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Automatic Cargo Load Planning: Special shipments

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Abstract : *The aircraft loading problem is a real-world combinatorial optimisation problem highly constrained. Indeed, loading the aircraft so the gross weight is less than the maximum allowable is not enough. This weight must be distributed to keep the centre of gravity within specified limits. Moreover, an aircraft has usually several cargo compartments with specific contours and structural limitations such as floor loading, combined load limits and cumulative load limitations. Finally, some shipments are particularly restrictive to transport, like dangerous goods, live animals and perishable goods. This paper is concerned with the incorporation of these latter constraints in a mixed integer linear program for the problem of loading a set of Unit Loading Devices and bulk into an aircraft. Experimental results show that our method achieves optimal solutions within only few seconds.*

Keywords : *Aircraft loading, weight and balance, hazardous*

1 Introduction

Several papers deal with the problem of loading a set of Unit Loading Devices (ULDs) and bulk into a cargo aircraft. An ULD is an assembly of components consisting of a container or a pallet with a net. Mongeau et Bès (2003); Souffriau et al. (2008); Limbourg et al. (2011) consider how to optimise the location of ULDs in an aircraft and their impact on the Centre of Gravity (CG). Mongeau et Bès (2003) optimise the mass of goods loaded while Souffriau et al. (2008) maximize the total cargo value. This implies that the aircraft is nearly always loaded at full capacity. However, there are often far fewer ULDs to load than what the aircraft is capable to carry, see International Air Transport Association (IATA (2010)). In these cases, we have to ensure that the loading should be concentrated or "packed" around the CG. That's why Limbourg et al. (2011) propose an approach based on the moment of inertia to tackle this problem.

According to IATA (2010), the airlines have sent 40 million tons of cargo, which corresponds to 35% of the world of trade by value. Indeed, the rapidity of air transport can be very important for high value product or for time sensitive cargo such as perishable goods or live animals. However, none of these papers takes into account the special requirements that apply to these special shipments and to hazardous material. That is precisely the aim of this paper.

According to the US Department of Transportation, a hazardous material (hazmats) is defined as any substance or material capable of causing harm to people, property, and the environment. On the one hand, the United Nations (UN) sort hazardous materials into 9 classes according to their physical, chemical, and nuclear properties (UN (2001)). Each hazard class is divided into several hazards divisions and specific labels are applied to each one of these classes or divisions. On the other hand, the IATA Dangerous Goods Regulations considers three types of dangerous goods: goods too dangerous to be transported by air, goods transported with cargo aircraft only (called CAO shipments) and goods transported both with cargo and passenger aircraft.

A literature review about hazardous materials transportation can be found in Erkut et al. (2007). Due to the large number of papers in this area, the authors propose a classification in four categories: risk assessment, routing, combined facility location and routing, network design. A significant majority of the literature on hazardous material (hazmat) routing focus on road shipments. Train shipments received considerably less attention from researchers and the literature on marine, air, and pipeline transport of dangerous goods is in its beginnings.

Finally, hazardous materials transportation must take into account that some goods may react dangerously with others. To avoid any interaction, a segregation table sums up the incompatibilities between different shipment types. The *segregated storage problem* (SSP) consists of determining an optimal distribution of products among existing storage compartments such that at most one product may be stored in a given compartment. It has been studied by several authors. Shilfer, E. et Naor, P. (1961) introduced a formulation of SPP. White, J.A. et Francis, R.L. (1971); Dannenbring, D.G. and Khumawala, B.M. (1973) investigated a branch and bound procedure. Neebe, A.W. et Rao, M.R (1976) proposed a column-generation procedure for a linear version of the problem and, Evans, J.R. and Cullen, F.H. (1977) introduced a mixed integer formulation of the problem.

Barbucha, D (2004) introduced and formally defined a new problem called the *generalized segregated storage problem* (GSSP). It involves the allocation of a certain number of goods to available compartments subject to segregation (physical separation) constraints. The subject of this paper was motivated by practical problems arising in maritime transportation of goods including dangerous goods. Because of the fact that both problems are computationally difficult (a proof of NP-completeness of SSP was presented in Barbucha, D (2004)) it is possible to obtain in reasonable time exact solutions only for instances of relatively small sizes.

