IBN HALDUN UNIVERSITY
SCHOOL OF GRADUATE STUDIES
DEPARTMENT OF AIR TRANSPORT MANAGEMENT

MASTER THESIS

A SIMULATION APPROACH FOR AIRCRAFT CARGO LOADING CONSIDERING WEIGHT AND BALANCE CONSTRAINTS

ERDEM AĞBAŞ

THESIS SUPERVISOR

ASSOC. PROF. ALİ OSMAN KUŞAKCI

ISTANBUL, 2021

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A SIMULATION APPROACH FOR AIRCRAFT CARGO LOADING CONSIDERING WEIGHT AND BALANCE CONSTRAINTS

by

ERDEM AĞBAŞ

A thesis submitted to the School of Graduate Studies in partial fulfillment of the requirements for the degree of Master of Science in Air Transport Management

THESIS SUPERVISOR

ASSOC. PROF. ALİ OSMAN KUŞAKCI

ISTANBUL, 2021

APPROVAL PAGE

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science in Air Transport Management

Thesis Jury Members

Title - Name Surname	Opinion	Signature

This is to confirm that this thesis complies with all the standards set by the School of Graduate Studies of Ibn Haldun University.

Date of Submission   Seal/Signature

ACADEMIC HONESTY ATTESTATION

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name Surname:

Signature:

ÖZ

HAVA KARGO UÇAKLARININ AĞIRLIK VE DENGE KISITLAMALARINI GÖZETEN BİR BENZETİM YAKLAŞIMI

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Tez Danışmanı: Doç. Dr. Ali Osman Kuşakcı
Temmuz 2021, 41 sayfa

Hava kargo taşımacılığı, dünya ticaretinin büyümesine ve artan e-ticarete paralel olarak büyüyen bir sektördür. Yolcu uçaklarının bagaj kısmı ve kargo uçakları ile gerçekleştirilir. Birim yük cihazlarının (unit load devices; ULDs) kargo uçağındaki belirli pozisyonlara atanması, manuel veya yarı manuel yöntemlerle loadmasterlar tarafından gerçekleştirilir. Küresel hava kargo taşımacılığı trafiği yoğunlaştıkça, minimum hata ile zamanında yükleme yapmanın önemi giderek artmaktadır. Bu nedenle hava kargo yükleme sürecinin dijitalleştirilmesine ihtiyaç duyulmaktadır. Bu çalışmada, ağırlık ve denge kısıtlamalarını gözeten ve deneyimli loadmasterlar tarafından gerçekleştirilen yükleme işlemini benzeten, ULD atamasını otomatik olarak gerçekleştiren bir program yazmayı amaçladık. Veriler analiz edilirken SEMMA (örnekle, araştır, değiştir, modelle, değerlendir) modeli kullanıldı. Programı değerlendirmek için elli tane gerçek veri kullanıldı. Program ve loadmaster tarafından yapılan (yarı manuel) ULD atanması işlemi, süre ve ağırlık merkezi açısından Mann Whitney U testi ile karşılaştırıldı. Programın verilen tüm ULD setlerini belirlenen güvenlik ve stabilite sınırları içinde yerleştirdiği görüldü. Program yüklemeleri daha kısa sürede gerçekleştirirken ağırlık merkezi load mastera göre benzerdi. Sonuç olarak, ULD atanma işleminin dijitallejmesi mümkündür ancak tüm kısıtlamaları kapsayacak şekilde geliştirilmesi gerekmektedir.

Anahtar Kelimeler: Ağırlık Merkezi, Ağırlık ve Denge Problemi, Birim Yük Cihazları, Hava Kargo, Kargo Uçağı, Yükleme Planlaması

ABSTRACT

A SIMULATION APPROACH FOR AIRCRAFT CARGO LOADING CONSIDERING WEIGHT AND BALANCE CONSTRAINTS

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Air cargo transport is a growing industry in parallel with world trade growth and increasing e-commerce. It is performed by the passenger aircraft belly and the pure cargo air crafts, i.e., the freighters. Assignment of Unit Load Devices (ULDs) to the specific positions on the freighter is performed by loadmasters by manual or semi-manual methods. As the global air cargo transport traffic gets busier, the importance of timely loading with minimum error increases. Therefore, digitalization of the air cargo loading process is needed. This study aimed to write a program that automatically performs the ULD assignment by simulating the loading process performed by the experienced loadmasters and considering the weight and balance constraints. The SEMMA (sample, explore, modify, model, assess) model is used while analyzing the data. Fifty real-world setting data were used to evaluate the program. The ULD assignment by the program and the loadmasters by semi-manual loading were compared regarding time and center of gravity by the Mann Whitney U test. The results demonstrated that the program could load all the given sets of ULDs, as efficiently as a loadmaster with a similar center of gravity in a shorter period of time. In conclusion, digitalization of the ULD assignment is possible, which needs to be improved to cover all the constraints.

