite
                elif engine_move_num>1:
                    transport_df, df = rfs_to_offsite(transport_df, rfs_engine, rfs_date, available_arrival_date, release_plan_df, df)
                    remark_string = f"Ship this engine to offsite as it needs to move {str(engine_move_num)} engines from haeco to offsite"
                    transport_df.loc[transport_df['engine']==rfs_engine, 'Remark'] = remark_string
                else:
                    # else, compare the ExtraMoneySpend of haeco engine to offsite and ExtraMoneySpend of rfs engine to offsite
                    esn_ship_out = haeco_space_checking(current_haeco_space, release_plan_df, rfs_engine, info, rfs_date)
                    haeco_ship_out_cost = int(esn_ship_out['ExtraMoneySpend'].values[0])
                    rfs_ship_out_cost = int(release_plan_df.loc[release_plan_df['ESN']==rfs_engine, 'ExtraMoneySpend'].values[0])
                    # ship rfs engine to offsite is cheaper
                    if haeco_ship_out_cost > rfs_ship_out_cost:
                        transport_df, df = rfs_to_offsite(transport_df, rfs_engine, rfs_date, available_arrival_date, release_plan_df, df)
                        remark_string = (f"Spend ${str(rfs_ship_out_cost)} to move this engine from shop to offsite for {str(date_diff)} days due to full haeco space."
                            f" Move this engine when there is available space in Haeco. \n(move ESN: {str(esn_ship_out['ESN'].values[0])} from haeco to offsite for {str(int(esn_ship_out['DateDiff'].value
                            f" days costs ${str(haeco_ship_out_cost)})")
                        transport_df.loc[transport_df['engine']==rfs_engine, 'Remark'] = remark_string
                    # ship haeco engine to offsite is cheaper
                    else:
                        current_haeco_space, df, esn_ship_out = haeco_to_offsite(esn_ship_out, rfs_engine, rfs_date, current_haeco_space, df)
                        engine_ship_out = engine_ship_out.append(esn_ship_out)
                        df['remaining_space_'+rfs_engine] = df['remaining_space_'+rfs_engine] - df[rfs_engine]
                        transport_df.loc[transport_df['engine']==rfs_engine, 'haeco_transfer_date'] = rfs_date
                        transport_df.loc[transport_df['engine']==rfs_engine, 'ExtraMoneySpend'] =  haeco_ship_out_cost
                        remark_string = (f"Spend ${str(haeco_ship_out_cost)} to move ESN: {str(esn_ship_out['ESN'].values[0])} from haeco "
                         f"to offsite for {str(int(esn_ship_out['DateDiff'].values[0]))} days due to full haeco space \n(move this engine from shop to offsite cost ${str(rfs_ship_out_cost)})")
                        transport_df.loc[transport_df['engine']==rfs_engine, 'Remark'] = remark_string
```

Fig. 14 shows the Engine management process function Python code (Part 4)

```python
                    transport_df.loc[transport_df['engine']==rfs_engine, 'Remark'] = remark_string
            else:
                # transfer to haeco directly
                transport_df.loc[transport_df['engine']==rfs_engine ,'haeco_transfer_date'] = rfs_date
            df['remaining_space'] = df['remaining_space_'+rfs_engine]
        transport_df.loc[transport_df['engine']==rfs_engine, 'ENGINETYPE'] = release_plan_df[release_plan_df['ESN']==rfs_engine]['ENGINETYPE'].values[0]