Besides hazmats, other materials often transported by air due to its rapidity, need the same consideration. It is the case of undeveloped films (FIL), human remains in coffin (HUM), foodstuff and perishable goods (EAT), hatching eggs (HEG), living animals (AVI), and laboratory animals (LAB AVI).

The originality of our model is in its ability to deal with the problem of loading a set of ULDs into a cargo aircraft, ensuring that the loading is concentrated around the required CG and taking into account the specificities of the goods.

The first part of the paper gives an overview of the air cargo flows and briefly presents a mathematical model designed for optimally loading a set of containers and pallets into a compartmentalised cargo aircraft. This is followed by a summary of the incompatibilities between different shipment types and by the incorporation of these segregation constraints into the model. The paper ends with case studies and conclusions.

2 Air cargo flows

Airports Council International publishes annual Worldwide Airport Traffic Report (abbreviated as WATR reports) (Airport Council International (2009)), based on the data from a number of airports, representing approximately 98% of the global airport traffic. Distinction is made between domestic cargo accounting for 37% of total cargo volume and international cargo accounted for 63% of the total cargo volume. The three main regions according to the cargo volume are: Asia-Pacific (35%), North America (32%) and Europe (19%), see Table 1.

Regions	Number of airports	Total Cargo(tons)
Africa	176	1 944 332
Asia-Pacific	185	27 700 660
Europe	459	15 445 874
Latin America-Caribbean	269	4 178 183
Middle East	53	5 144 183
North America	212	25 403 389
Total	1 354	79 817 412

Table 1: Cargo volume by regions (Source WATR reports 2009)

A few main commodities govern air commerce between the major trading partners. According to Boeing World Air Cargo Forecast (WACF) (2010), industrial products and miscellaneous manufactured goods are major components of both eastbound and westbound flows between Europe and North America.

71% of eastbound air cargo traffic between Asia-North America is made up by office machines and computers, apparel, telecommunication equipment, electrical equipment, general industrial equipment, and specialized and scientific equipment; while 47% of the westbound traffic is made up by general industrial equipment, documents and small packages, electrical machinery, scientific and specialized equipment, and chemical materials (5%).

For 72.6% and in descending order, the Asia-to-Europe flow consists of general industrial machinery, electrical machinery and apparatus, express packages, pharmaceutical products, automobile parts and accessories, and miscellaneous manufactured goods; while the Europe-to-Asia flow is primarily manufactured goods.

Europe represents 66% of Africa's market for international air cargo. Principal northbound commodities are perishables. Southbound commodities are far more varied and include pharmaceuticals, machinery and transport equipment, oil-related supplies, and manufactured goods. The same trends are observed between Latin America and North America where 69% of total northbound traffic is perishable, while southbound flows included small packages and documents, industrial machinery and parts, computers, office machines, and specialized equipment.

A closer look on hazardous goods can be obtained in the Commodity Flow Survey, Hazardous Materials (2007). This survey provides data on the movement of freight by type of commodity shipped and by mode of transportation. More than 90% of goods transported by air for the United States are nonhazardous, and main hazard goods transported in terms of weight are perfumery products with flammable solvents and radioactive materials.

3 Mathematical model without special shipment

On this section, we present the mixed integer programming (MIP) CargoOpt model (Limbourg et al. (2011)). This model considers that all the ULDs contain products that do not require segregation. Its aim is to find the optimal allocation into a compartmentalised cargo aircraft of a set of ULDs of different types, contours and weights by optimising the moment of inertia under CG constraints.

