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Automatic air cargo selection and weight balancing: A mixed integer programming approach

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ABSTRACT

The present contribution introduces a mixed integer linear programming model as a decision support tool for air cargo load planning. The main objective for the model is to find the most profitable selection from a set of cargo to be loaded on an aircraft. The secondary objective is to minimise the deviation between the aircraft's centre of gravity, and a known target value so as to reduce fuel consumption and improve stability. The model is subject to a large number of constraints that ensure structural integrity and stability of the aircraft, as well as the safety of the cargo and crew. A set of additional constraints guarantees safe and efficient loading and unloading. Experimental results on real-life data show that the model outperforms human expert planners on both objectives, while remaining computationally fast enough for interactive use. This advocates the use of such a decision support model for all air cargo load planning.

1. Introduction

For many airlines cargo transport constitutes a major source of income; for cargo carriers it is a core business. Logically, both will try to perform their operations as safely and as efficiently as possible. In the very process, one cargo operation is of strategic importance, namely the selection, loading and positioning of cargo on an individual aircraft. The type of cargo and its positioning on board of the plane is liable to a high number of operational and safety constraints complicating decision making during cargo load planning. When too much weight is loaded at the rear, the aircraft will tip on its tail. Loading too heavy cargo at the front, makes the aircraft nose-heavy, preventing take-off. Other safety constraints are imposed to avoid anomalous stresses on the aircraft's structure. All these constraints prevent that flying characteristics differ from the safety norms which, in a worst-case scenario, might result in a crash.

In the present paper the Aircraft Weight and Balance Optimization Problem (AWBP) has been introduced as characterised by two different, be it independent, goals: to maximise revenue obtained from transporting a set of cargo items and, secondary, to optimise the centre of gravity (CG) of the loaded aircraft in both the lateral and longitudinal direction. Reducing the difference between the actual CG and a given target value (defined by the manufacturer) improves stability of the aircraft and indirectly, also decreases fuel consumption during the flight.

The AWBP can be summarised as follows: select the most profitable combination of cargo units from a given set and load them on an aircraft while satisfying a large set of linear and non-linear (safety) constraints, and minimising the deviation from the aircraft's target CG. In practice, the complex problem just described is being solved about half an hour before flight

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departure, leaving little time, or none, for finetuning. Charts and software tools are available to the expert planners for assisting in the CG calculation and for checking the constraints. It is, however, a time consuming manual process which oftentimes lacks quality. Therefore, the present paper proposes a mixed integer linear programming model for solving the AWBP.

The model presented was designed to be part of a decision support tool developed by our software partner, B. Rekencentra NV.[1] The first responsibility of this tool is the issuing of safe and legal flight documentation. As an add-on, the flight performance is improved by means of optimising the CG. The goal of the mixed integer programming model is to automate this aircraft loading in such a way that the cargo profit is maximised and that the target CG is approached in both the longitudinal and lateral dimension, without violating any (safety) constraints. The model is unique in that it combines characteristics of a knapsack problem, load balancing and the addition of several important real-life features such as overlapping loading configurations, oversized containers and cargo priority. Given that our model definition is flexible, we can state that the W&B as considered in this paper, is NP-Hard. For example, Knapsack instances can be reduced to W&B instances by considering a simple aircraft layout with only a single *'Bulk' position slot* (explained in Section 3.1) and a weight constraint on that position. Simply stated, a bulk position slot is an area on an aircraft where several bulk cargo items can be stored. Letting knapsack items correspond to bulk cargo items, with item value corresponding to cargo profit and item weight corresponding to cargo weight, it is easy to see that solving such a W&B instance corresponds to solving the knapsack problem (i.e. selecting the most profitable set of cargo items subject to a weight constraint).

The paper is organised in such a way that first, in Section 2, a literature review of related work is given. The AWBP as considered for the present purpose is discussed in detail in Section 3. Section 4 shows the details of the proposed mixed integer model for the AWBP. In Section 5 the proposed model is assessed using real-life data. Finally, Section 6 concludes the paper while indicating possible directions for further research.

2. Literature review

2.1. Related work

The earliest discussions on the load balancing problem for aircraft were reviewed by Martin-Vega (1985), who observed that, up till that point, most research had focussed on computer assistance rather than on computer generation of load plans. Noteworthy are the early academic contributions by Larsen and Mikkelsen (1980) and Brosh (1981). Larsen and Mikkelsen developed an interactive system for cargo load planning on the Boeing 747 combi aircraft, integrating two heuristics for the generation of an initial load plan and respecting a wide range of structural and safety constraints. Like in the present contribution, they specifically considered loading standardised containers/pallets (Unit Loading Devices, or ULDs, see Section 3). Their goal was to minimise unloading and reloading operations at intermediate airports in case of multi-leg flights. These operations are required when cargo to be offloaded is positioned after other destined cargo in the offloading sequence. As a secondary goal, their system aimed at obtaining a CG at the centre of its feasible interval, to allow for more flexibility in last minute changes. However, no details were given on how these heuristics achieved these goals or how well they performed except for the average CPU time.

Brosh (1981) formulated a fractional programming model for finding an optimal load layout for a particular case study, considering volume and weight constraints as well as constraints on the CG. The aim of the research was to determine the maximum amount of load that could be transported in different bays of an aircraft without violating any constraints. However, the author did not focus on where to actually place specific units of load (pallets, containers, etc.) in an aircraft, which is the main focus of our contribution.

More recently, Amiouny et al. (1992) focused solely on the one-dimensional balancing problem (applicable to general vehicle/aircraft loading). It is shown that the decision version of the one-dimensional balancing problem is NP-Complete. Several heuristics were developed for packing weighted items into a bin such that the CG achieves a certain target value. However, the approach is limited in that items must be packed contiguously, one after another, without items being placeable side-by-side.

Heidelberg et al. (1998) and Kaluzny and Shaw (2009) discussed the AWBP in a military context, dealing with non-standardised cargo. Kaluzny and Shaw presented a mixed integer linear model for positioning non-standard cargo (modelled as rectangles of variable size), suitable for either minimising deviation from optimal CG or maximising cargo value. However, apart from item spacing and CG envelope constraints (which define limits for the CG during different stages of flight, see Section 3), the problem description did not consider structural and safety constraints such as those related to floor strength, which play a key role in safe and legal cargo transportation.

The contributions of Mongeau and Bès (2003) and Limbourg et al. (2011) have the strongest relation to this paper. Both consider the placement of standardised containers (denoted ULDs) to predefined positions and the impact thereof on the aircraft's centre of gravity. Mongeau and Bès developed a linear integer programming model that maximises the total loaded cargo onto an aircraft, and ensures that the CG is within a certain ϵ from a target value. Furthermore, the authors consider important structural integrity constraints such as those on the maximum load as well as volume capacity constraints. Limbourg et al. (2011) on the other hand, assume that the most interesting selection of containers has already been made.

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[1] http://www.rekencentra.be.