Keywords: Air Cargo, Center of Gravity, Freighter, Load Planning, Unit Load Devices, Weight and Balance Problem

DEDICATION

It is dedicated to my wife Ayşe and my lovely kids Kerem and Nil Mercan…

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I would like to thank to my supervisor Assoc. Prof. Ali Osman Kuşakcı, for sharing his professional experience, support, guidance and patience while writing my thesis.

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Erdem Ağbaş

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LIST OF SYMBOLS AND ABBREVIATIONS

ACI	Airports Council International
ACL	Air Cargo Loading
ACLP	Air Cargo Load Planning
ACLPP	Air Cargo Load Planning Problem
ATOW	Actual Take-off Weight
AZFW	Actual Zero Fuel Weight
CG	Center of Gravity
COVID-19	Coronavirus Disease-19
CTK	Cargo Tonne-Kilometers
DHL	Dalsey, Hillblom and Lynn
DHMI	Devlet Hava Meydanları İşletmesi
DRGs	Dangerous Goods
DOW	Dry Operation Weight
IATA	International Air Transport Association
LEMAC	Leading Edge of the Mean Aerodynamic Chord,
LW	Landing Weigh
MAC	Mean Aerodynamic Cord
SEMMA	Sample, Explore, Modify, Model, Assess
SHGM	Sivil Havacılık Genel Müdürlüğü
TEMAC	Trailing Edge of the mean aerodynamic chord
THS	Trimmable Horizontal Stabilizer
THY	Türk Hava Yolları
TOW	Take-off weight

ULD	Unit load devices
UPS	United Parcel Service
USD	United States Dollar
WBP	Weight and balance problem
ZFW	Zero fuel weight

CHAPTER I

INTRODUCTION

Air cargo transportation has an important role in the global economy, which offers safety, speed and high-capacity. As global supply chain and global trading has been improved, a tremendous growth has been observed in international air cargo transport. Although air cargo represents less than 1% of global trade by volume, in terms of value it represents about one third, which is above 6.7 trillion USD (IATA, 2020). Furthermore, within the next 20 years, despite COVID-19 pandemic, world air cargo traffic was expected to grow 4.2% and the world freighter fleet was expected to grow by 70% from 1770 to 3010 airplanes (IATA, 2020).

From a local perspective, air cargo improves the engagement of a country in the international trade. Countries with 1% better air cargo connectivity engage in trade 6% more (IATA, 2020). Therefore, governments have the potential to improve their trade competitiveness on a global level if they invest and implement policies to support air cargo.

In Turkey, the international air cargo handling was increased 67.7% within 10 years (DHMI, 2020). Furthermore, it is expected to grow further. Firstly, Istanbul airport was opened at 2018 with an air cargo capacity of 2.5 million tonnes and expected to increase up to 5.5 million tonnes by 2021. That is higher than the capacity of Hong Kong airport, the busiest airport in the world, with about 4.5 million tonnes in 2019 (IGA, n.d.). Considering the capacity and the geographically strategic advantage of Istanbul Airport, it is expected to be one of the major cargo hubs in the world. Secondly, Turkish cargo, which is the flag carrier of the air cargo of Turkey, has an increasing growth and market share in the world air cargo industry. Despite the COVID-19 pandemic, the company continued to grow becoming the 6th company in all over the world in terms of world air cargo traffic. Therefore, the market place of Turkey in the global air cargo industry is increasing.

Consequently, air cargo traffic is increasing globally. Unlike the passenger transport, which has a known capacity, cargo space has greater uncertainty regarding demand

and allocation. Therefore, how airline companies can effectively perform air cargo loading operations such as loading rates and revenues has become an important issue.

1.1. The Problem We Face

Air cargo traffic is increasing and air cargo operations should handle this increased traffic. One of the major operational steps is the loading of the ULDs to the specific positions on the freighters, which is mostly performed by load masters with manual, semi-manual or heuristic methods. For a safe flight, many constraints regarding safety and stability must be taken into account while assigning of each ULD to a specific position. Most of the time the loading is completed at the last moment, without fine tuning. Therefore, a software may decrease the time consumed and provide better solutions for the air cargo loading.

