Institution: University of Birmingham		
Unit of Assessment: UoA 10, Mathematical Sciences		
Title of case study: Optimisation of commercial flight profiles to save fuel, harmful emissions and over $100 million		
Period when the underpinning research was undertaken: 2008–2013		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Dr Jan-Joachim Ruckmann	Reader in Mathematical Optimisation	2007–2013
Dr Matthias Gerdts	Lecturer in Mathematical Optimisation	2007–2009 (honorary until 2013)
Period when the claimed impact occurred: 2015–2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

The impacts of MIDACO optimisation software are **environmental and commercial**. The **spin-out company MIDACO-Solver** sells the optimisation software, MIDACO, which is based upon University of Birmingham researchers' Oracle Penalty Method. MIDACO is used by numerous multinational companies (including, Ford and GM in USA, Nippon Steel in Japan, Siemens in Germany). To demonstrate the significance and global reach of MIDACO, this case study focuses on a single use case of MIDACO as the **cornerstone of the Pacelab Flight Profile Optimizer**. This product is used by **Lufthansa, Finnair and Hawaiian Airlines**. This new product has delivered:

- **Reductions in the use of natural resources**: Fuel use reduced, saving at least **174,000 tonnes** of fuel in this impact period;
- **Reductions in environmentally damaging emissions**: Reduced fuel burn by 1–2% each flight, stopping at least **0.55 million tonnes of CO_2** from entering the atmosphere in this impact period;
- **Significant gains in productivity and improved cost-effectiveness**: Increased earnings by 5–10% each flight, **increasing earnings by over $100 million** in this impact period.

2. Underpinning research

All businesses must manage competing objectives; for instance, minimising the weight of a product while maximising its strength and durability, or maximising factory production whilst minimising emissions. Mathematically, this is known as a multi-objective optimisation problem, which will often have constraints.

The most frequent way to treat constrained optimisation problems is reformulate them into an equivalent unconstrained version. Penalisation methods are the most popular way to achieve this, but carry the burden of choosing proper penalisation parameters. The **Oracle Penalty Method** (R1) was derived by Matthias Gerdts and Martin Schlüter (PhD student, UoB) to tackle this difficulty.

The idea behind the Oracle Penalty Method is to first create an additional equality constraint to the constrained problem, entailing the 'Oracle' parameter (R1). This parameter corresponds to the global optimal (feasible) objective function value of a given problem, and **the key finding** is that this transformation of the objective function allows direct comparison between minimising the new constraint and minimising the residual of the original constraints. This comparability is then exploited by creating a penalty function for the unconstrained problem that uses an adaptive parameter (α), which acts as critical factor in the convex combination of the original objective function and the residual function (e.g. L1–Norm) over all constraints. The Oracle Penalty Method thus compresses the optimisation performance of a 'many-tuneable-parameter' penalisation approach into a single parameter algorithm.

The Oracle Penalty Method enabled the development of MIDACO (Mixed Integer Distributed Ant Colony Optimization) (R2–4), with significant contributions by Rückmann, for numerical optimisation based on evolutionary computing (R2). MIDACO implements an extended Ant Colony Optimisation algorithm for mixed-integer non-linear programming (MINLP) problems. **The Oracle Penalty Method is crucial** in enabling MIDACO to solve problems with hundreds of (non-linear) constraints quickly and robustly (S1b). MIDACO was created in collaboration with the European Space Agency (ESA) and European Aeronautic Defence and Space (EADS) subsidiary, EADS Astrium [G1] to solve constrained MINLP problems occurring in space applications (R2–4).

The Birmingham research embodied in the Oracle Penalty Method has generated the impact that follows via Schlüter's development of the MIDACO software package into a spinout company (S1a).

3. References to the research

R1. Schlüter, M., and Gerdts, M. 'The oracle penalty method', *Journal of Global Optimisation*, 47: 293 (2010). DOI: 10.1007/s10898-009-9477-0.

R2. Schlüter, M., Gerdts, M., and Rückmann, J. 'A numerical study of MIDACO on 100 MINLP benchmarks', *Optimization*, 61: 7, 873–900, (2012). DOI: 10.1080/02331934.2012.668545.

R3. Schlüter, M., Erb, S. O., Gerdts, M., Kemble, S., and Rückmann, J. 'MIDACO on MINLP space applications', *Advances in Space Research*, 51: 7, 1116–1131 (2013). DOI: 10.1016/j.asr.2012.11.006.

R4. Schlüter M., PhD thesis UoB (supervised by Ruckmann, J.). 'Nonlinear mixed integer based optimization technique for space applications' (2012).