        transport_df.loc[transport_df['engine']==rfs_engine, 'Remaining_igloo_space'] = df[df['date']==rfs_date]['remaining_space'].values[0]
        # add rfs engine to current_haeco_space when it arrive haeco
        current_haeco_space = current_haeco_space.append(ship_to_haeco)
        release_plan_df = release_plan_df[release_plan_df['ESN']!=rfs_engine]
        release_plan_df = release_plan_df.sort_values('AvailableStartDate')
    return transport_df[['ENGINETYPE', 'engine', 'haeco_transfer_date', 'haeco_transfer_date(With_delay)', 'offsite_transfer_date', 'engine_delay_date', 'CostSaved', 'ExtraMoneySpend', 'Remaining_igloo_space
            engine_ship_out, df, serviceable_engine_df

def create_to_do_list(transport_df, haeco_engine, engine_ship_out, df):
    transport_df = transport_df[['ENGINETYPE', 'engine', 'haeco_transfer_date', 'haeco_transfer_date(With_delay)', 'offsite_transfer_date']].copy()
    transport_df_offsite = transport_df[~transport_df['offsite_transfer_date'].isna()]
    transport_df = transport_df[transport_df['offsite_transfer_date'].isna()]

    haeco_engine = haeco_engine[haeco_engine['ShipToXmnOffsite']==True][['ENGINETYPE', 'ESN', 'EndDate']].copy()
    df = df[['ENGINETYPE', 'ESN', 'ShopReleasefromshop', 'QECStart', 'QECCompletion', 'EngineInstallation', 'ShopVisitInduction']].copy()
    engine_ship_out = engine_ship_out[['ENGINETYPE', 'ESN', 'EndDate']].copy()
    engine_ship_out = engine_ship_out.append(haeco_engine)
    transport_df_offsite = transport_df_offsite.rename(columns={'ENGINETYPE': 'Engine Type', 'engine': 'ESN', 'haeco_transfer_date': 'Offsite to Haeco', 'haeco_transfer_date(With_delay)': 'Shop to Haeco (Wit
                                                    'offsite_transfer_date': 'Shop to Offsite'}).melt(id_vars=['Engine Type', 'ESN'], var_name='Engine Movement', value_name='Date').dropna()

    transport_df = transport_df.rename(columns={'ENGINETYPE': 'Engine Type', 'engine': 'ESN', 'haeco_transfer_date': 'Shop to Haeco', 'haeco_transfer_date(With_delay)': 'Shop to Haeco (With delay)', \
                                                    'offsite_transfer_date': 'Shop to Offsite'}).melt(id_vars=['Engine Type', 'ESN'], var_name='Engine Movement', value_name='Date').dropna()

    engine_ship_out = engine_ship_out.rename(columns={'ENGINETYPE': 'Engine Type', 'EndDate': 'Date'})
    engine_ship_out['Engine Movement'] = 'Haeco to Offsite'
    df = df.rename(columns={'ENGINETYPE': 'Engine Type', 'ShopReleasefromshop': 'Release From Shop', 'QECStart': 'QEC Start', 'QECCompletion': 'QEC Completion', \
                                'EngineInstallation': 'Engine Installation', 'ShopVisitInduction': 'Shop Visit Induction'}).melt(id_vars=['Engine Type', 'ESN'], var_name='Engine Movement', value_name='Date').dro
    final_df = pd.concat([transport_df, transport_df_offsite, engine_ship_out, df])
    return final_df.sort_values(by=['Engine Type', 'ESN', 'Date']).reset_index(drop=True)
```

Fig. 15 shows the Engine management process function Python code (Part 5)

6. Appendix B (Excel input)

Data input for Cathay Pacific - 1

	A	B	C	D	E	F	G	H	I	J	K
1	ENGINE TYPE	ESN	Status	Location	Shop Release from shop	QEC Start	QEC Completion	Engine Installation	Ready for pick-up (From CLK	Shop Visit Induction	Remarks
