



SYSTEM OF SYSTEMS ANALYSIS OF AUTONOMOUS AIRCRAFT OPERATIONS IN AIR CARGO FEEDER NETWORKS

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Abstract

Air freight operations play an essential part in the cargo delivery infrastructure. The two main contributions are through time sensitive deliveries and providing service to otherwise hard to reach rural or isolated communities. Using a System of Systems approach that couples aircraft capabilities with the design of the operational network can provide higher utilization of existing resources and can take advantage of opportunities to improve operations and determined system requirements when new technologies such as resilient pilotless flight technologies are introduced. In this work a methodology is introduced to optimize the allocation problem of an existing cargo aircraft for a given cargo network. A model that allows for the analysis of autonomous operation and the effect of using autonomy in the utilization of an aircraft and the change in operating cost is also given. Two test cases are analysed for the effect of autonomous operations for several cargo networks in Canada, the first is for existing networks operated by FedEx, while the second is for extend networks in the same regions. It is observed that by using the coupled System of Systems approach for the air cargo allocation the possible cost savings by autonomous operations in all regions and for all gives test cases exceed the reduction in cost from removing the pilot. These reductions in cost are even more pronounced for the extend networks. This indicates autonomous operations has the opportunity to make larger networks with lower demand routes profitable, which in turn allows to extended service into remote and isolated communities, such as the Canadian North.

Keywords: System of Systems, Autonomous Aircraft, Air Cargo Operations, Network Optimization, Regional Cargo

1. Introduction

Air cargo networks provide an important logistical support to large cities and remote communities alike. They also serve an important role to fulfill time sensitive freight across countries. The size of air cargo networks can vary significantly from highly populated areas to rural and isolated communities. Similarly the size of the aircraft that serve these networks can also differ in size. In Canada air cargo is very important for both roles of on-time delivery between larger cities and in delivering even basic cargo and supplies to remote and isolated communities. For these communities air freight is often the only supply line in or out during summer month and even during winter the reliability of ice roads is decreasing. Most of the cargo aircraft fleets in North America and other parts of the world will need to be replaced within the next decade [1, 2], for which the selection or design of new airframes requires a deeper understanding of the operation of these networks.

Tighter coupling between aircraft analysis and their actual use in operators' route networks can lead to more efficient and sustainable resource utilization [3, 4, 5]. Solving for tighter couplings poses a significant System of Systems challenge due to the complexity and scale of the problems being

solved [6]. A System of Systems approach is the process of abstracting, analysing and optimizing interconnected complex systems that consists of a collection of entities that collaborate for a unique purpose while retaining individual levels of operational and managerial independence [7]. There are several works that have investigated the coupling of aircraft design, route design and assignment, and passenger allocation [8, 9, 5, 10]. In these works it is observed that closer coupling between the different aspects of the aircraft selection or design and the operations use of these aircraft with the design of the corresponding network provides a better utilization of these aircraft on the corresponding network. There are no recent current works that focus on cargo operations, with some older works from Taylor and de Weck [11] investigated the effect of concurrent optimization of the design of an aircraft coupled to a package delivery network problem and Choi, *et. al.* [12] investigating the demand uncertainty in the acquisition decision for military airlift operations. More recent works explore system of system analysis with a focus on urban air mobility or unmanned aerial vehicles for inner-city package delivery in order to determine system requirements and possibilities[13, 14].

The system of system analysis approach can provide an opportunity to improve operations and determined system requirements when new technologies such as resilient pilotless flight technologies are introduced. Through the closer coupling of the pilotless aircraft capabilities and the design of the operational network the gains from autonomy can ne maximized, such as flexibility and robustness on flight scheduling, increase fleet utilization, as well as increased aircraft payload capacity [15, 16, 17, 18, 14].

This research presents a Systems of Systems analysis of the operational changes that autonomous vehicles can bring within existing regional air cargo feeder networks. Additionally it shows the potential that such technology can bring to expand and enhance the existing routes network. Section 2. outlines the problem formulation and analysis methods. Details on specific feeder network test cases are presented in Section 3.with results presented in Section 4. Finally Section 5.presents the conclusions reached on this study.

2. Methodology

The network design problem is modelled as a resource allocation problem whereby the packages to be transported represent the resource being allocated to optimize a given utility function representing the resource for minimum cost:

$$\begin{aligned}
 \min \quad & \sum_{i=1}^{n_{ap}} \sum_{j=1}^{n_{ap}} \sum_{\substack{l=1, \\ l \neq i, l \neq j}}^{n_{id}} \hat{C}_{i,j,l} (f_{i,l} + f_{l,j}) + \sum_{i=1}^{n_{ap}} \sum_{j=1}^{n_{ap}} \hat{C}_{i,j,i} f_{i,j} + \sum_{i=1}^{n_{ap}} \sum_{j=1}^{n_{ap}} \hat{C}_{i,j,j} f_{i,j} \\
 \text{w.r.t} \quad & \hat{C}_{i,j,l} \in \mathbb{Z} \\
 \text{s.t.} \quad & \sum_{l=1}^{n_{hubs}} \hat{C}_{i,j,l} = C_{i,j} \quad \text{for } \begin{cases} i \dots n_{ap} \\ j \dots n_{ap} \end{cases}
 \end{aligned}$$

where the cargo allocation is handled as a number of fractions of maximum payload ($\hat{C}_{i,j,l}$). The operating cost along a given origin destination pair is given by $f_{i,j}$ and depend on the aircraft used and its load factor. The subscript l denotes a non-direct flight from origin i to destination j , a direct flight is performed if either the subscript i or j are repeated The total number of flights required is determined from servicing the entire network. The defined constraints in the formulation above ensure that all the required cargo to be transported ($C_{i,j,l}$) is delivered from each origin to each destination.

2.1 Aircraft Design Analysis

The performance and corresponding cost of operating an aircraft when assigned on routes in the network is determined using an object-oriented, multi-fidelity aircraft conceptual design framework

pyACDT in Python [19, 20]. For this work, analytical and semi-empirical disciplinary analysis methods commonly used in conceptual aircraft design are utilized, with numerical methods being limited to use only in mission performance. Weights and balance, aerodynamics, performance, propulsion, stability and control, and economics are considered.

The aircraft weight is calculated from the main component and system weights as well as a given mission required fuel and payload. Induced drag is determined for lifting surfaces and parasitic drag is calculated using detailed component build-up. The effect of trim in lift and drag characteristics is also accounted for. The aerodynamic derivatives for stability and control are determined using semi-empirical models. Turboprop engine characteristics are estimated using a parametric engine model derived from engine decks of existing engines. Similarly the propeller performance is modelled semi-empirically as described in the authors previous paper [10]. The performance module uses a combination of analytical formulations and numerical simulation in the space domain. The computational burden when analyzing the performance of aircraft over a wide range of routes and payloads is substantial. To accelerate the analysis a bi-quadratic response surface is generated for performance and direct operating cost with respect to payload and flight range as the independent variables [21, 9]. A representative mission profile for a feeder cargo aircraft used in the performance analysis for all routes is shown in Figure 1. The profile follows air traffic control (ATC) restrictions and includes a 45 min instrument flight rule (IFR) hold for a reserve mission. Exact mission profile details depend on cruise speed and altitude, climb speed and mission range of each flight route.