Note: R1 was received by the journal on 16th November 2008, while Gerdts was a staff member at the University of Birmingham.

4. Details of the impact

The impacts of MIDACO are **environmental and commercial** and of **global reach**. MIDACO is used directly by several **leading national and transnational space agencies**, such as the ESA, German Aerospace (DLR), Japan Aerospace Exploration Agency (JAXA), and the Korean Aerospace Research Institute (KANRI; S1c). **MIDACO is world-leading**, holding three out of eight current world-record solutions for the European Space Agencies' Global Trajectory Optimisation Problems (S1d).

Additionally, MIDACO is sold directly to **multiple major global commercial entities** (for example Altair, Ford, General Motors, EDF, LG Electronics, Mitsubishi, McKinsey, Siemens) and is also a **critical embedded component in the products of multiple software companies** (for instance ASTOS, InuTech, ProSim, Ranplan Wireless, SigmaXL), which in turn license their software to companies across the globe. Pace Aerospace Engineering, the creators of the **Pacelab FPO**, are such a company.

Space constraints make it infeasible to detail the impact that MIDACO has on each of these companies and their end users (we provide S2 from SigmaXL as an example, for context). Thus, to illustrate and evidence the significance of MIDACO, we focus on the impact MIDACO has had vis-à-vis Pacelab FPO, which through its adoption by several national carriers has global reach and very high significance.

Birmingham research has underpinned the design and delivery of the new product, MIDACO, which is a critical component of the Pacelab FPO.

MIDACO is a **critical embedded component** of the Pacelab Flight Profile Optimizer (FPO) produced by PACE GmbH. The Pacelab FPO is currently being employed by **Lufthansa, Finnair and Hawaiian Airlines**. The significance of the new product MIDACO to the Pacelab FPO is attested to by a managing partner at PACE (S3):

"Our Pacelab Flight Profile Optimizer (FPO) is a key product in our portfolio, and the only commercial tool to optimize the entire vertical flight trajectory, from climb through to descent. Since 2014 **MIDACO has been an essential part of the technical backend** of our FPO software product […] **The MIDACO algorithm has allowed us to solve this challenging problem directly on board**, within the cockpit, assisting the pilot to manoeuvre the airplane along the least cost flight trajectory."

The FPO uses live aircraft and weather data to advise flight crews on the most cost-efficient speeds and altitudes to maximise the efficiency of flight operations (S4). **MIDACO is the crucial component** that allows the Pacelab FPO to perform these live, reactive calculations in the cockpit (S3), giving a **significant improvement over other FPO providers**. The impact is manifest in three key ways: reduction in the use of natural resources, reduction in environmentally damaging emissions and gains in productivity and improved cost-effectiveness.

1. Reduction in the use of natural resources: Fuel use reduced by 1–2%, saving 174,000–348,000 tonnes of fuel in this impact period.

By optimising an aeroplane's flight path, the Pacelab FPO, directly underpinned by MIDACO, reduces the amount of fuel used per flight, **resulting in a significant reduction of use of natural resources**. The managing partner of PACE attests (S3) "On average, use of our FPO results in **1–2% fuel savings**". The Head of EFB (Electronic Flight Bag) for Lufthansa (S4), confirmed "With Pacelab FPO, we can save a few hundred kilograms [of fuel] **per long-haul flight**."

Powered by our research, the Pacelab FPO "became a standard tool on board Lufthansa's long-haul fleet […] in August 2015" (S4). The Lufthansa group's sustainability reports from 2016–19 (S5 a–d, calculations in S5a) show that approximately 23 million tonnes of fuel have been used on Lufthansa passenger flights this impact period, with 68% of this on long-haul flights. We therefore estimate that **between 156,000–315,000 tonnes of jet fuel** have been saved by Lufthansa this impact period, thanks to implementation of the Pacelab FPO.

Finnair rolled out Pacelab FPO to their fleet in 2018. The effectiveness of the tool was so apparent to Finnair that its usage grew from 52% of flights in June 2018 to around **80–90% of all flights** by March 2019 (S6, Fig. 4). The Finnair group's sustainability report for 2019 and their half-year report (S7 a–b, calculations in S5a) show that approximately 1.96 million tonnes of fuel have been used by Finnair this impact period. We therefore estimate that **between 14,000–29,000 tonnes of jet fuel** have been saved by Finnair this impact period, thanks to implementation of the Pacelab FPO.

Hawaiian airlines (HAL) was the first US airline to adopt the Pacelab FPO in May 2019. In their 2019 annual report, HAL estimate that the Pacelab FPO reduces their "annual fuel consumption by approximately 1.3 million gallons", or 4,000 tonnes (S8a, p. 4).

