RGC Ref. No.:
UGC/FDS14/E05/18
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RESEARCH GRANTS COUNCIL
COMPETITIVE RESEARCH FUNDING SCHEMES FOR THE LOCAL SELF-FINANCING DEGREE SECTOR

FACULTY DEVELOPMENT SCHEME (FDS)

Completion Report
(for completed projects only)

Submission Deadlines:	*1. Auditor's report with unspent balance, if any: within **six** months of the approved project completion date.* *2. Completion report: within **12** months of the approved project completion date.*

Part A: The Project and Investigator(s)

1. Project Title

The Impacts of Heterogeneous Maintenance Actions on Aircraft Routing Problems in regard to Airline Operations Reliability and Profitability

2. Investigator(s) and Academic Department(s) / Unit(s) Involved

Research Team	Name / Post	Unit / Department / Institution
Principal Investigator	Dr MA Hoi-Lam (Associate Professor)	Supply Chain and Information Management, The Hang Seng University of Hong Kong
Co-Investigator	Prof CHAN Hing-Kai (Professor)	Operations Management, The University of Nottingham
Co-Investigator	Dr CHUNG Sai-Ho (Associate Professor)	Industrial and Systems Engineering, The Hong Kong Polytechnic University

3. Project Duration

	Original	Revised	Date of RGC / Institution Approval *(must be quoted)*
Project Start Date	1 January 2019		
Project Completion Date	31 December 2021		
Duration *(in month)*	36		

Deadline for Submission of Completion Report	31 December 2022		

Part B: The Final Report

5. Project Objectives

5.1 Objectives as per original application

1. To conduct data analysis using machine learning to estimate the time and risk associated with each maintenance packages
2. To develop a new package-based ARP modeling approach that can consider heterogeneous maintenance activities
3. To develop a new Column Generation-based methodology for the package-based ARP model
4. To verify the proposed Column Generation-based methodology
5. To conduct various numerical experiments to study the impacts of the new maintenance practice on ARP towards improving airline operations reliability and profitability

5.2 Revised objectives

Date of approval from the RGC: N/A

Reasons for the change:

1.

2.

3. ..

5.3 Realisation of the objectives
(Maximum 1 page; please state how and to what extent the project objectives have been achieved; give reasons for under-achievements and outline attempts to overcome problems, if any)

To achieve *Objective 1*, we collected historical maintenance data regarding Airbus A320 from the project advisor. Then, we conducted data cleaning and pre-processing. We firstly applied Artificial Neural Network for maintenance time prediction with a prediction accuracy of about only 60%. Then, we explored to apply Long Short-Term Memory (LSTM) network and found that the prediction accuracy was improved to about 80% by using sigmoid activation function in the hidden layers and ReLU for the output layer. Moreover, we proposed to model the maintenance risk associated with each individual maintenance task (package) by using the ratio between the deviation of the predicted maintenance time found in different prediction runs and the available ground time assigned, e.g., if a task is predicted to be completed in 60 min and the deviation is 20 min being assigned to a ground time of 100 min, the risk of this maintenance task is regarded as low in causing flight delay. In addition, in our extended work, we further explored to apply fuzzy logic approach to model the maintenance risk. Thus, Objective 1 is fully achieved.

To achieve *Objective 2*, we first of all conducted a comprehensive literature review. As prior literature commonly assumes homogeneous maintenance tasks, we proposed a novel ARP modeling approach for heterogeneous maintenance tasks. We modelled the route generation process with a new network model with two types of arcs – flight connection arcs and maintenance arcs. Then, a maintenance task was conducted through a maintenance arc with uncertainties. In addition, to explicitly consider the maintenance uncertainties of heterogenous maintenance tasks in robust aircraft maintenance routings, we modelled the duration of a heterogenous maintenance task using a proper probability distribution (i.e., truncated lognormal distribution), which we estimated from Objective 1. Thus, Objective 2 is fully achieved.