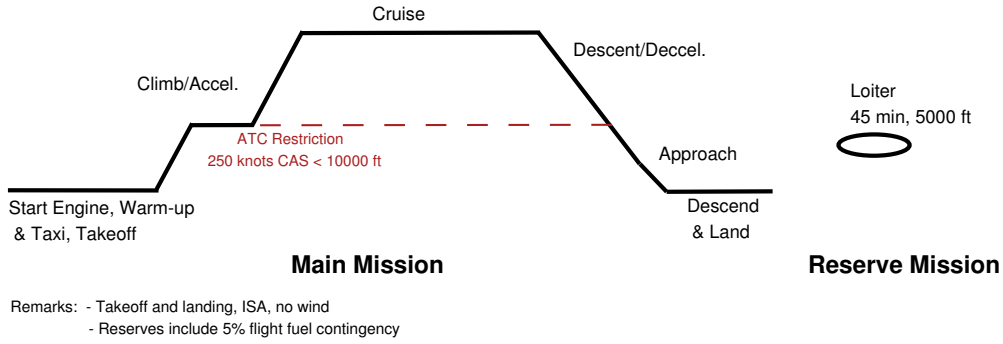


Figure 1 – Example mission profile for a cargo feeder aircraft.

3. Network Test Case

The Systems of Systems analysis methodology presented in Section 2 is applied to a representative air cargo feeder network that closely follows the FedEx cargo operations in Canada. Figure 2 shows the geographical distribution of the network which is comprised of 32-city origin-destination pairs and provide a complex enough transport system to demonstrate the usefulness of a System of Systems analysis yet simple enough to characterize the sources of any potential improvements.

Two set of analysis are performed. The first one quantifies the effect of autonomous operations on existing network origin-destination pairs as shown in Figure 2. The second one allows for the expansion of the network to new cities beyond the original network thereby showing any potential emergent changes that can become possible through a System of Systems analysis of autonomous operations.

3.1 Route Demand

The cargo demand in the route network is calculated using a modified Gravity model [22]. The model was developed from historical cargo information along each route and predicts total weekly origin to destination cargo weight from socio-economic and geographical data [23, 24]. The demand is predicted as:

$$V_{i,j} = P_{i,j}^{k_1} C_{i,j}^{k_2} D_{i,j}^{k_3} T_{i,j}^{k_4} H_{i,j}^{k_5} I_{i,j}^{k_6} k_7 \quad (1)$$

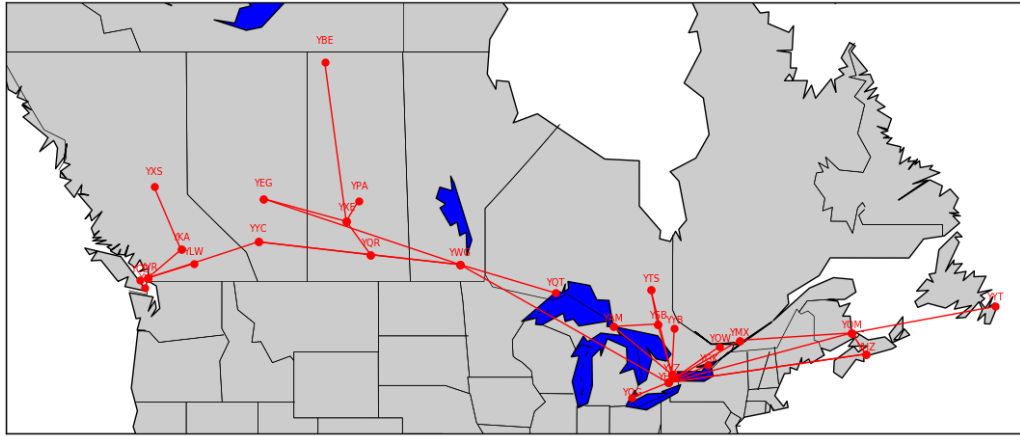


Figure 2 – 32 cargo feeder route network

where $P_{i,j}$ is the product of population sizes in Millions, $C_{i,j}$ is the ratio of population catchment areas, $D_{i,j}$ and $T_{i,j}$ are the greater circle distance in nautical miles and travel time in hours between origin and destination respectively. Compared to the traditional gravity model two additional parameters are introduced, $H_{i,j}$ is the product of the distances between each airport and the nearest highway in order to account for road cargo network accessibility and $I_{i,j}$ is the ratio of average after-tax incomes used to quantify economic effects on cargo demand. Table 1 shows the model coefficients calculated for the Canadian regional cargo network presenting a high correlation with an adjusted R^2 value of 0.91.

Table 1 – Demand model Coefficients for Canadian Regional Air Cargo Network.

k_1	k_2	k_3	k_4	k_5	k_6	k_7	Adjusted R^2
0.24	0.31	2.57	-3.10	0.22	-0.95	7.7e-4	0.917

Figure 3 shows the entire air cargo network demand for Canada and its range distribution. Additional connecting routes between large cargo centres covered by large cargo aircraft are also shown but not considered part of the feeder cargo network analysis as described above. Total demand between the selected origin-destination pairs is shown in Table reftab:routes. The model predicted demand is considered asymmetric between origin-destination city pairs due to the nature of cargo freight operation, *i.e.* the inbound flight carries significantly more cargo than the returning one, hence the cargo constraints are enforced on outbound flights only.

3.2 Aircraft

A Cessna 208 Caravan was modelled in `pyACDT` to operate in the test case networks as shown in Figure 4. The Cessna 206 was selected as is the aircraft used by FedEx in its current Canadian operations. This vehicle is the most common feeder cargo aircraft in North America and its currently being operated in all of the analysed network routes.

Disciplinary analysis were calibrated to match flight manual performance data. Figure 5 shows the modelled Payload-Range diagram of the vehicle. The aircraft maximum payload weight was 4200 lb_f, but was limited to a maximum load factor of 85% and 95% for a crewed and an autonomous operation aircraft respectively. This loads factors are derived from standard operators knowledge that aircraft are typically limited by volume and not weight and cargo density is typically around 6.3 lb/ft³.