2	T700	42126	US	CLK		N/A	N/A			1/5/2023	
3	T700	41034	US	XMNTY		N/A	N/A			1/1/2024	No SV plan in 2023
4	T700	41060	US	XMNTY		N/A	N/A			1/1/2024	No SV plan in 2023
5	T700	41197	US	CLK		N/A	N/A			1/1/2024	No SV plan in 2023
6	T700	41203	US	XMNTY		N/A	N/A			8/5/2023	
7	T700	41275	US	CLK		N/A	N/A			1/9/2023	
8	T700	41417	US	XMNTY		N/A	N/A			1/10/2023	
9	T700	41860	US	CLK		N/A	N/A			15/4/2023	
10	T700	42088	US	XMNTY		N/A	N/A			1/1/2024	No SV plan in 2023
11	T700	42568	S	XMNTY		N/A	N/A	1/7/2023			
12	T800	51096	US	CLK						1/7/2023	
13	TXWB-84	21092	S	CLK		11/5/2023	15/5/2023	17/5/2023			
14	TXWB-84	21138	S	CLK		23/4/2023	27/4/2023	29/4/2023			
15	TXWB-84	21142	US	Shop	27/4/2023	25/8/2023					
16	TXWB-84	21167	US	Shop	17/3/2023	10/6/2023	14/6/2023	15/6/2023			
17	TXWB-84	21306	US	CLK		23/4/2023	27/4/2023		28/4/2023	1/6/2023	
18	TXWB-97	26028	S	CLK		7/3/2023	11/3/2023	12/3/2023			
19	TXWB-97	26035	S	CLK		16/3/2023	20/3/2023	23/3/2023			
20	TXWB-97	26036	Repair	Shop	4/5/2023	5/5/2023	9/5/2023	10/5/2023			
21	TXWB-97	26043	Repair	Shop	9/4/2023	10/4/2023	14/4/2023	15/4/2023			
22	TXWB-97	26058	Repair	Shop	23/4/2023	24/4/2023	28/4/2023	29/4/2023			
23	TXWB-97	26081	Repair	Shop	28/3/2023	29/3/2023	2/4/2023	4/4/2023			
24	GEnx-2B	959361	Repair	Shop	28/4/2023	29/4/2023	3/5/2023	5/5/2023			
25	GEnx-2B	959406	US	CLK					21/3/2023	20/4/2023	
26	GEnx-2B	959368	US	CLK					15/3/2023	14/4/2023	
27	GEnx-2B	959687	Repair	Shop	17/5/2023	8/6/2023	13/6/2023	15/6/2023			
28	GEnx-2B	959692	Repair	Shop	17/9/2023	TBC					
29	GEnx-2B	959636	Repair	Shop	17/7/2023	TBC				29/3/2023	
30	GE90-115B	906354	S	XMNTY		1/7/2023	5/7/2023	7/7/2023			Propulsor
31	GE90-115B	906927	S	CLK		23/3/2023	27/3/2023	29/3/2023			Whole Engine
32	GE90-115B	907310	S	XMNTY		20/7/2023	24/7/2023	26/7/2023			Propulsor
33	GE90-115B	907311	S	XMNTY		15/8/2023	19/8/2023	21/8/2023			Propulsor
34	GE90-115B	907365	Repair	Shop	26/4/2023	9/5/2023	13/5/2023	15/5/2023			Propulsor
35	GE90-115B	907366	Repair	Shop	1/10/2023	5/10/2023	9/10/2023	11/10/2023			Propulsor
36	GE90-115B	907435	Repair	Shop	20/5/2023	24/5/2023	28/5/2023	30/5/2023			Propulsor
37	GE90-115B	907553	S	XMNTY		4/4/2023	8/4/2023	12/4/2023			Propulsor
38	GE90-115B	907566	S	XMNTY		25/4/2023	29/4/2023	30/4/2023			Propulsor
39	GE90-115B	907835	S	XMNTY		20/9/2023	24/9/2023	26/9/2023			Propulsor
40	GE90-115B	907836	S	XMNTY		1/9/2023	5/9/2023	7/9/2023			Propulsor
41	PW4062A-3	P727633	S	CLK				1/1/2024			No plan for 2023
42	PW4062A-3	P729250	Repair	Shop	15/3/2023			1/1/2024			No plan for 2023
43	PW4062A-3	P729252	Repair	Shop	15/4/2023			1/1/2024			No plan for 2023
44	PW4062A-3	P729253	S	CLK				1/1/2024			No plan for 2023