Let's $\mathbb{U}$ be the set of ULDs, w_i the weight of the i^{th} ULD (U_i) and $\mathbb{P}$ the set of predefined positions (P_j) in the aircraft. We denote by P_L (resp. P_R) the set of positions on the left (resp. right) side. The longitudinal location of each position is expressed in inches as the distance from a virtual point called *datum*, this distance is denoted as the *arm*. We also define the central arm value a_j of P_j as the point where the ULD weight will be concentrated, L denotes the total length of the aircraft in inches, ID is the *index datum* value representing the requested CG and the total weight of the load is $W = \sum_{i \in \mathbb{U}} w_i$.

$$\text{minimise} \sum_{i \in \mathbb{U}} \sum_{j \in \mathbb{P}} w_i (a_j - ID)^2 x_{ij} + L^2 W y$$

subject to

$$x_{ij} = 0 \qquad \forall i \in \mathbb{U}, \forall j \in \mathbb{P} \mid U_i \text{ does not fit in } P_j \tag{1}$$

$$\sum_{i \in \mathbb{U}} x_{ij} \leq 1 \qquad \forall j \in \mathbb{P} \tag{2}$$

$$x_{ij} + x_{i'j'} \leq 1 \qquad \forall i, i' \in \mathbb{U}, \forall j \in \mathbb{P}, \forall j' \in \mathbb{O}_j \tag{3}$$

$$\sum_{j \in \mathbb{P}} x_{ij} = 1 \qquad \forall i \in \mathbb{U} \tag{4}$$

$$-\epsilon \leq \sum_{i \in \mathbb{U}} \sum_{j \in \mathbb{P}} w_i (a_j - ID) x_{ij} / W \leq \epsilon \tag{5}$$

$$-\bar{D} \leq \sum_{i \in \mathbb{U}} w_i \Big(\sum_{j \in \mathbb{P}_{\mathbb{R}}} x_{ij} - \sum_{j \in \mathbb{P}_{\mathbb{L}}} x_{ij} \Big) \leq \bar{D} \tag{6}$$

$$\sum_{i \in \mathbb{U}} \sum_{j \in \mathbb{P} \mid P_j \cap O_k^D \neq \emptyset} x_{ij} o_{ijk}^D \leq \bar{O}_k^D \qquad \forall D \in \mathbb{D}, \forall k \in \mathbb{O}^D \tag{7}$$

$$\sum_{i \in \mathbb{U}} \sum_{j \in \mathbb{P} \mid P_j \cap \bigcup_{c=1}^k F_c \neq \emptyset} \sum_{l=1}^{k} x_{ij} f_{ijl} \leq \bar{F}_k \qquad \forall k \in \mathbb{F} \tag{8}$$

$$\sum_{i \in \mathbb{U}} \sum_{j \in \mathbb{P} \mid P_j \cap \bigcup_{c=1}^k T_c \neq \emptyset} \sum_{l=1}^{k} x_{ij} t_{ijl} \leq \bar{T}_k \qquad \forall k \in \mathbb{T} \tag{9}$$

$$\sum_{i \in \mathbb{U}} \sum_{j \in \mathbb{P} \mid P_j \cap \bigcup_{c=1}^k T_c \neq \emptyset} \sum_{l=1}^{k} x_{ij} t_{ijl} - W y \leq \bar{R}_k \quad \forall k \in \mathbb{T} \tag{10}$$

$$x_{ij} \in \{0, 1\} \qquad \forall i \in \mathbb{U}, \forall j \in \mathbb{P} \tag{11}$$