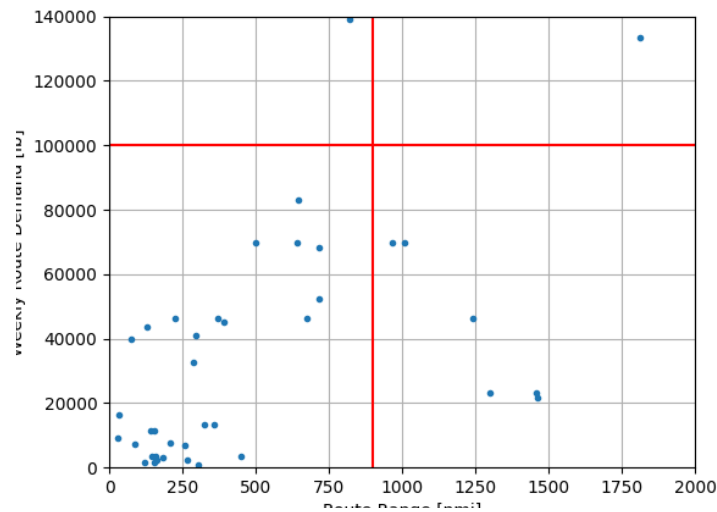


Figure 3 – Cargo feeder route network demand and range distribution

Table 2 – 32 cargo feeder route network demand and range

Origin Airport ¹	Destination Airport ¹	Distance [nm]	Demand [lb _m] ²
East Coast			
YHM	YQM	676.0	46400
YHM	YHZ	717.0	52512
YQM	YHZ	89.0	7348
YQM	YYT	499.0	69600
YHZ	YHM	717.0	68172
YMX	YQM	393.0	45164
Ontario			
YHM	YGK	158.0	3363
YHM	YOW	225.0	46400
YHM	YMX	295.0	40796
YYZ	YSB	184.0	3082
YYZ	YAM	267.0	2315
YYZ	YYB	161.0	2315
YSB	YTS	119.0	1548
YAM	YSB	154.0	1548
YQG	YHM	144.0	3363
YTS	YYZ	303.0	767
Prairies			
YYC	YWG	645.0	82880
YYC	YQR	358.0	13280
YXE	YQR	130.0	43544
YXE	YBE	448.0	3363
YXE	YPA	73.0	39840
YEG	YXE	260.0	6727
YEG	YWG	643.0	69600
YWG	YQT	325.0	13239
YQR	YWG	288.0	32658
West-Coast			
YVR	YKA	140.0	11611
YVR	YYJ	34.0	16242
YVR	YCD	28.0	9261
YVR	YYC	372.0	46400
YVR	YLW	156.0	11611
YKA	YXS	208.0	7765

¹ Airports specified by their IATA code.

² Cargo demand specified for a week

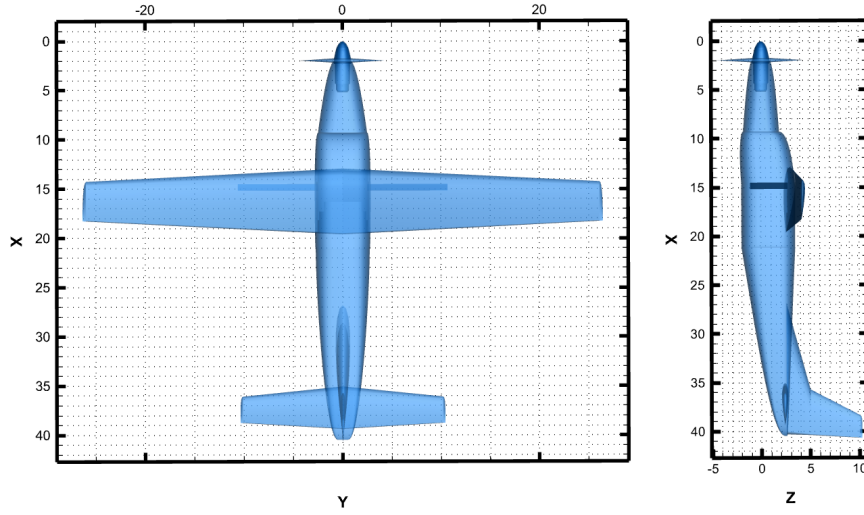


Figure 4 – Cessna 208 Caravan Model

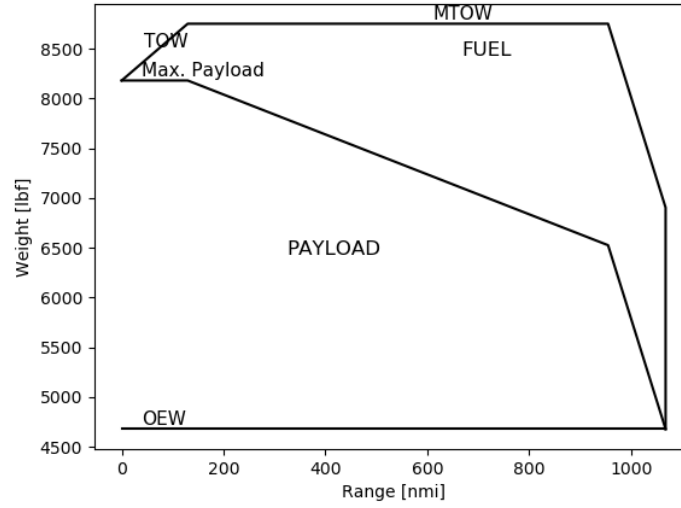


Figure 5 – Estimated Cessna 208 Caravan Payload Range

4. Results

The two autonomous operation test cases were solved using an extended ant colony optimizer MIDACO [25] implemented in the Python object-oriented optimization framework `pyOPT` [26] while aircraft relevant information was obtained using `pyACDT` as described before.

4.1 Effect of Autonomy on Cargo Operations

Results for the feeder cargo network is divided into four specific regions (British Columbia, the Prairies, Ontario, and the East Coast, or Maritimes). All regions are comprised of multiple hub-and-spoke as well as direct routes that span different flight ranges. The details on the routes and the respective weekly demand can be seen in Table 2. Each region has a different mix of short to long range routes and low and high demand routes, with the shortest route being from Vancouver (YVR) to Nanaimo (YCD) at only 24 nmi. The highest cargo demand route is from Calgary (YYC) to Winnipeg (YWG) with a weekly demand for 82880 lb_m.

As discussed in Section 3.2 to account for autonomous operations the maximum load factor was allowed to increase to 95% thereby accounting for more available volume to store cargo. In addition the direct operating cost is adjusted to exclude a flight crew of one, while accounting for the cost of a ground handling crew to un-/load the aircraft. For a standard 350 nmi mission with the same takeoff

weight the removal of the pilot cost results in a reduction of 17% in direct operating cost.

4.1.1 East Coast Region

Figure 6 shows the region route allocation with the thicknesses as indicator for the flight frequency on each route. There is no difference in the allocation between that for autonomous operations and the currently being operated by crews. In this region few possibilities exist for new route structures that minimize operating cost as cargo moves mainly eastward from main international city centres to major regional cities. Hence all the cargo is delivered using direct flights from the main hubs in Hamilton (YHM), Moncton (YQM), Halifax (YHZ), and Montreal (YMX).

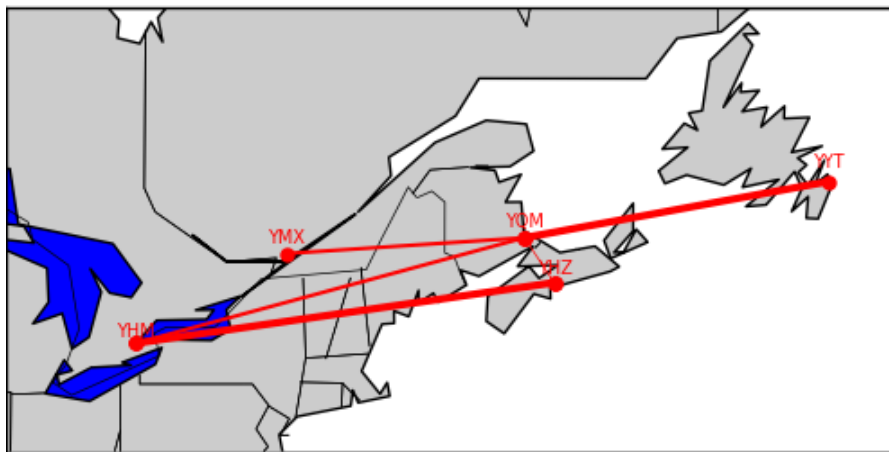


Figure 6 – Autonomous Operations East Coast Routes

Table 3 shows the cost of operation, number of flights and load factors for crewed and autonomous operations. Autonomy provides a 24% reduction in total operation cost for the east coast network. This reduction in total cost arises not only from crew cost reduction but also from a decrease in required total flights by 5% that is a result of an increased in load factors due to the additional available internal volume, with the average load factor across all flight increasing by 5%. The total cost reduction exceeds the expected reductions in operation cost by the removal of the flight crew cost significantly.