45	PW4062A-3	P729255	S	CLK				1/1/2024			No plan for 2023 - Restricted for non-Japanese flight only.
46	PW4062A-3	P729263	Repair	Shop	15/5/2023			1/1/2024			No plan for 2023
47											
48											

Fig. 16 shows Excel Data input for Cathay Pacific - 1

Data input for Cathay Pacific - 2

	A	B
1	Measure	Value
2	large_reserved_igloo	15
3	small_reserved_igloo	2
4	large_daily_hkg_onsite_fee	1421
5	small_daily_hkg_onsite_fee	1040
6	daily_xmn_offsite_fee	228
7	hkg_xmn_transportation_fee	44490
8	xmn_transportation_fee	14930
9	small_engine_type	PW4062A-3
10	xmn_engine_type	GE90-115B
11	engine_type	T700, T800, TXWB-84, TXWB-97, GEnx-2B, GE90-115B, PW4062A-3
12	delay_day	3
13		

Fig. 17 shows Excel Data input for Cathay Pacific - 2

6. Appendix C (Excel outputs)

Reason for each movement

	A	B	C	D	E	F	G	H	I	J
1	ENGINETYPE	engine	haeco_transfer_date	haeco_transfer_date(With_delay)	offsite_transfer_date	engine_delay_date	CostSayed	ExtraMoneySpend	Remaining_igloo_space	Remark
2	T700	42568	2023-03-05 00:00:00				0	9049	2	Spend $9049.0 to move ESN: 21092 from haeco to offsite for 67 days due to full haeco space
3	TXWB-84	21167	2023-06-08 00:00:00		2023-03-17 00:00:00		10039	0	6	Move this engine to offsite for 83 days can save $10039.0
4	TXWB-97	26081	2023-03-28 00:00:00				0	0	6	
5	GE90-115B	907553	2023-03-31 00:00:00				0	51997	7	Spend $51997.0 to move ESN: 42126 from haeco to offsite for 31 days due to full haeco space
6	TXWB-97	26043	2023-04-09 00:00:00				0	75857	0	Spend $75857.0 to move ESN: 959406 from haeco to offsite for 11 days due to full haeco space
7	GE90-115B	907566	2023-04-23 00:00:00				0	0	0	Move this engine from offsite to haeco when there is available igloo space in haeco
8	TXWB-97	26058	2023-04-23 00:00:00				0	0	10	
9	GE90-115B	907365	2023-04-26 00:00:00				0	0	9	
10	TXWB-84	21142	2023-08-23 00:00:00		2023-04-27 00:00:00		51794	0	9	Move this engine to offsite for 118 days can save $51794.0
11	GEnx-2B	959361	2023-04-28 00:00:00				0	0	8	
12	TXWB-97	26036	2023-05-04 00:00:00				0	0	10	
13	GEnx-2B	959687	2023-06-06 00:00:00	2023-05-20 00:00:00	2023-05-17 00:00:00	3	0	65120	0	Spend $65120 to move this engine from shop to offsite for 20 days due to full haeco space (move ESN: 21306 from haeco to offsite for 15 days costs $71085)
14	GE90-115B	907435	2023-05-20 00:00:00				0	0	12	
15	GE90-115B	906354	2023-06-27 00:00:00				0	0	13	
16	GE90-115B	907310	2023-07-16 00:00:00				0	0	14	
17	GEnx-2B	959636	2023-07-17 00:00:00				0	0	13	
18	GE90-115B	907311	2023-08-11 00:00:00				0	0	13	
19	GE90-115B	907836	2023-08-28 00:00:00				0	0	13	
20	GE90-115B	907835	2023-09-16 00:00:00				0	0	13	