1.2. Research Question and the Objectives of the Study

The main objective is to load all the given sets of ULDs within safety and legal limits by an automatic air cargo loading program, which simulates the loading process performed by the load masters. The model will be performed for Airbus 330 cargo air craft and for a single leg flight.

Accordingly, we formulate our main research question as follows: Can air cargo loading process simulated by an automated software that will be developed by SEMMA model for data mining in order to load all the given set of ULDs within safety and legal limits, considering the weight and balance constraints.

The secondary questions of the study can be listed as such:

- Can the simulation model load the air craft in a shorter time compared to a semi-manual process by a load master that is currently in use.?
- Can the simulation model load the air craft with a better CG compared to a semi-manual process? Can the model provide a lower fuel consumption, which can be obtained with a better CG?

1.3. Contributions of the Thesis

In summary, air cargo transportation is a growing area. Unlike passenger transportation, the air cargo loading process is not very digitalized and is still based on manual, semi-manual and heuristic methods. To meet the increasing demands and to increase the revenue, it is important to use technology and time wisely. With this study, we aim to propose a new alternative approach that will be used for the air cargo loading process considering the safety and stability constraints of the weight and balance problem in addition to reducing the cost. The aim of the study was to write a computer program which performs the ULD assignment on to the specific positions on an Airbus 330 Freighter. The program performs the loading starting from a given list of ULDs and is designed to consider the main safety and stability constraints of the weight and balance problem. Furthermore, the experiences of the loadmasters were used to design the program. Finally, it is designed to simulate the air cargo loading process which is done by the experienced loadmasters. Air cargo loading is a dynamic process with multiple confounding factors, with an efficient program the loading time can be decreased and the best safe options can be produced, which eventually decrease the pressure and stress on loadmasters and will let the fine tuning of the loading.

CHAPTER II

AIR CARGO TRANSPORT

2.1. Air Cargo Transport in the World and the Effect of the COVID-19 Pandemic

Air cargo transport is a growing area in parallel with the world trade growth. Therefore, it is affected by the global crisis, that affects world trade such as the COVID-19 pandemic. Air cargo represents less than 1% of global trade by volume. However, in terms of value, it represents about one third, which is above 6.7 trillion USD (IATA, 2020). Furthermore, within the next two decades, world air cargo traffic is expected to grow 4.2% and the world freighter fleet is expected to grow by 70% from 1770 to 3010 airplanes (IATA, 2020) even considering the effect of the pandemic.

World freight traffic had already been slowing due to decelerating industrial production and geopolitical uncertainty before the COVID-19 pandemic. After the pandemic there was a steep decline of -27.7% YoY in April 2020, when the pandemic had a peak (Figure 2.1). However, afterwards, air cargo traffic started to grow month by month in terms of FTK and finally saw positive growth and even exceeded the pre-COVİD period, 2019 levels. Despite the new waves in the pandemic, air cargo demand remained robust (ICAO, 2021).

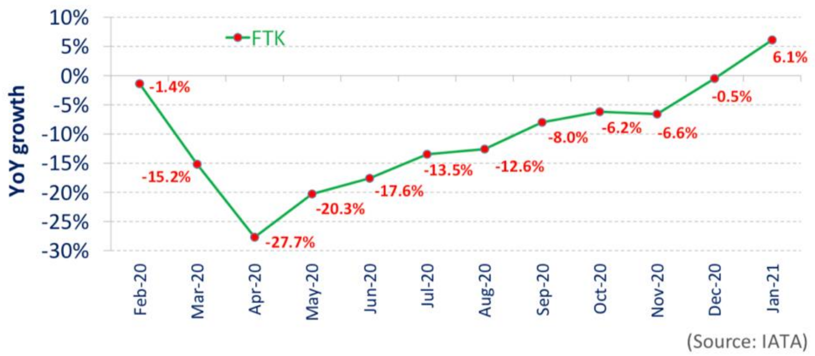


Figure 2.1. The Year-Over-Year Growth of the World Air Cargo Transport.

Source: ICAO, 2021

In 2019, Coronavirus disease, caused by Severe Acute Respiratory Syndrome Coronavirus 2 (SARS - CoV - 2), first appeared in Wuhan, China and was later declared as a pandemic in March 2020. With the declaration of lock downs, pandemic affected the global economy and the air transportation industry severely. The revenue of the airlines in 2020 is forecasted to drop 50%, which is about 419 billion dollars, due to COVID-19 pandemic. As the half of the global air cargo is carried by the belly of the passenger aircrafts, the decrease in passenger transport due to pandemic caused a decrease in global air cargo capacity (available cargo tonne kilometers, ACTKs) (Figure 2.2). By May 2020 although it was still down 11.1% compared to pre-crisis values, air cargo capacity continues to improve slowly (IATA, 2021).