Table 3 – Operation Details for East Coast Routes

	Crewed	Autonomous
Total Operating Costs, [Thousand US\$]	534	406 (-24%)
Hub to Spoke Routes	8	8
Indirect Routes	0	0
Total Number of Flights	100	95 (-5%)
Average Network Load Factor	83%	87% (+5%)

¹ Values in brackets are the percent relative difference

4.1.2 Ontario Region

The second region analysed is in Ontario and extending to Montreal (YMX) in Quebec, as such this is one of the most populous regions in Canada. The network consists of large city centres located close to the US–Canada border to more rural small cities located further north, such as Timmins (YTS). Figure 8 shows the region route allocation for autonomous operations for this region.

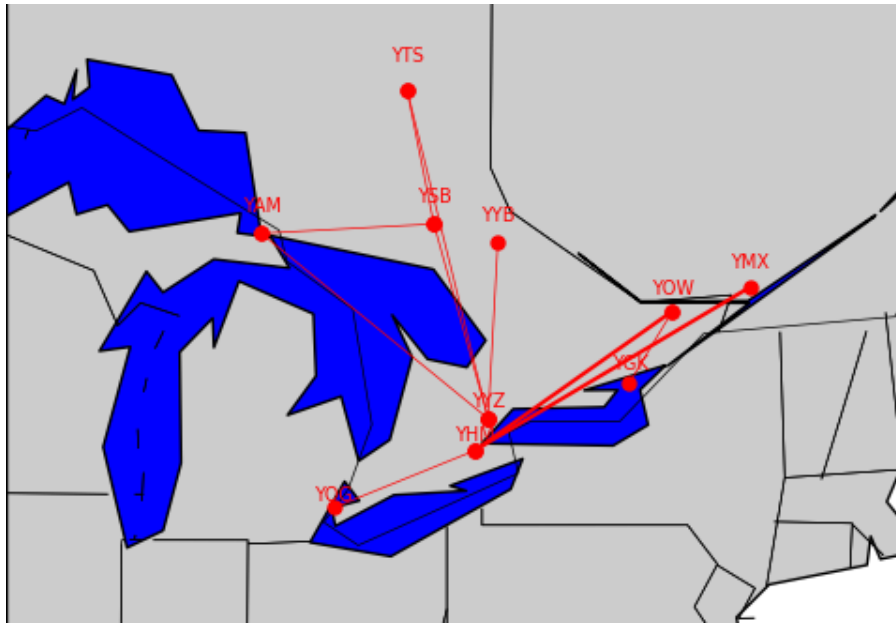


Figure 7 – Autonomous Operations Ontario Routes

There is a change in the network structure for autonomous operations. One direct route for crewed operations from Hamilton (YHM) to Kingston (YGB) is performed indirect over Ottawa (YOW), since for the crewed flight only low load factors are achieved. Another change is a shift from the Toronto (YYZ) to North Bay (YYB) which has a connection by Sudbury (YSD) when crewed, while begin direct when autonomous.

Total cost of operation, number of flights and load factors for crewed and autonomous operations are shown in Table 4. The change in the structure of routes and increased available volume allows for a 6% increase in average load factor and a reduction by three flights to operate the network. This results in a total cost savings of 18% for operating the network autonomously, which only marginally the reduction by removing just the cost for the flight crew.

Table 4 – Operation Details for Ontario Routes

	Crewed	Autonomous
Total Operating Costs, [Thousand US\$]	129	106 (-18%)
Hub to Spoke Routes	9	9
Indirect Routes	1	1
Total Number of Flights	42	39 (-5%)
Average Network Load Factor	75%	80% (+6%)

¹ Values in brackets are the percent relative difference

4.1.3 Prairies Region

The Prairies region is dominated by long range, high demand routes between the major cities in the Provinces of Manitoba, Saskatchewan, and Alberta. Figure 8 shows this region's route allocation for autonomous operations. Compared to the currently crewed operated routes, the Saskatoon (YXE) to Uranium City (YBE) direct is replaced with an indirect route over Regina (YQR). The demand between Saskatoon and Uranium City route requires 2 flights with a low load factor of 48%, by transporting this cargo first to Regina, no extra flight are required by the average load factor is increased to 89%, possible by the extra available volume, while the two flights to Uranium city are at lower cost then the flights from Saskatoon.

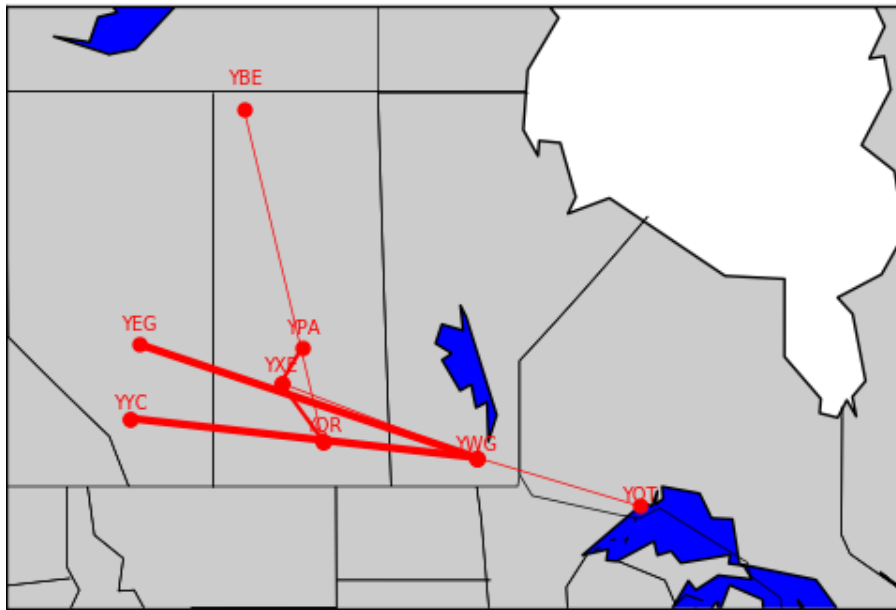


Figure 8 – Autonomous Operations Prairies Routes

Table 5 shows the cost of operation, number of flights and load factors for operating on the Prairies network. Autonomy provides a 21% reduction in operation cost. Similar to the other regions the average load factors increase by 4%, total number of flights required decreases by three flights. The reduction in cost exceeds the reduction due to the removal of the flight crew, since the routes are dominated by long range high demand routes with increased utilization of the aircraft.