In total, the Pacelab FPO, containing MIDACO, has led to a **significant reduction in the use of natural resources estimated to be in the range of 174,000–348,000 tonnes of jet fuel** this impact period.

2. Reduction in environmentally damaging emissions: Reduced fuel burn each flight, stopping 0.55–1.1 million tonnes of CO_2 from entering the atmosphere in this impact period.

The second impact, following directly from this reduction in fuel burn, is the **reduction of environmentally damaging emissions**. This is recognised by all the airlines, and Finnair concluded its report highlighting the significance of this impact stating that "most importantly, we are keeping fuel burn and **harmful emissions to a functional minimum**" (S6, conclusion). In a similar vein, HAL reported that, "guests arrive on our islands well rested and on time to begin their vacation, while we further **reduce our environmental footprint**" (S8b).

The carbon dioxide emissions from jet fuel are 3.15 tonnes per tonne of fuel used (S5, Lufthansa factsheet, p. 7). Thus, for the 174,000–348,000 tonnes of fuel saved by the Pacelab FPO, and thus MIDACO, our research has led to a **reduction of harmful CO_2 emissions in the range of 0.55–1.1 million tonnes** in this impact period.

3. Significant gains in productivity and improved cost-effectiveness: Increased earnings by 5–10% each flight, saving airlines over $100 million in this impact period.

The final impact arising from the reduction of fuel burn is a significant gain in productivity, typically increasing earnings per flight by 5–10% (S3), arising from the high cost of fuel. That the Pacelab FPO, utilising MIDACO, directly and materially led to this gain in productivity and improved cost effectiveness is evidenced by a Finnair report, which states: "The implementation of the Pacelab FPO software has helped us **realize a substantial part of the technological and economic potential** of our next-generation A350 aircraft and the connectivity provided by its AID — we have successfully **improved our operational efficiency** and work processes, empowered our flight crews and created a safer, more enjoyable passenger experience" (S6, conclusion).

Estimating the savings: The year-end reports for the airlines do not subdivide total fuel costs, however the year-end reports of Lufthansa (S5 a–d) report the average price they paid for jet fuel per tonne (after hedging) for that year; these values are summarised in S5a (the average from 2015–19 is $643 USD/tonne). Using a conservative estimate of $343.86 USD/tonne (S5a, S9) for 2020, **we estimate increased earnings of $96–$194 million USD** for Lufthansa, arising from implementation of the Pacelab FPO, this impact period.

Using, as an approximation, these same yearly costs for Finnair, **we estimate increased earnings of $8.6–$17.4 million USD** this impact period. Similarly, for HAL we estimate a lower bound of $343.86*4000 = **$1.4 million USD** in this impact period.

Thus, taking the conservative lower bound, **adopting the new product, MIDACO, within the Pacelab FPO** has saved a minimum of **174,000 tonnes of jet fuel, 0.55 million tonnes of CO_2 emissions and increased earnings by over $100 million USD** in this impact period.

5. Sources to corroborate the impact

S1: MIDACO Solver webpages:

a) Homepage [accessed 16/11/2020]
b) Oracle Penalty Method [accessed 16/11/2020]
c) Users [accessed 16/11/2020]
d) Record solutions [accessed 16/11/2020]

S2: Testimonial from SigmaXL (20 February 2020)

S3: Testimonial from Pacelab (29 October 2019)

S4: Pacelab Case study for Lufthansa [accessed 15/02/2021]

S5: Calculation of fuel, CO_2 and cost savings

a) Spreadsheet calculation: source_5_1_percent_saving.pdf and source_5_2_percent_saving.pdf
b) Lufthansa annual sustainability reports 2015–19 (source_5_sustain_16.pdf to source_5_sustain_19.pdf)
c) Lufthansa sustainability factsheet 2019 (source_5_factsheet_19.pdf)
d) Lufthansa annual reports 2015–19 (source_5_ar_15.pdf to source_5_ar_19.pdf)

S6: Finnair Case Study, pp. 46–51 [accessed 29/02/2020]

S7: Finnair reports

a) Finnair sustainability report 2019 (source_7_sustain_2019.pdf)
b) Finnair Q2 reports 2020 (source_7_half_year.pdf)

S8: Hawaiian airlines reports

a) HAL annual report 2019 (source_8a.pdf)
b) HAL press release (source_8b.pdf) [accessed 15/06/2020]

S9: Predictions on airline travel for 2020

a) S&P global analysis [accessed 16/11/2020]
b) Jet fuel baseline commodity price [accessed 20/10/2020 when commodity price was 1.06; evidence gathered 16/11/2020]