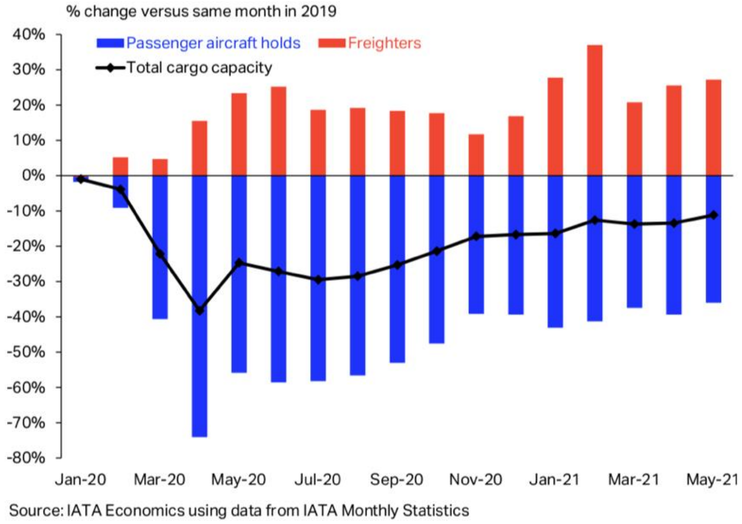


Figure 2.2. International Belly Cargo and Freighter Capacity Growth.

Source: IATA, 2021

In terms of cargo volume carried in tonnes, there was a steep decrease due to the pandemic. However, there was an improvement in CTKs (Cargo Tonne Kilometers) even better than in the pre-crisis period, which was driven by increased manufacturing activity and export orders with an increased e-commerce demand (IATA, 2021) (Figure 2.3). As mentioned before, the available capacity (ACTKs) was still lower than the pre-crisis levels, however the carried cargo (CTKs) is increased, resulting in higher cargo load factors. By May 2021, the international cargo load factor was 65%, which was a new record-high for any month of May.

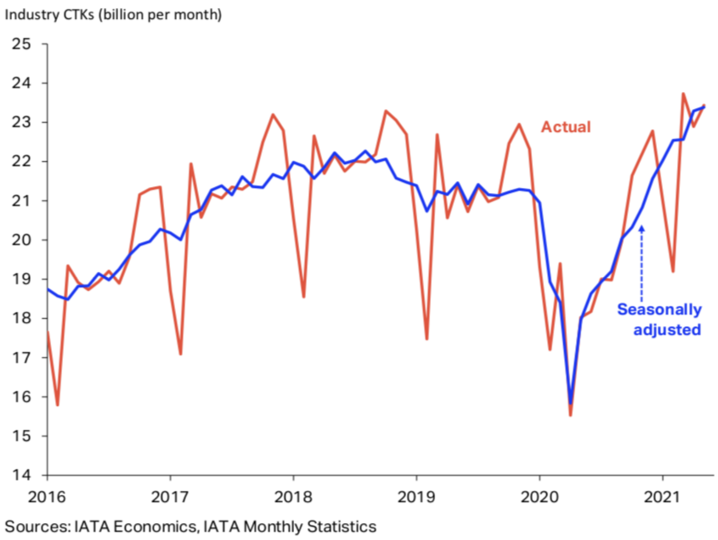


Figure 2.3. Actual and Seasonally Adjusted CTK Levels.

Source: IATA, 2021

The effect of the pandemic on passenger transport was not so dramatic for air cargo. Even though the volume carried by air cargo had dropped the revenue was increased (IATA, 2021). Between March 2020 and September 2020, during the COVID-19 pandemic, in addition to flights for the main supply chains, about 1.5 million tonnes of cargo, mostly medical equipment, were carried by 46,600 special cargo flights. Therefore, the importance of air cargo has increased further (ATAG, 2020). By May 2021, one third of the revenue from air transport was coming from air cargo transport which was about 10-15% before the crisis (IATA, 2021).

In summary, the effects of the COVID-19 pandemic on the air cargo industry is improving. The CTKs and revenue have reached levels better than the pre-crisis levels. Despite the pandemic this industry has continued to grow.