Table 5 – Operation Details for Prairies Routes

	Crewed	Autonomous
Total Operating Costs, [Thousand US\$]	473	375 (-21%)
Hub to Spoke Routes	8	9
Indirect Routes	1	1
Total Number of Flights	109	106 (-3%)
Average Network Load Factor	82%	85% (+4%)

¹ Values in brackets are the percent relative difference

4.1.4 West Coast Region

The routes in the West Coast region are a mix of very short range routes to Victoria island and longer range routes to or over the Rocky Mountains. The route network does not change for the crewed and autonomous operations and all the cargo is transported using direct flights only in both cases.

The summary for operating the West Coast region is given in Table 6. Autonomy provides a 19% reduction in total operation cost, the increase in average load factor allows for a removal of two flights in order to deliver all the cargo to its respective destinations.

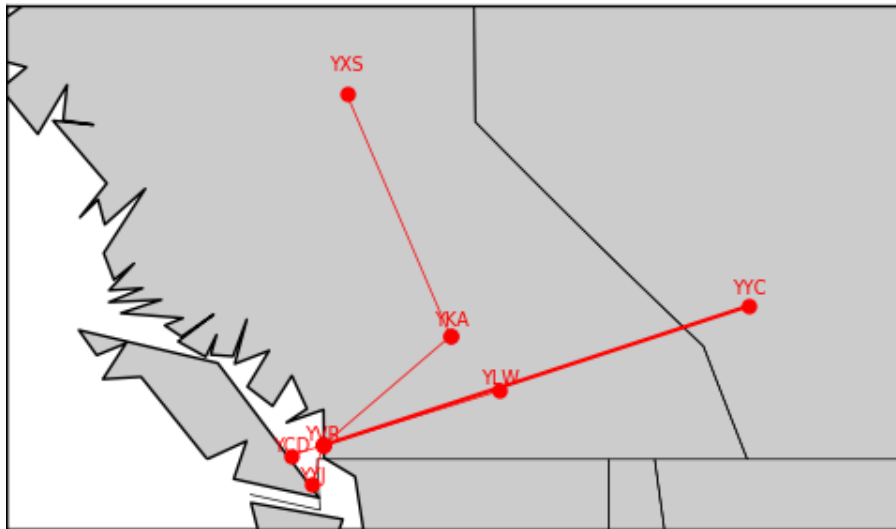


Figure 9 – Operations West Coast Routes

Table 6 – Operation Details for West Coast Routes

	Crewed	Autonomous
Total Operating Costs, [Thousand US\$]	111	89 (-19%)
Hub to Spoke Routes	6	6
Indirect Routes	0	0
Total Number of Flights	37	35 (-5%)
Average Network Load Factor	79%	84% (+5%)

¹ Values in brackets are the percent relative difference

Based on the results for the different regions in Canada, it can be observed that overall for the existing established route networks a reduction in operating cost is possible from the use of autonomy. Figure 10 shows the overall reduction in cost, changes in average load factor and number of flights relative to the crewed operations.

The improvements comes from both, a decrease in flight crew cost, as well as operational improvements that arise from increased load factors which enables lower number of required flights and more efficient route redistribution.

4.2 Emerging Changes on Cargo Operations due to Autonomy

The second test case explore the possibilities of expanding the routes network including additional cities that were not economically feasible before to be include as part of the network. The cities added are not currently covered by any carrier. Therefore, to estimate the demand of cargo that can expected for these new routes the gravity demand model is used. Figure 11 shows the extended air cargo network demand and range distribution covered with the additional routes added in red; similarly Table 7 shows the respective origin-destination demand of the additional routes added to each of the region.

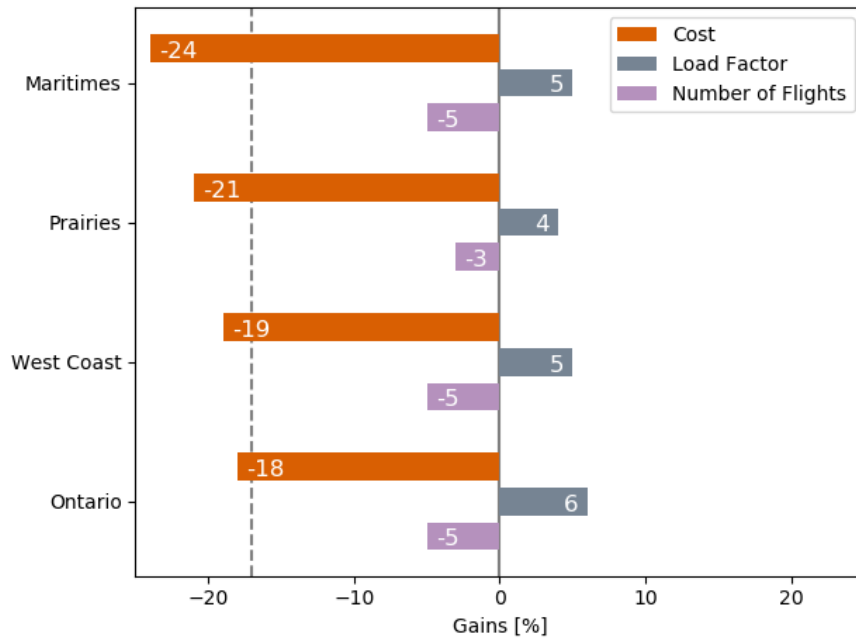


Figure 10 – Summary of Autonomous Operations

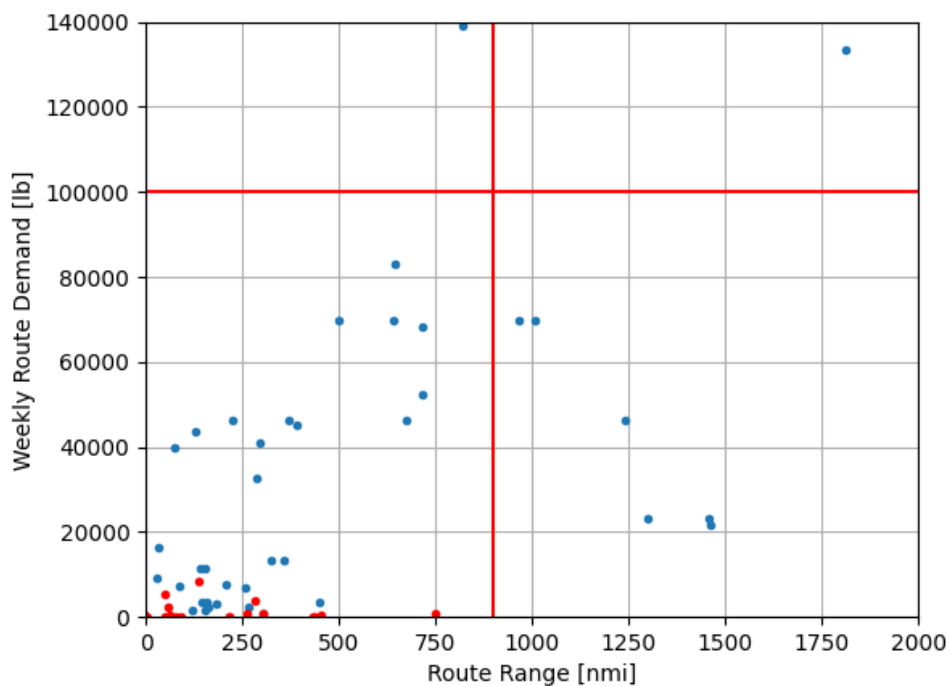


Figure 11 – Extend cargo network demand and range distributions

Most of the new routes are lower demand routes with varying ranges, this accounts for the extension of the existing route network to more remote locations in the north of Canada. New origin-destination pairs are added to the West Coast, Prairies, and Ontario region. For the East cost region no new routes were added due to its relative size and geographic characteristics.