21	GEnx-2B	959692	2024-02-28 00:00:00		2023-09-17 00:00:00		106672	0	13	Move this engine to offsite for 164 days can save $106672.0
22	GE90-115B	907366	2023-10-01 00:00:00				0	0	13	
23	PW4062A-3	P729250	2023-12-30 00:00:00		2023-03-15 00:00:00		146500	0	1	Move this engine to offsite for 290 days can save $146500.0
24	PW4062A-3	P729252	2023-12-30 00:00:00		2023-04-15 00:00:00		121328	0	1	Move this engine to offsite for 259 days can save $121328.0
25	PW4062A-3	P729263	2023-12-30 00:00:00		2023-05-15 00:00:00		96968	0	1	Move this engine to offsite for 229 days can save $96968.0
26										
27										

Fig. 18 shows the overview and reason for each movement

To-do list

	A	B	C	D
1	Engine Type	ESN	Engine Movement	Date
2	GE90-115B	906354	Shop to Haeco	2023-06-27 00:00:00
3	GE90-115B	906354	QEC Start	2023-07-01 00:00:00
4	GE90-115B	906354	QEC Completion	2023-07-05 00:00:00
5	GE90-115B	906354	Engine Installation	2023-07-07 00:00:00
6	GE90-115B	906927	QEC Start	2023-03-23 00:00:00
7	GE90-115B	906927	QEC Completion	2023-03-27 00:00:00
8	GE90-115B	906927	Engine Installation	2023-03-29 00:00:00
9	GE90-115B	907310	Shop to Haeco	2023-07-16 00:00:00
10	GE90-115B	907310	QEC Start	2023-07-20 00:00:00
11	GE90-115B	907310	QEC Completion	2023-07-24 00:00:00
12	GE90-115B	907310	Engine Installation	2023-07-26 00:00:00
13	GE90-115B	907311	Shop to Haeco	2023-08-11 00:00:00
14	GE90-115B	907311	QEC Start	2023-08-15 00:00:00
15	GE90-115B	907311	QEC Completion	2023-08-19 00:00:00
16	GE90-115B	907311	Engine Installation	2023-08-21 00:00:00
17	GE90-115B	907365	Shop to Haeco	2023-04-26 00:00:00
18	GE90-115B	907365	Release From Shop	2023-04-26 00:00:00
19	GE90-115B	907365	QEC Start	2023-05-09 00:00:00
20	GE90-115B	907365	QEC Completion	2023-05-13 00:00:00
21	GE90-115B	907365	Engine Installation	2023-05-15 00:00:00
22	GE90-115B	907366	Shop to Haeco	2023-10-01 00:00:00
23	GE90-115B	907366	Release From Shop	2023-10-01 00:00:00
24	GE90-115B	907366	QEC Start	2023-10-05 00:00:00
25	GE90-115B	907366	QEC Completion	2023-10-09 00:00:00
26	GE90-115B	907366	Engine Installation	2023-10-11 00:00:00
27	GE90-115B	907435	Shop to Haeco	2023-05-20 00:00:00
28	GE90-115B	907435	Release From Shop	2023-05-20 00:00:00
29	GE90-115B	907435	QEC Start	2023-05-24 00:00:00
30	GE90-115B	907435	QEC Completion	2023-05-28 00:00:00

Fig. 19 shows the to-do list

Cost-calculation support

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	ENGINETYPE	ESN	Status	Location	ShopReleasefromshop	QECStart	QECCompletion	EngineInstallation	Readyforpick-up(FromCLK)	ShopVisitInduction	Remarks	CurrentDate	AvailableStartDate	AvailableEndDate	DateDiff	HaecoCost	XmnCost	CostSaved