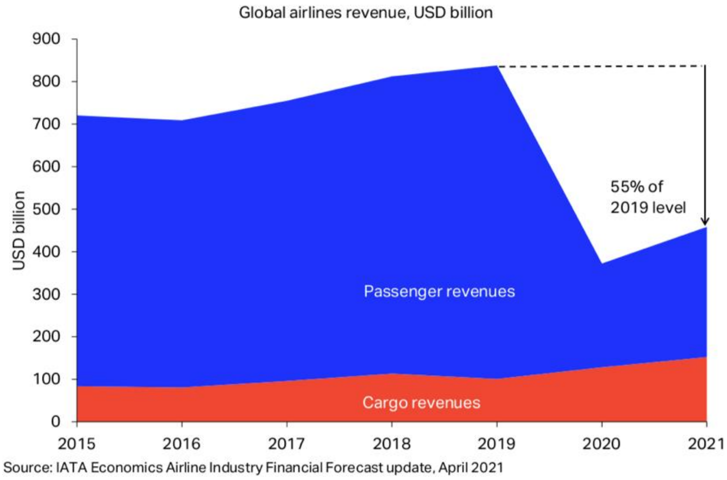


Figure 2.4. There was a Sharp Decrease in Passenger Revenue Whereas Cargo Revenues Increased After Pandemic.

Source: IATA, 2021

2.2. Air Cargo Transport in Turkey

In Turkey, by the end of 2019 the total handled cargo was 1,522,404 tonnes, international was 1.456.737 tonnes, and the domestic was 65,667 tonnes, which were 541,357 tonnes, 470,141 tonnes and 71,216 tonnes in 2010, respectively. There was a 67.7% increase in international air cargo handling whereas domestic was almost stable (DHMI, 2020). Furthermore, Istanbul airport was opened in 2018 with an air cargo capacity of 2.5 million tonnes. In 2019, about 600 thousand tonnes of cargo was handled. By 2021, the airport is planned to handle a capacity of 5.5 million tonnes, which is higher than the capacity of Hong Kong airport, the busiest airport in the world, with about 4.5 million tonnes in 2019 (IGA, 2021). If we consider the capacity and the geographically strategic advantage of Istanbul Airport, it is expected to be one of the major cargo hubs in the world. Therefore, the market place of Turkey in the global air cargo industry is increasing.

By the end of 2020, there were four air cargo companies and a total of 30 freighters in Turkey by the end of 2020 (SHGM, 2020). The biggest one is Turkish Cargo, which had a total of 25 freighters (10 Airbus 330, 8 Boeing 777, 4 Boeing 747, 1 Airbus 300). Turkish Cargo has been performing the air cargo transportation operations of Turkish Airlines, since 1933. Operating with the fleet of Turkish Airlines, with a total of 363 aircrafts (338 passenger aircraft and 25 freighters). Turkish Cargo flies to more than

320 destinations in 127 countries. Ninety-five of them are direct cargo destination (THY, 2020).

The company has an increasing growth and market share in the world air cargo industry. Despite the COVID-19 pandemic, the company continued to grow and has become the 6th company in the world in terms of world air cargo traffic. In 2020, the company carried over 1,5 million tonnes of air cargo. They transported one out of every twenty air cargo loads. While the world air cargo shrunk by 28.5%, the company increased its market share to 5.1%. A total of 8,563 flights were performed by freighters in 2020. The annual revenue of Turkish Cargo was increased by 62% from 1,688 million USD in 2019 to 2,722 million USD in 2020 (THY, 2020).

In summary, Turkey's market place in the air cargo transport industry is expected to grow further with the flag carrier company Turkish Cargo and an important international air cargo hub Istanbul Airport.

2.3. Components of Air Cargo Transport

2.3.1. Aircrafts

There are two ways to carry cargo by air transport (a) in the belly space of a passenger aircraft, also called passenger aircraft lower hold and (b) using dedicated full freighter aircraft. Each has unique advantages.

The passenger aircrafts provide more flexibility regarding frequencies and destinations. However, it offers limited and unexpected cargo capacity, which depends on the number of the checked passengers per aircraft.

Passenger wide-body aircrafts have played an important role in the growth of the air cargo industry in the last decade. However, more than half of the air cargo traffic is expected to be carried by dedicated freighters as most passenger belly capacity does not serve key cargo trade routes, twin-aisle passenger schedules often do not meet timing needs, freight forwarders prefer palletized capacity, passenger airplane bellies cannot serve hazardous cargo, and payload-range considerations on passenger airplanes may limit cargo transport (Boeing, 2021).