Table 7 – Additional Routes on Extended Cargo Network

Origin Airport ¹	Destination Airport ¹	Distance [nmi]	Demand [lb _m] ²
Ontario			
YHM	YPQ	93	126
YHM	YLK	80	88
YYZ	YGK	136	8225
YYZ	YPQ	64	389
YYZ	YLK	49	216
YQG	YAM	261	754
YQG	YQT	454	455
Prairies			
YEG	YMM	217	202
YEG	YQU	218	242
YWG	YQG	750	816
West-Coast			
YVR	YXS	283	4016
YVR	YXJ	432	55
YKA	YXS	208	7765
YXX	YYJ	48	5420
YXX	YCD	60	2461

¹ Airports specified by their IATA code.² Cargo demand specified for a week

As for the previous cases the network problems are solved using MIDACO [25] following the same problem formulation for crewed and autonomous operation. The computational complexity increases significantly with the addition of new origin-destination pairs, since the number of design variables increase exponentially. Following are the results for the three different regions with the extended networks.

4.2.1 Extended Ontario Region

In Ontario seven new routes are added to the network by adding cities such as Peterborough (YPQ) and Thunder Bay (YQT), and adding direct demand between cities already in the network. The resulting network structure for autonomous operation can be seen in Figure 12.

The addition of the new lower demand routes results in generally a higher utilization of indirect flights. Autonomous operations overall has a lower number of indirect flights and shift some of the route structure. Some of the most notable changes are the removal of seven indirect flight from Hamilton (YHM) to Kingston (YGK), while removing six direct flights from Hamilton (YHM) to Peterborough (YPQ). Similar, an indirect flight from Kenora (YQK) to Sault Ste. Marie over Thunder Bay (YQT) is covered directly.

The changes in the route structure and removal of some of the indirect flights results in a reduction of 12 total flight (or 16% of flight), while the average load factor is only increased slightly by 0.2%. Table 8 shows the summary of the total crewed and autonomous operation of the extended Ontario route network. The reduction in flights and more direct utilization of the aircraft results in a cost reduction of 25%, which exceed the cost reductions on the previous case for the smaller network.

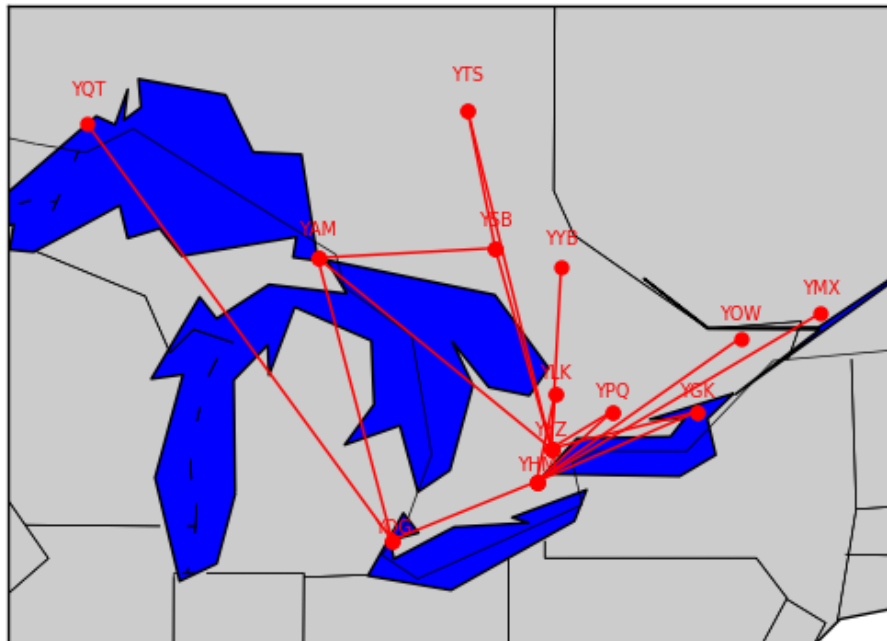


Figure 12 – Autonomous Operations Ontario Routes

Table 8 – Operation Details for Ontario Routes

	Crewed	Autonomous
Total Operating Costs, [Thousand US\$]	258	195 (-25%)
Hub to Spoke Routes	15	15
Indirect Routes	20	17
Total Number of Flights	76	64 (-16%)
Average Network Load Factor	61%	62% (+.2%)

¹ Values in brackets are the percent relative difference

4.2.2 Extended Prairies Region

In the Prairies three new destinations are added in the north of the region, namely, Fort Mac Murry (YMM), Grande Prairie (YQU) and Windsor (YQG). As was the case for the Ontario network, autonomous operation reduces the number of indirect flights, Figure 13 shows the routes for the autonomous operations.

The autonomous operation removes all indirect flight from Calgary (YYC) to Winnipeg (YWG) and Regina (YQR), as well as from Saskatoon (YEX) to Regina (YQR), while reducing the number of indirect flight for other routes.

Table 9 provides the summary for the network. In addition to reducing the indirect flight, autonomous operations increase the average load factor and also reduce the total number of flight required by 16%. The combination of higher utilization of the aircraft and a reduction of flights results in a significant reduction of cost by 27%.

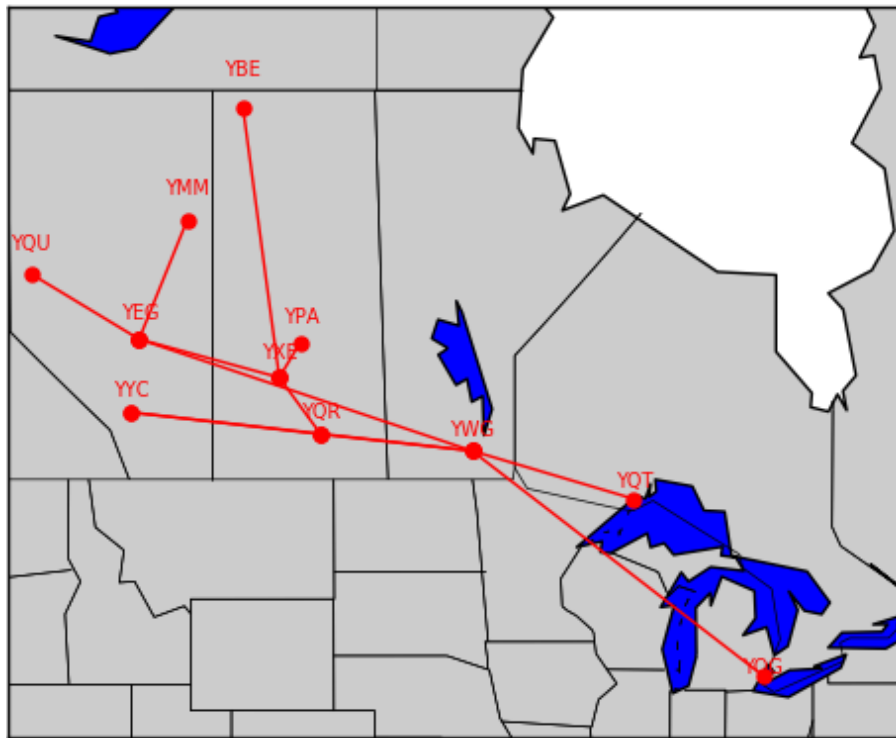


Figure 13 – Autonomous Operations Prairies Routes

Table 9 – Operation Details for Prairies Routes

	Crewed	Autonomous
Total Operating Costs, [Thousand US\$]	560	424 (-27%)
Hub to Spoke Routes	11	12
Indirect Routes	11	9
Total Number of Flights	135	114 (-16%)
Average Network Load Factor	77%	81% (+5%)