2	T700	42568	S	XMNTY				2023-07-01 00:00:00				2023-03-01 00:00:00	2023-03-05 00:00:00	2023-03-09 00:00:00	116	164836	0	0
3	TXWB-84	21167	US	Shop	2023-03-17 00:00:00	2023-06-10 00:00:00	2023-06-14 00:00:00	2023-06-15 00:00:00				2023-03-01 00:00:00	2023-03-17 00:00:00	2023-06-08 00:00:00	83	117943	107904	10039
4	TXWB-97	26081	Repair	Shop	2023-03-28 00:00:00	2023-03-29 00:00:00	2023-04-02 00:00:00	2023-04-04 00:00:00				2023-03-01 00:00:00	2023-03-28 00:00:00	2023-03-29 00:00:00	1	1421	89208	0
5	GE90-115B	907553	S	XMNTY		2023-04-04 00:00:00	2023-04-08 00:00:00	2023-04-12 00:00:00			Propulsor	2023-03-01 00:00:00	2023-03-31 00:00:00	2023-04-02 00:00:00	2	2842	0	0
6	TXWB-97	26043	Repair	Shop	2023-04-09 00:00:00	2023-04-10 00:00:00	2023-04-14 00:00:00	2023-04-15 00:00:00				2023-03-01 00:00:00	2023-04-09 00:00:00	2023-04-10 00:00:00	1	1421	89208	0
7	GE90-115B	907566	S	XMNTY		2023-04-25 00:00:00	2023-04-29 00:00:00	2023-04-30 00:00:00			Propulsor	2023-03-01 00:00:00	2023-04-21 00:00:00	2023-04-23 00:00:00	2	2842	0	0
8	TXWB-97	26058	Repair	Shop	2023-04-23 00:00:00	2023-04-24 00:00:00	2023-04-28 00:00:00	2023-04-29 00:00:00				2023-03-01 00:00:00	2023-04-23 00:00:00	2023-04-24 00:00:00	1	1421	89208	0
9	GE90-115B	907365	Repair	Shop	2023-04-26 00:00:00	2023-05-09 00:00:00	2023-05-13 00:00:00	2023-05-15 00:00:00			Propulsor	2023-03-01 00:00:00	2023-04-26 00:00:00	2023-05-07 00:00:00	11	15631	61928	0
10	TXWB-84	21142	US	Shop	2023-04-27 00:00:00	2023-08-25 00:00:00						2023-03-01 00:00:00	2023-04-27 00:00:00	2023-08-23 00:00:00	118	167678	115884	51794
11	GEnx-2B	959361	Repair	Shop	2023-04-28 00:00:00	2023-04-29 00:00:00	2023-05-03 00:00:00	2023-05-05 00:00:00				2023-03-01 00:00:00	2023-04-28 00:00:00	2023-04-29 00:00:00	1	1421	89208	0
12	TXWB-97	26036	Repair	Shop	2023-05-04 00:00:00	2023-05-05 00:00:00	2023-05-09 00:00:00	2023-05-10 00:00:00				2023-03-01 00:00:00	2023-05-04 00:00:00	2023-05-05 00:00:00	1	1421	89208	0
13	GEnx-2B	959687	Repair	Shop	2023-05-17 00:00:00	2023-06-08 00:00:00	2023-06-13 00:00:00	2023-06-15 00:00:00				2023-03-01 00:00:00	2023-05-17 00:00:00	2023-06-06 00:00:00	20	28420	93540	0
14	GE90-115B	907435	Repair	Shop	2023-05-20 00:00:00	2023-05-24 00:00:00	2023-05-28 00:00:00	2023-05-30 00:00:00			Propulsor	2023-03-01 00:00:00	2023-05-20 00:00:00	2023-05-22 00:00:00	2	2842	59876	0
15	GE90-115B	906354	S	XMNTY		2023-07-01 00:00:00	2023-07-05 00:00:00	2023-07-07 00:00:00			Propulsor	2023-03-01 00:00:00	2023-06-27 00:00:00	2023-06-29 00:00:00	2	2842	0	0
16	GE90-115B	907310	S	XMNTY		2023-07-20 00:00:00	2023-07-24 00:00:00	2023-07-26 00:00:00			Propulsor	2023-03-01 00:00:00	2023-07-16 00:00:00	2023-07-18 00:00:00	2	2842	0	0