To achieve *Objective 3*, we developed a new column generation-based method. In the master problem, we developed new constraints to govern the maintenance capacity of the maintenance stations. In addition, we used the network model developed in Objective 2 as the pricing problem of the proposed column generation method. Moreover, to consider heterogeneous maintenance activities, each task of an individual aircraft has its own maximum flight time according to the current processing task. Therefore, the task being handled is dynamically recorded. As a result, we proposed labels to track: (1) the cost of the (partial) route, (2) the expected propagated delay, (3) the current processing task, and (4) the accumulated flight time. To ease the computational complexity and the significantly increased growth of the network size and the number of resources, we proposed one extension strategy and two dominance strategies as our acceleration strategies to reduce the computational burden. The dominance rule reduces the number of labels, while the extension rule reduces the effort in exploration. Thus, Objective 3 is achieved.

To achieve *Objective 4*, we conducted different computational experiments to verify the proposed column generation methodology. First, we examined the computational burden reduced by our proposed extension strategy and the two acceleration strategies. We compared the situations between without any acceleration strategy and with i) one of the proposed acceleration strategies at a time, and ii) all the proposed strategies together. Moreover, we examined the solution quality in different problem scales. The results demonstrated that the proposed methodology could obtain optimal or near-optimal solutions. Thus, Objective 4 is achieved.

To achieve *Objective 5*, we conducted comparative experiments to study the impacts of maintenance tasks with different degrees of maintenance duration uncertainties on aircraft schedules. We found that maintenance duration significantly influences the reliability of aircraft schedules, and the variability in the delays in selected routes also highlights the importance of capturing maintenance uncertainties within the aircraft routing framework. We further conducted experiments to examine the robustness enhancement of the proposed approach. We derived some scenarios by tightening the ground time when processing heterogenous maintenance tasks. The results show that the ratio of maintenance duration to ground time is more balanced. This indicated that the proposed model, which incorporates new maintenance practices on ARP could generate aircraft routes with better buffer times to absorb certain quantities of extended execution times of maintenance tasks and, as a result, improving airline operations reliability and profitability. In addition, in our extended work, we explored the impact of disruption on ARP and proposed a re-routing algorithm for recovery as well as spare parts management on ARP.

5.4 Summary of objectives addressed to date

Objectives *(as per 5.1/5.2 above)*	**Addressed** *(please tick)*	**Percentage Achieved** *(please estimate)*
1. To conduct data analysis using machine learning to estimate the time and risk associated with each maintenance packages	✓	100%
2. To develop a new package-based ARP modeling approach that can consider heterogeneous maintenance activities	✓	100%
3. To develop a new Column Generation-based methodology for the package-based ARP model	✓	100%
4. To verify the proposed Column Generation-based methodology	✓	100%
5. To conduct various numerical experiments to study the impacts of the new maintenance practice on ARP towards improving airline operations reliability and profitability	✓	100%

6. Research Outcome

6.1 Major findings and research outcome

(Maximum 1 page; please make reference to Part C where necessary)

During the project period, our team has:

(i) Classifications of AMR literature in handling uncertainties (Part C – Attachment 2)

We found that the existing AMR literature can be classified into 4 categories, i) Uncertainties and robust solutions, ii) Big data and machine learning solutions, iii) Smart technologies, and iv) Integrated information systems. In addition, among these papers, maintenance tasks are commonly assumed to be homogeneous. This finding was obtained based on a comprehensive literature review conducted on AMR, in particular to the papers related to handling uncertainties. We reviewed papers between Nov 2011 to Nov 2021, a total of 75 articles (including review papers).

(ii) Relationship of Maintenance Time and Aircraft Age (Part C – Attachments 4 and 5)

We found that for the same maintenance task, the maintenance time required was related to the aircraft age. Moreover, in general, the deviation of the maintenance time required for the same maintenance task is higher if the aircraft age was order. This finding was obtained based on the analysis of the historical maintenance data obtained from the project advisor. The dataset was about the aircraft maintenance records for 10 Airbus A320s in the period of 2014 to 2017. The aircraft age ranged from 4 years to 17 years. We applied these characteristics for the generation of maintenance time of maintenance tasks in the papers (Attachments 4 and 5).