$$y \in \{0, 1\}. \tag{12}$$

Due to their dimensions, all the ULDs do not fit in all the positions, i.e. each position accepts only some ULD types; this leads to the set of constraints (1). A second set of constraints (2) ensures that one position can accept at most one ULD. The third set of constraints is related to the fact that it is possible to load larger ULDs in some special positions overlaying several smaller ones. When an ULD is loaded in such a position, the underlying positions must remain free and, conversely, when an ULD is loaded in a basic position, the overlaying position is no longer available. In (3), O_j denotes the set of position indices underlying position P_j. Constraints (4) ensure that each ULD is loaded, while constraint (5) ensures that the deviation of the CG from ID is very small. Constraint (6) warrants that the lateral imbalance is less than a threshold ($\bar{D}$). The combined load limits constraints (7) guarantee that there is not too much weight on given sections of the aircraft. This is done for the main deck, the lower deck and both decks together, and hence we distinguish the three cases by the index D. For deck D, the k^{th} area is denoted by O_k^D, the maximal weight of this area is $\bar{O}_k^D$ and o_{ijk}^D is the proportion of w_i falling in $\{P_j \cap O_k^D\}$. Constraints (8) stipulate that the cumulative weight distribution from the nose to the centre of the aircraft must lie below a forward piecewise linear limit function and constraints (9) that the cumulative weight distribution from the tail to the centre of the aircraft must lie below an aft piecewise linear limit function. We denote by F_k (resp. T_k) the consecutive forward (resp. aft) areas, f_{ijk} (resp. t_{ijk}) is the proportion of w_i falling in $\{F_k \cap P_j\}$ (resp. $\{T_k \cap P_j\}$) and $\bar{F}_k$ (resp. $\bar{T}_k$) the maximal cumulative allowable weight for the section starting at the nose (resp. the tail) and ending with F_k (resp. T_k). For the Boeing 747, it is preferable to load the aft section so as to satisfy a more restrictive cumulative aft limit. That's why the new limit values by $\bar{R}_k$ instead of $\bar{T}_k$ (with $\bar{R}_k \leq \bar{T}_k$) and a binary variable y equal at 0 if this new constraints are proved and otherwise, it is equal at 1. We add a penalty term $L^2 W y$ in the objective function. The interested reader will find detailed explanations of this model in Limbourg et al. (2011).

4 Incompatibilities between different shipment types

Whenever dangerous goods are loaded onto a mean of transport, the segregation requirements must be fully satisfied. There may be variations between the land, air and maritime regulations and the minimum distances between ULDs denote particular requirements related to types of aircraft, types of stowage (vertical or horizontal), types of packing (open or closed), place to store packages (on main deck or lower deck), and so on. Segregation can be achieved by either separating the ULDs or by locating ordinary compatible cargo ULDs between incompatible ULDs.

For air transport, the *International Civil Aviation Organization* (ICAO) produces the legal basic requirements concerning the handling of dangerous goods. The IATA also sets regulations on dangerous goods which apply to its member airlines, associate members and interline partners. Nevertheless, every company is free of having its own requirements as long as they comply with the legal requirements.

The general rules that can be extracted from these regulations are:

- Dangerous goods from class 1 (Explosives) shall not be loaded in close proximity of dangerous goods from classes 2 (Gases), 3 (Flammable liquids), 4 (Flammable solids and reactive substances), 5 (Oxidizers and organic peroxides) and 8 (Corrosive articles and substances).
- Dangerous goods from class 7 (Radioactive material) must be separated from animals, hatching eggs and unexposed films. Moreover, during the flight, minimum horizontal and vertical distances must separate these radioactive packages from each other and from passengers.
- Live animals cannot be loaded in close proximity of foodstuffs or human remains.
- Live animals and hatching eggs must not be loaded in close proximity of dry ice. Note that dry ice is used as a refrigerant for perishable goods transportation.
- Live animals should be separated from laboratory animals.
- Animals that are natural enemies such as cats and dogs should not be loaded insight, sound, smell or reach of each other.
- Foodstuffs must not be loaded in close proximity of human remains.
- Live animals and perishable goods are particularly restrictive shipments to transport. First, they can't be directly loaded on the floor of the aircraft. Secondly, in addition to the temperature, several other factors must be considered: on the one hand, animals and perishable goods need a relatively fresh air, but on the other hand they give off substances which can be harmful. Thirdly, when transporting live animals and perishable goods, the basic rule is "Last in - First out". For the cargo to arrive in the best condition, it must be loaded as near as possible to the aircraft departure time and collected as soon as possible at the destination airport. That means that it must be loaded close to the cargo door.
- Moreover, for goods emitting radiations such as magnetized or radioactive materials, the separation distances depend on the level of radiations. Magnetized materials must not be loaded in such a position that they will have a significant effect on the direct-reading magnetic compasses or on the master compass detector sections of the aircraft. The separation distances from packages of radioactive materials to passengers are based on a reference dose. If more than one ULD containing radioactive materials is placed in the aircraft, the minimum separation distance for each individual ULD must be determined on the basis of the sum of the reference doses.