17	GEnx-2B	959636	Repair	Shop	2023-07-17 00:00:00	2024-03-01 00:00:00				2023-03-29 00:00:00		2023-03-01 00:00:00	2023-07-17 00:00:00	2024-02-28 00:00:00	226	321146	140508	180638
18	GE90-115B	907311	S	XMNTY		2023-08-15 00:00:00	2023-08-19 00:00:00	2023-08-21 00:00:00			Propulsor	2023-03-01 00:00:00	2023-08-11 00:00:00	2023-08-13 00:00:00	2	2842	0	0
19	GE90-115B	907836	S	XMNTY		2023-09-01 00:00:00	2023-09-05 00:00:00	2023-09-07 00:00:00			Propulsor	2023-03-01 00:00:00	2023-08-28 00:00:00	2023-08-30 00:00:00	2	2842	0	0
20	GE90-115B	907835	S	XMNTY		2023-09-20 00:00:00	2023-09-24 00:00:00	2023-09-26 00:00:00			Propulsor	2023-03-01 00:00:00	2023-09-16 00:00:00	2023-09-18 00:00:00	2	2842	0	0
21	GEnx-2B	959692	Repair	Shop	2023-09-17 00:00:00	2024-03-01 00:00:00						2023-03-01 00:00:00	2023-09-17 00:00:00	2024-02-28 00:00:00	164	233044	126372	106672
22	GE90-115B	907366	Repair	Shop	2023-10-01 00:00:00	2023-10-05 00:00:00	2023-10-09 00:00:00	2023-10-11 00:00:00			Propulsor	2023-03-01 00:00:00	2023-10-01 00:00:00	2023-10-03 00:00:00	2	2842	59876	0

Fig. 20 shows the Cost-calculation support (part1)

	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
1	QECStart	QECCompletion	EngineInstallation	Readyforpick-up(FromCLK)	ShopVisitInduction	Remarks	CurrentDate	AvailableStartDate	AvailableEndDate	DateDiff	HaecoCost	XmnCost	CostSaved	ExtraMoneySpend	ShipToXmnOffsite	EndDate	StartDate
2			2023-07-01 00:00:00				2023-03-01 00:00:00	2023-03-05 00:00:00	2023-03-09 00:00:00	116	164836	0	0	0	FALSE	2023-07-01 00:00:00	2023-03-05 00:00:00
3	23-06-10 00:00:00	2023-06-14 00:00:00	2023-06-15 00:00:00				2023-03-01 00:00:00	2023-03-17 00:00:00	2023-06-08 00:00:00	83	117943	107904	10039	0	TRUE	2023-06-15 00:00:00	2023-03-17 00:00:00
4	23-03-29 00:00:00	2023-04-02 00:00:00	2023-04-04 00:00:00				2023-03-01 00:00:00	2023-03-28 00:00:00	2023-03-29 00:00:00	1	1421	89208	0	87787	FALSE	2023-04-04 00:00:00	2023-03-28 00:00:00
5	23-04-04 00:00:00	2023-04-08 00:00:00	2023-04-12 00:00:00			Propulsor	2023-03-01 00:00:00	2023-03-31 00:00:00	2023-04-02 00:00:00	2	2842	0	0	0	FALSE	2023-04-12 00:00:00	2023-03-31 00:00:00
6	23-04-10 00:00:00	2023-04-14 00:00:00	2023-04-15 00:00:00				2023-03-01 00:00:00	2023-04-09 00:00:00	2023-04-10 00:00:00	1	1421	89208	0	87787	FALSE	2023-04-15 00:00:00	2023-04-09 00:00:00
7	23-04-25 00:00:00	2023-04-29 00:00:00	2023-04-30 00:00:00			Propulsor	2023-03-01 00:00:00	2023-04-21 00:00:00	2023-04-23 00:00:00	2	2842	0	0	0	FALSE	2023-04-30 00:00:00	2023-04-21 00:00:00
8	23-04-24 00:00:00	2023-04-28 00:00:00	2023-04-29 00:00:00				2023-03-01 00:00:00	2023-04-23 00:00:00	2023-04-24 00:00:00	1	1421	89208	0	87787	FALSE	2023-04-29 00:00:00	2023-04-23 00:00:00