(iii) Reduction of Computational Burden by our Proposed Acceleration Strategies (Part C – Attachment 5)

We found that our proposed acceleration strategies (one extension strategy and two dominance strategies) could greatly reduce the computational burden for the proposed column generation method. This finding was obtained based on the numerical experiments we conducted regarding problem size analysis. We generated different hypothetical scenarios by using different numbers of flight legs, aircraft, airports, and maintenance stations. In the largest problem scale with 270 flight legs (per week) for 11 aircraft covering 55 airports with 2 maintenance stations, the computational time was greatly reduced from 12,195s down to 742s, a total of about 94% reduction but without sacrificing the solution quality. With the proposed acceleration strategies, we would be able to solve large-scale problems.

(iv) Enhanced Reliability of Aircraft Route by Modeling Heterogeneous Maintenance Tasks in AMR (Part C – Attachments 4 and 5)

We found that by modeling maintenance task heterogeneously, the reliability of aircraft route obtained could be increased. This finding was obtained based on the numerical experiments we conducted regarding route reliability. In the proposed new approach, we modelled maintenance time according to the maintenance task. In addition, based on the length of the ground time assigned and the potential deviation of the maintenance time, we modelled its related risk level. Then, by defining a reliability level (i.e., the risk level for each assignment of maintenance task to ground time cannot exceed), the reliability of each maintenance assignment was increased and thus the overall reliability increases.

(v) Importance of aircraft spare parts management and re-routing to AMR

In our extended works, we further found two more findings. First, we found that if aircraft spare parts and the rotation of tooling are planned together with the AMR optimization, aircraft maintenance companies could achieve a better spare part plan. In another extended work, we found that when airlines have to recover from disruption due to flight delay, it is wise for airlines to cancel flights instead of forcing aircraft to be used in order to increase unnecessary utilization.

6.2 Potential for further development of the research and the proposed course of action *(Maximum half a page)*

Several potential future research directions worthy of investigating have emerged. One of the valuable directions would be integrating other robust strategies, such as cruise speed control and departure retiming, into our robust aircraft routing framework, to further enhance the route robustness. Furthermore, it would be an interesting topic to incorporate uncertainties of maintenance tasks into the recovery problem, which may help airlines to save more recovery costs.

7. Layman's Summary

(Describe in layman's language the nature, significance and value of the research project, in no more than 200 words)

To enhance aircraft utilization, many airlines have started to adopt a new aircraft maintenance policy, which encourages maintenance tasks to be performed during the ground time of two connected flights during the normal airline operations. As a result, the traditional huge maintenance task (refer to A-check) is broken down into many smaller maintenance tasks. Consequently, homogeneous maintenance task becomes heterogeneous one. However, in the existing literature, there is a lack of studies focusing on heterogenous maintenance task. Thus, this research project is one of the first attempts in studying heterogenous task in AMR literature. First of all, we conducted analysis on the real data set regarding 10 Airbus A320s. We found maintenance time required by maintenance task and the maintenance time deviation for the same maintenance task were related to the aircraft age. In addition, by modelling the maintenance time and its potential deviation with respect to the ground time assigned, a maintenance risk level can be defined. By controlling the risk level, the reliability of aircraft route obtained can be increased. In addition, because of heterogenous maintenance task, the problem complexity in column generation method is increased dramatically compared to heterogenous one. Thus, acceleration strategies become more significant.

Part C: Research Output

8. Peer-Reviewed Journal Publication(s) Arising Directly From This Research Project

(Please attach a copy of the publication and/or the letter of acceptance if not yet submitted in the previous progress report(s). All listed publications must acknowledge RGC's funding support by quoting the specific grant reference.)