Finally, some dangerous goods are subject to maximum weight or quantity limitations. It is the case of dry ice, also depending on the presence of living animals. And concentrations are limited for some corrosive products.

5 Incorporation of segregation constraints into the model

To deal with the segregation between ULDs, we first define m categories of goods according to the possible incompatibilities mentioned in the previous section (starting with ICAO and IATA regulations). The first category is for neutral products that can be set close to any other ones. We make the simplifying hypothesis that an ULD can contain only one kind of special shipment plus the neutral ones. We can therefore associate to each ULD a unique label corresponding to one of the m categories. The generalisation to different special goods is direct. We then define a $m \times m$ segregation matrix S. Element s_{ij} of S belongs to $\mathbb{Z}^+$ and corresponds to the minimal distance (in inch) required between the two categories of goods i and j. Note that S is symmetrical and that the elements on the main diagonal are equal to zero.

Each position of the aircraft is defined by two values: the *forward arm* and the *aft arm* (see Figure 1). The distance d_{kz} between a position P_k and a position P_z is the difference between the aft (forward) arm of P_z and the forward (aft) arm of P_k when P_z is located after (before) P_z.

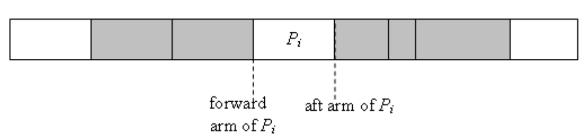

Figure 1: Neighbour positions

We propose the following algorithm to take into account the segregation constraints.

For each U_i $(i \in \mathbb{U})$
For $j = i + 1$ to the number of ULDs
    $i' =$ the category index of U_i

$j' =$ the category index of U_j
For each P_k in which U_i, can fit
For each P_z of the same deck in which U_j, can fit
If $s_{i'j'} > d_{kz}$ then

$$x_{ik} + x_{jz} \leq 1 \tag{13}$$

End if
Next P_z
Next P_k
Next j
Next U_i

Each constraint (13) states that the 2 incompatible ULDs i and j cannot fit at the same time in the positions k and z if the distance between these positions is less than the required segregation distance. While up to now we tried to show that taking into account special shipments during the loading is of great interest for firms, we can wonder if these new constraints are mathematically difficult to satisfy. Indeed, each of them is a simple linear combination of only two variables. However, the difficulty arises due to their number, as a function of the number of 4-tuples (U_i,U_j,P_k,P_z), that quickly explodes. The size of the problem becomes therefore rapidly important even if the matrix of constrains is mainly sparse. Fortunately, we can observe that only a subset of constraints (13) is usually binding during the optimisation, we have therefore an acceptable computation time.

Beside the segregation between ULDs, we have also to consider the segregation between some ULDs and some parts of the aircraft. Indeed, some goods are forbidden in some areas due to their nature or due to the proximity with some aircraft equipments (e.g. due to magnetic emissions). This is easy to manage by extending the set of constraints (1). At the opposite, sometimes ULDs must or should preferably be limited to specific positions to facilitate handling. Again, it can be done through constraints of type (1) since the infeasible space is complementary to the feasible space. For very specific constraints that cannot be handled by the model, we modified the software such that, the load master can lock some ULDs in specific positions and a optimal solution for the positions of the other ULDs is found.

6 Case studies

We have written a software in Java to prepare the data, to call the professional optimisation library IBM ILOG CPLEX and to analyse the results. It has been compiled and tested under Windows XP and under Linux (Ubuntu 10.04). The optimisation steps were performed on a personal laptop computer (Windows XP, Dual-Core 2.5GHz, 2.8GB of RAM) and with CPLEX 12. Since we must solve a mixed integer linear program, we have used the classical branch-and-cut CPLEX solver with the default parameters.