9	23-05-09 00:00:00	2023-05-13 00:00:00	2023-05-15 00:00:00			Propulsor	2023-03-01 00:00:00	2023-04-26 00:00:00	2023-05-07 00:00:00	11	15631	61928	0	46297	FALSE	2023-05-15 00:00:00	2023-04-26 00:00:00
10	23-08-25 00:00:00						2023-03-01 00:00:00	2023-04-27 00:00:00	2023-08-23 00:00:00	118	167678	115884	51794	0	TRUE	2023-11-25 00:00:00	2023-04-27 00:00:00
11	23-04-29 00:00:00	2023-05-03 00:00:00	2023-05-05 00:00:00				2023-03-01 00:00:00	2023-04-28 00:00:00	2023-04-29 00:00:00	1	1421	89208	0	87787	FALSE	2023-05-05 00:00:00	2023-04-28 00:00:00
12	23-05-05 00:00:00	2023-05-09 00:00:00	2023-05-10 00:00:00				2023-03-01 00:00:00	2023-05-04 00:00:00	2023-05-05 00:00:00	1	1421	89208	0	87787	FALSE	2023-05-10 00:00:00	2023-05-04 00:00:00
13	23-06-08 00:00:00	2023-06-13 00:00:00	2023-06-15 00:00:00				2023-03-01 00:00:00	2023-05-17 00:00:00	2023-06-06 00:00:00	20	28420	93540	0	65120	FALSE	2023-06-15 00:00:00	2023-05-17 00:00:00
14	23-05-24 00:00:00	2023-05-28 00:00:00	2023-05-30 00:00:00			Propulsor	2023-03-01 00:00:00	2023-05-20 00:00:00	2023-05-22 00:00:00	2	2842	59876	0	57034	FALSE	2023-05-30 00:00:00	2023-05-20 00:00:00
15	23-07-01 00:00:00	2023-07-05 00:00:00	2023-07-07 00:00:00			Propulsor	2023-03-01 00:00:00	2023-06-27 00:00:00	2023-06-29 00:00:00	2	2842	0	0	0	FALSE	2023-07-07 00:00:00	2023-06-27 00:00:00
16	23-07-20 00:00:00	2023-07-24 00:00:00	2023-07-26 00:00:00			Propulsor	2023-03-01 00:00:00	2023-07-16 00:00:00	2023-07-18 00:00:00	2	2842	0	0	0	FALSE	2023-07-26 00:00:00	2023-07-16 00:00:00
17	24-03-01 00:00:00				2023-03-29 00:00:00		2023-03-01 00:00:00	2023-07-17 00:00:00	2024-02-28 00:00:00	226	321146	140508	180638	0	TRUE	2024-06-01 00:00:00	2023-07-17 00:00:00
18	23-08-15 00:00:00	2023-08-19 00:00:00	2023-08-21 00:00:00			Propulsor	2023-03-01 00:00:00	2023-08-11 00:00:00	2023-08-13 00:00:00	2	2842	0	0	0	FALSE	2023-08-21 00:00:00	2023-08-11 00:00:00
19	23-09-01 00:00:00	2023-09-05 00:00:00	2023-09-07 00:00:00			Propulsor	2023-03-01 00:00:00	2023-08-28 00:00:00	2023-08-30 00:00:00	2	2842	0	0	0	FALSE	2023-09-07 00:00:00	2023-08-28 00:00:00
20	23-09-20 00:00:00	2023-09-24 00:00:00	2023-09-26 00:00:00			Propulsor	2023-03-01 00:00:00	2023-09-16 00:00:00	2023-09-18 00:00:00	2	2842	0	0	0	FALSE	2023-09-26 00:00:00	2023-09-16 00:00:00
21	24-03-01 00:00:00						2023-03-01 00:00:00	2023-09-17 00:00:00	2024-02-28 00:00:00	164	233044	126372	106672	0	TRUE	2024-06-01 00:00:00	2023-09-17 00:00:00
22	23-10-05 00:00:00	2023-10-09 00:00:00	2023-10-11 00:00:00			Propulsor	2023-03-01 00:00:00	2023-10-01 00:00:00	2023-10-03 00:00:00	2	2842	59876	0	57034	FALSE	2023-10-11 00:00:00	2023-10-01 00:00:00

Fig. 21 shows the Cost-calculation support (part2)