¹ Values in brackets are the percent relative difference

4.2.3 Extended West Coast Region

On the West Coast four new routes are added, which include a new destination of Fort St. John (YXJ) in the north of British Columbia, and a new origin of Abbotsford (YXX) close to the US-Canada border.

For this region the autonomous operation does not reduce the number of indirect flights, but rather shifts some of the connections. Actually, two direct routes are removed, Vancouver (YVR) and Abbotsford (YXX) to Fort St. John (YXJ), while shifting many connections through Fort Frances (YAG).

The total number of indirect routes is the same for crewed and autonomous operations, but the structure of the connections does change, the total cost and routes can be seen in Table 10. The number of total flights is reduced by three and the average load factor is increased by 6%. The modest reduction in the total number of flight results in a cost reduction by 19%, which is the same as for the existing route network as shown before.

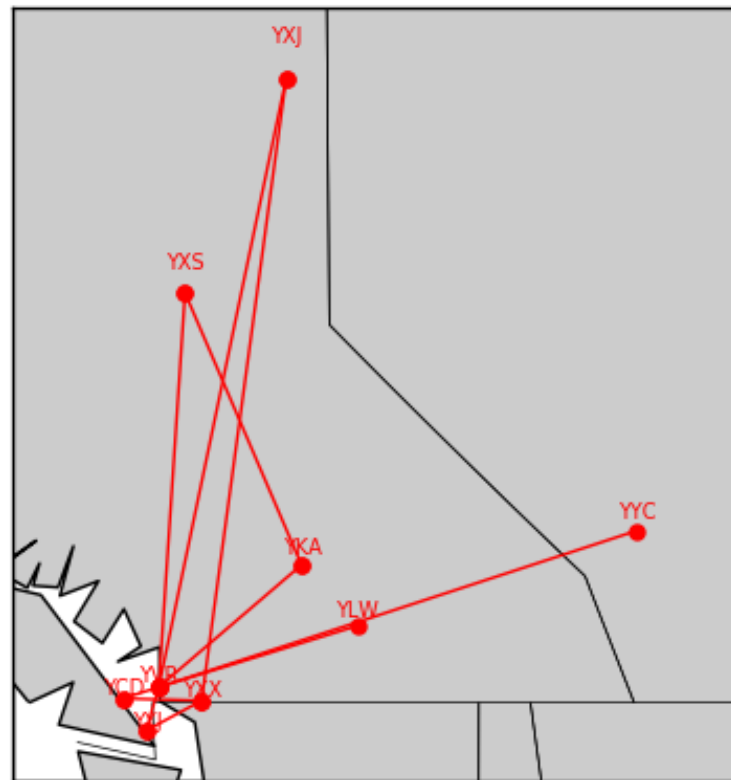


Figure 14 – Autonomous Operations West Coast Routes

Table 10 – Operation Details for West Coast Routes

	Crewed	Autonomous
Total Operating Costs, [Thousand US\$]	220	179 (-19%)
Hub to Spoke Routes	11	12
Indirect Routes	11	9
Total Number of Flights	62	59 (-5%)
Average Network Load Factor	69%	73% (+5%)

¹ Values in brackets are the percent relative difference

Figure 15 shows a summary of the respective changes in cost, average load factor and number of flights for autonomous operations in each region with extended routes. For the three regions it can be observed that added more routes has a more pronounced effect on the total cost reductions can be achieved between the crewed and autonomous operations, with the exception of the West Coast region, which achieves the same reduction. This indicates that with autonomy even low demand extended networks can be profitable, which allows the extension of exiting cargo networks into previously underserved regions, especially in the more remote North of Canada with its isolated indigenous communities, which rely on air cargo, especially with the deterioration of accessibility by ice roads during the winter month.

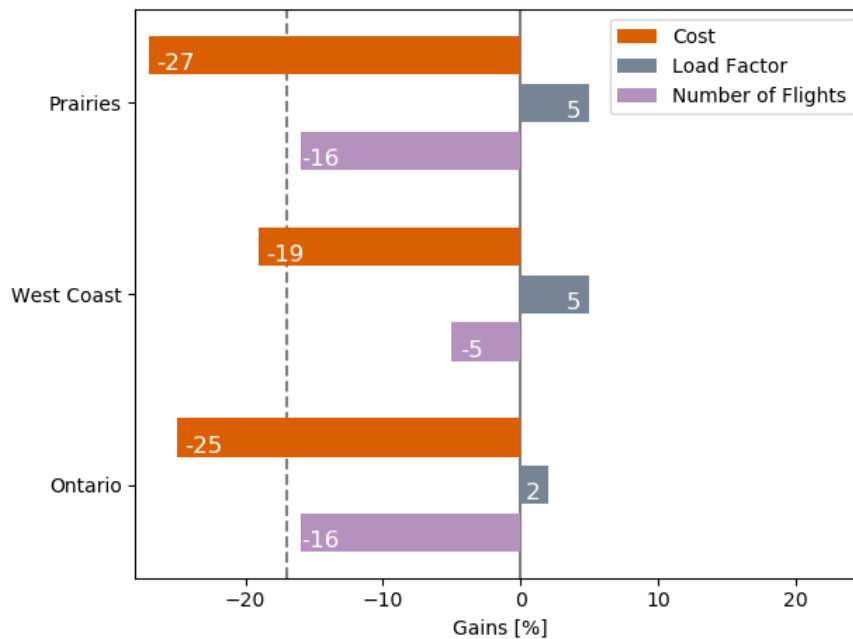


Figure 15 – Summary of Extended Autonomous Operations

5. Conclusions

In this work the methodology to solve the cargo allocation problem for air cargo operations of a given network is introduced. Furthermore a model is given that allows for the analysis of autonomous operation and the effect of using autonomy in the utilization of an aircraft and the change in operating cost.

Using existing cargo networks in different regions of Canada that are served by FedEx using Cessna C208 Caravans the effect of introducing autonomous operations is investigated. The results show that autonomy allows for a reduction in operating cost not just by reducing crew cost but also allowing for higher utilization of the aircraft within the network. In all regions the reductions in total cost exceed the expected reduction of around 17% from removing crew cost, with the highest reduction being observed in the east coast region by 24%, while the lowest improvement is in the Ontario region with a reduction of 18% relative to the crewed operations.