The Latest Status of Publications				Author(s) *(denote the correspond-ing author with an asterisk*)*	Title and Journal / Book *(with the volume, pages and other necessary publishing details specified)*	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this Report *(Yes or No)*	Acknowl-edged the Support of RGC *(Yes or No)*	Accessible from the Institutional Repository *(Yes or No)*
Year of Publication	**Year of Acceptance** *(For paper accepted but not yet published)*	**Under Review**	**Under Preparation** *(optional)*						
2020				Y. Qin, **Hoi-Lam Ma***, F.T.S. Chan, W. Khan	**Title:** A scenario-based stochastic programming approach for aircraft expendable and rotable spare parts planning in MRO provider. **Journal:** Industrial Management & Data Systems, Vol. 120, No. 9, pp.1635-1657	**Yes (2020 Progress Report)**	**Yes (Attachment 1)**	**Yes**	**https://www.emerald.com/insight/search?q=A+scenario-based+stochastic+programming+approach+for+aircraft+expendable+and+rotable+spare+parts+planning+in+MRO+provider&showAll=true**
2022				**Hoi-Lam Ma,** Yige Sun, Sai-Ho Chung*, Hing Kai Chan	**Title:** Tackling uncertainties in aircraft maintenance routing: A review of emerging technologies. **Journal:** Transportation Research Part E: Logistics and Transportation Review, Vol.164, 102805.		**Yes (Attachment 2)**	**Yes**	**https://www.sciencedirect.com/science/article/pii/S1366554522001946?via%3Dihub**
2022				Xin Wen, Xuting Sun*, **Hoi-Lam Ma,**	**Title:** A column generation approach for operational		**Yes (Attachment 3)**	**Yes**	**https://www.sciencedirect.com/science/article/pii/S09**

				Yige Sun	flight scheduling and aircraft maintenance routing **Journal:** Journal of Air Transport Management, Vol. 105, 102270.				**696997220 00904?via %3Dihub**
		✓		Qing Zhang, Sai-Ho Chung*, **Hoi-Lam Ma,** Xuting Sun	**Title:** Robust Aircraft Maintenance Routing with Heterogenous Aircraft Maintenance Tasks **Submitted to:** Engineering Applications of Artificial Intelligence		**Yes (Attachme nt 4)**		**No**
			✓		**Title:** Robust aircraft routing under uncertainties considering heterogenous maintenance tasks		**Yes (Attachme nt 5)**		**No**

9. Recognized International Conference(s) In Which Paper(s) Related To This Research Project Was / Were Delivered

(Please attach a copy of each conference abstract)

Month / Year / Place	**Title**	**Conference Name**	**Submitted to RGC** *(indicate the year ending of the relevant progress report)*	**Attached to this Report** *(Yes or No)*	**Acknowledged the Support of RGC** *(Yes or No)*	**Accessible from the Institutional Repository** *(Yes or No)*
N/A						

10. Whether Research Experience And New Knowledge Has Been Transferred / Has Contributed To Teaching And Learning
(Please elaborate)

This research project involved studies of some important topics, such as big data analysis, machine learning, airline risk management. These topics and some findings were also introduced to our students who are studying "Airline Operations and Revenue Management". In the future, some models, such as risk assessment model, could also be converted into the teaching materials to benefit students.

11. Student(s) Trained
(Please attach a copy of the title page of the thesis)

Name	Degree Registered for	Date of Registration	Date of Thesis Submission / Graduation
N/A			

12. Other Impact
(e.g. award of patents or prizes, collaboration with other research institutions, technology transfer, teaching enhancement, etc.)

N/A

13. Statistics on Research Outputs

	Peer-reviewed Journal Publications	Conference Papers	Scholarly Books, Monographs and Chapters	Patents Awarded	Other Research Outputs (please specify)	
No. of outputs	3	0	0	0	Type	No.

arising directly from this research project						

14. Public Access Of Completion Report

(Please specify the information, if any, that cannot be provided for public access and give the reasons.)

Information that Cannot Be Provided for Public Access	**Reasons**
N/A	