	RCX	RXB	RXD	RNG	RFL	RSC	RFW	ROX	ROP	RRY	RCM	ICE	FIL	AVI
RCX	0	D	0	D	D	D	D	D	D	0	D	0	0	D
RXB	D	0	D	D	D	D	D	D	D	0	D	0	0	D
RXD	0	D	0	D	D	D	D	D	D	0	D	0	0	D
RNG	D	D	D	0	0	0	0	0	0	0	0	0	0	0
RFL	D	D	D	0	0	0	0	D	0	0	0	0	0	0
RSC	D	D	D	0	0	0	0	0	0	0	D	0	0	0
RFW	D	D	D	0	0	0	0	0	0	0	0	0	0	0
ROX	D	D	D	0	D	D	0	0	0	0	0	0	0	0
ROP	D	D	D	0	0	0	0	0	0	0	0	0	0	0
RRY	0	0	0	0	0	0	0	0	0	0	0	0	5D	1
RCM	D	D	D	0	0	0	D	0	0	0	0	0	0	0
ICE	0	0	0	0	0	0	0	0	0	0	0	0	0	4D
FIL	0	0	0	0	0	0	0	0	0	5D	0	0	0	0
AVI	D	D	D	0	0	0	0	0	0	1	0	4D	0	0

RCX : Explosive ; RXB : Explosive ; RXD : Explosive ; RNG : Non-flammable Gas ; RFL : Flammable Liquid ; RSC : Spontaneously Combustible ; RFW : Dangerous when Wet ; ROX : Oxidiser ; ROP : Organic Peroxide ; RRY : Radioactive ; RCM : Corrosive ; ICE : Dry Ice ; FIL : Undeveloped Film ; AVI : Live Animals

D is a typical size of a position

Table 2: Segregation matrix

The case study contains a large number of ULDs (42) and, a high capacity and largely operated aircraft, i.e. a Boeing 747. A Boeing 747 is generally divided into 67 basic positions, plus 10 larger ones overlaying some of the basic positions, which is theoretically 4.10^6 (A_{77}^{42}) arrangements to consider. We know the exact location and dimensions of each position, as well as the list of ULD types that each may contain. The positions are represented by boxes in Figure 2. Some positions are on the main deck (first row) and others are on the lower deck (second row). Each position is identified by a code on the side of the box.

Figure 2 also illustrates the solution obtained by the software. Each green box is a ULD with its type and weight. All constraints of the model presented in section 3, when no special shipments are considered, are satisfied.

Concerning the quality of the solution, we may measure the deviation between the CG obtained and its ideal position. In this case, the location of the requested CG is expressed as a percentage of the mean aerodynamic chord (MAC) value and equals 28 with a precision required of 0.01. With a result of 27.997, the goal is achieved. Finally, less than two seconds were required to solve this instance.

Several tests using the segregation matrix represented in Table 2 (this table is an outline of the table in Tusek, A. (2011) and we use the regulations of the dangerous products of IATA) have been performed. As it is often done in practice, we set the minimal segregation distance between two incompatible products to a multiple of the typical size D of a position). Figure 3 represents a case with seven ULDs having separation requirements, solved in 4.9s. The cargo- Interchange Message Procedures (IMP) code of these ULDs is in red in the green box.

To test our approach, we also present a case with 15 special ULDs. It is solved in less than 7 s (Figure 4).

Finally, let's assume that in the case represented in Figure 5, we have three additional constraints : the ULDs 6 and 14 must be located near the doors and that the ULD 31 contains magnetic component that must be located far from electronic equipments, if possible in the tail (position T) of the aircraft. The load master can restrict these ULDs to some positions (in blue, see Figure 5). Starting from this configuration, it takes less than 4 s to obtain the optimal solution.