Extending the existing networks to account for expanding air cargo operations to serve more remote and lower demand destinations show that autonomy can provide even higher reductions in cost through higher utilization of these aircraft, more direct oriented route structures, and reduced flights and crew cost, resulting in cost reduction of up to 27% for operating in the Prairies to the same reductions in cost on the West Coast. This indicates that autonomy can allow routes to be profitable that are currently only marginal or not profitable at all, increasing access to air cargo to remote and isolated communities.

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References

- [1] Andrews, J., Lara, M., Yon, R., Del Rosario, R., Block, J., Davis, T., Hasan, S., Weingart, D., Frankel, C., Spitz, B., Pfaender, H., Je Sung, W., Mavris, D., and Justin, C., "LMI Automated Air Cargo Operations Market Research and Forecast," Tech. Rep. NASA CR-20210015228, Logistics Management Institute, NASA Ames Research Center, April 2021.
- [2] Sakakeeny, J., Dimitrova, N., and Idris, H., "Preliminary Characterization of Unmanned Air Cargo Routes Using Current Cargo Operations Survey," *AIAA AVIATION 2022 Forum*, 2022.
- [3] Mane, M. and Crossley, W., "Allocation and Design of Aircraft for On-Demand Air Transportation with Uncertain Operations," *Journal of Aircraft*, Vol. 49, No. 1, January–February 2012, pp. 141 – 150.
- [4] Jansen, P. and Perez, R., "Coupled Optimization of Aircraft Design and Fleet Allocation with Uncertain Passenger Demand," *AVIATION 2013, Aviation Technology, Integration, and Operations Conference*, No. AIAA 2013-4392, Los Angeles, CA, August 12-14 2013.
- [5] Jansen, P. and Perez, R., "Effect of Passenger Preferences on the Integrated Design and Optimization of Aircraft Families and Air Transport Network," *AIAA AVIATION Conference, 17th AIAA Aviation Technology, Integration, and Operations Conference*, No. AIAA 2017-4249, Denver, CO, June 5-9 2017.
- [6] DeLaurentis, D., "Understanding Transportation as a System of Systems Design Problem," *43rd AIAA Aerospace Sciences Meeting*, No. AIAA-2005-0123, Reno, Nevada, January 10–13 2005.
- [7] Maier, M., "Architecting Principles for Systems-of-Systems," *Systems Engineering*, Vol. 1, No. 4, 1998, pp. 267–284.
- [8] Govindaraju, P. and Crossley, W., "Profit Motivated Airline Fleet Allocation and Concurrent Aircraft Design for Multiple Airlines," *2013 Aviation Technology, Integration, and Operations Conference (ATIO)*, AIAA, Los Angeles, CA, August 2013.
- [9] Jansen, P. and Perez, R., "Effect of Passenger Preferences on the Integrated Design and Optimization of Aircraft Families and Air Transport Network," *AIAA AVIATION Conference, 17th AIAA Aviation Technology, Integration, and Operations Conference*, No. AIAA 2017-4249, Denver, CO, June 5-9 2017.
- [10] Reid, S. J., Perez, R. E., Jansen, P. W., and Bil, C., "Influence of Carbon Pricing on Regional Aircraft and Route Network Design," *AIAA Scitech 2021 Forum*, American Institute of Aeronautics and Astronautics, Jan 2021.
- [11] Taylor, C. and de Weck, O., "Coupled Vehicle Design and Network Flow Optimization for Air Transportation Systems," *Journal of Aircraft*, Vol. 44, No. 5, September–October 2007, pp. 1478–1486.
- [12] Choi, J., Govindaraju, P., Davendralingam, N., and Crossley, W., "Platform Design for Fleet-level Efficiency under Uncertain Demand: Application for Air Mobility Command (AMC)," *2013 Aviation Technology, Integration, and Operations Conference*, AIAA, Los Angeles, CA, August 2013.
- [13] Kaneko, S. and Martins, J., "Fleet Design Optimization of Package Delivery UAVs Considering Operations," *AIAA SCITECH 2022 Forum*, No. AIAA 2022-1503, Jan. 2022.
- [14] Ratei, P., Naeem, N., and Prakasha, P., "Development of an urban air mobility vehicle family concept by system of systems aircraft design and assessment," *Journal of Physics: Conference Series*, Vol. 2526, No. 1, Jun 2023, pp. 012043.
- [15] Howard, R., Wright, E., Mudumba, S., Gunady, N., B.E., S., and Maheshwari, A., "Assessing the Suitability of Urban Air Mobility Vehicles for a Specific Aerodrome Network," *AIAA AVIATION 2021 FORUM*, No. AIAA 2021-3208, Aug. 2021.
- [16] Maheshwari, A., Sells, B., Harrington, S., D., D., and Crossley, W., "Evaluating Impact of Operational Limits by Estimating Potential UAM Trips in an Urban Area," *AIAA AVIATION 2021 FORUM*, No. AIAA 2021-3174, Aug. 2021.
- [17] Roy, S., Maheshwari, A., Crossley, W., and DeLaurentis, D., "Future Regional Air Mobility Analysis Using Conventional, Electric, and Autonomous Vehicles," Vol. 29, 2021, pp. 113–126.
- [18] Prakasha, P., Naeem, N., Ratei, P., and Nagel, B., "Aircraft Architecture and Fleet Assessment Framework for Urban Air Mobility Using a System of Systems Approach," *Aerospace Science and Technology*, Vol. 125, 2022, pp. 107072.
- [19] Perez, R. E. and Martins, J. R. R. A., "pyACDT: An Object-Oriented Framework for Aircraft Design Modelling and Multidisciplinary Optimization," *12th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, AIAA, Victoria, BC, September 2008.
- [20] Henderson, R. P., Martins, J. R. R. A., and Perez, R. E., "Aircraft Conceptual Design for Optimal Environmental Performance," *The Aeronautical Journal*, Vol. 116, No. 1175, January 2012, pp. 3712–3733.
- [21] Jansen, P. W. and Perez, R. E., "Coupled Optimization of Aircraft Families and Fleet Allocation for Multiple Markets," *Journal of Aircraft*, *In Press*, 2016.

- [22] Grosche, T., Rothlauf, F., and Heinzl, A., "Gravity models for airline passenger volume estimation," *Journal of Air Transport Management*, Vol. 13, 2007, pp. 175—183.
- [23] Alexiev, M., Jansen, P., Perez, R., and Wang, J.-H., "Demand Modeling of Regional Air Transport Cargo Networks in Canada," *CASI AERO Conference*, Ottawa, ON, Nov. 2023.
- [24] Alexiev, M., Jansen, P., Perez, R., and Wang, J.-H., "Modeling Cargo Demand for Regional Air Transport Networks in Canada and the United States," *ICAS 2024 - 34th Congress of the International Council of the Aeronautical Sciences*, Florence, Italy, Sept 9-13 2024.
- [25] Schluter, M., Egea, J., and Banga, J., "Extended Ant Colony Optimization for Non-convex Mixed Integer Nonlinear Programming," *Computers and Operations Research*, Vol. 36, No. 7, 2009, pp. 2217–2229.
- [26] Perez, R. E., Jansen, P. W., and Martins, J. R. R. A., "pyOpt: A Python-Based Object-Oriented Framework for Nonlinear Constrained Optimization," *Structures and Multidisciplinary Optimization*, Vol. 45, No. 1, 2011, pp. 101–118.