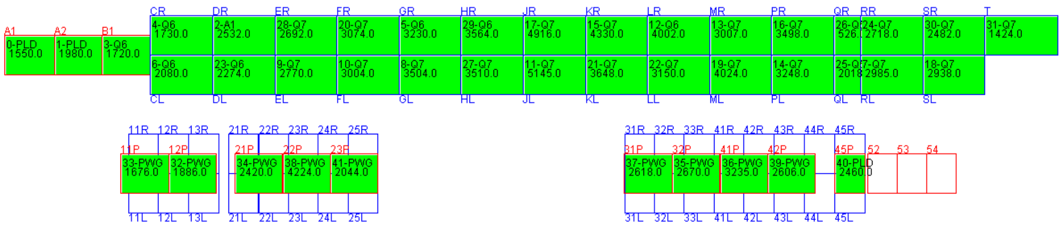

Figure 2: Loading without incompatibly constraints

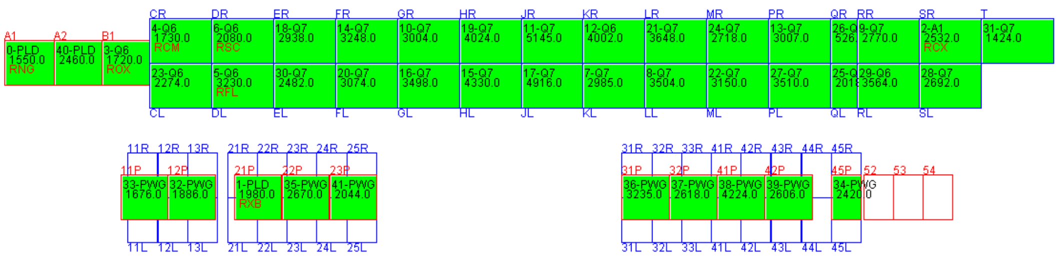

Figure 3: Loading with 7 special ULDs

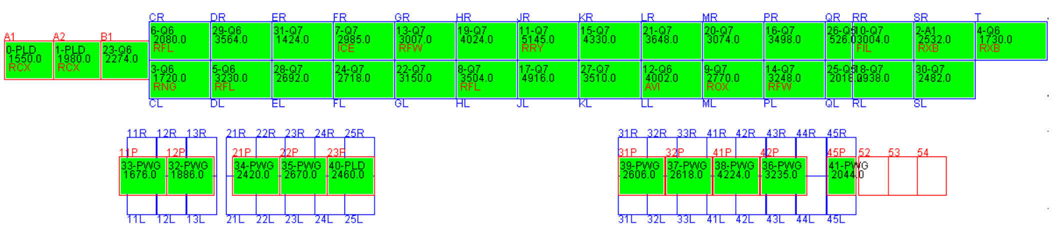

Figure 4: Loading with 15 special ULDs

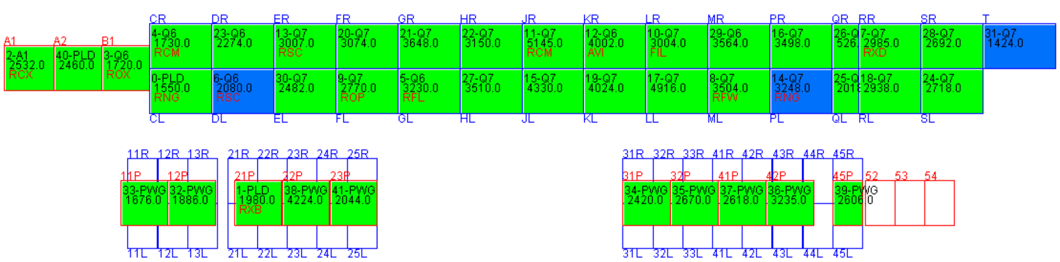

Figure 5: Fixed positions for 3 ULDs

7 Conclusion

Some shipments are particularly restrictive to transport. This is the case of dangerous goods, live animals and perishable goods. Our goal is to take the segregation constraints related to these special shipments into account in a mixed integer linear program for the optimal loading of a set of containers and pallets into a compartmentalised cargo aircraft. To deal with this problem, we associate to each ULD a unique label corresponding to one of the categories of goods according to the possible incompatibilities and we propose an algorithm to add the segregation constraints in the model.

In our knowledge and according to the commodity flow data, the number of incompatibilities between ULDs by flight is not too important. That's why, to test our model, we consider there are less than 15% of special ULDs to load. Experimental results show that our method achieves optimal solutions within only few seconds.

Moreover, we modified the software to combine the freedom of the classical manual approach based on the load master's knowledge of practical constraints with the power of the optimiser. That means that the load master can lock some ULDs in specific positions to satisfy additional rules such as those for magnetic or radioactive materials before the optimisation process.

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