The freighters, are particularly useful for transporting high value cargo as they provide highly controlled transport, direct routing and unique capacity considerations (volume, weight, dimensions and hazardous materials). These advantages increase the value of service, which leads freighters to generate nearly 90% of the total air cargo industry revenue whereas it compromises about half of the World Air Cargo transport (Boeing, 2021).

The freighters can be classified as small, medium and large sized aircrafts according to payload. The American Boeing and the European Airbus companies are the two main aircraft companies producing both passenger and freighter aircrafts. Table 2.1 demonstrates the cargo aircraft types according to volume and companies (Boeing, 2018).

There were about 1800 freighters in service globally by 2018, which comprise 7.6% of the world commercial jet transport fleet by 2018 among single-aisle (74.9%) and widebody (17.5%) passenger jets (Boeing 2018). In 2020, the number increased to 2010 freighters. Each freighter type (small-, mid- and large-sized) consists of about one third of the global freighter fleet. As intercontinental trade continues to grow, especially large-sized freighter demand continues, which are preferred for the intercontinental air cargo transport because of their payload capacity and long flight performances (Boeing 2021). Therefore, more than one-third of these deliveries will be new widebody cargo airplanes.

Table 2.1. The Types of Cargo Aircrafts According to Volume and Company (Boeing, 2018)

Small sized (standard body) (payload <45 tonnes) (n=671)	**Mid-sized (medium widebody) (payload 40-80 tonnes) (n=544)**	**Large sized Large widebody) (payload >80 tonnes) (n=565)**
Boeing 707	Boeing 767*	Boeing 747*
Boeing 727	Boeing 787	Boeing 777*
Boeing 737*	Boeing DC-10	Boeing MD-11*
Boeing 757*	Airbus 300*	Airbus 350
Boeing MD-80*	Airbus 310	Antonov-124
Boeing DC-8, DC-9	Airbus 330*	Ilyushin II-96T
Airbus 320	Ilyushin II-76TD	
Bae 146		
TU-204		

*At peak use, or expanding role going forward.

2.3.2. Airports

Airports that are organized for cargo transport are essential for an organized air cargo transportation. The capacities of the top 20 cargo airports in 2019 and in the first quartile (Q1) of 2020 are given in the Table 2.2 (ACI, 2020). Most of the airports are in Asia and America. The busiest airport in total air cargo and international freight traffic was Hong Kong with a capacity of about 4.8 million tonnes in 2019. Memphis is the second busy airport in total air cargo with a capacity of 4.3 million tonnes. However, it is not within the first twenty airports when we exclude mail and consider only freight (Table 2.3) (ACI, 2020).

Table 2.2. Total Air Cargo Traffic and Year-Over-Year Percentage Change. (ACI, 2020)

CARGO (METRIC TONNES)*						
2019	2018	AIRPORT	2019 total	2019 vs 2018 % change	Q1 2020	Q1 2020 vs Q1 2019 % change
1	1	HONG KONG, HK (HKG)	4 809 485	-6.1	988 000	-10.9
2	2	MEMPHIS TN, US (MEM)	4 322 740	-3.3	1 030 854	-6.8
3	3	SHANGHAI, CN (PVG)	3 634 230	-3.6	743 923	-7.6
4	7	LOUISVILLE KY, US (SDF)	2 790 109	6.4	628 942	2.2
5	4	INCHEON, KR (ICN)	2 764 369	-6.4	664 889	2.5
6	5	ANCHORAGE AK, US (ANC)**	2 745 348	-2.2	591 462	-3.5
7	6	DUBAI, AE (DXB)	2 514 918	-4.8	568 142	-14.3
8	11	DOHA, QA (DOH)	2 215 804	0.8	537 712	4.4
9	8	TAIPEI, TW (TPE)	2 182 342	-6.1	499 073	-0.3
10	9	TOKYO, JP (NRT)	2 104 063	-6.9	502 918	2.0
11	14	PARIS, FR (CDG)	2 102 268	-2.5	398 703	-15.3
12	15	MIAMI FL, US (MIA)	2 092 472	-1.8	490 760	-6.2
13	10	LOS ANGELES CA, US (LAX)	2 091 622	-5.4	459 799	-7.9
14	13	FRANKFURT, DE (FRA)	2 091 174	-3.9	457 556	-11.8
15	12	SINGAPORE, SG (SIN)	2 056 700	-6.3	462 900	-7.8
16	16	BEIJING, CN (PEK)	1 957 779	-6.0	301 449	-33.3
17	17	GUANGZHOU, CN (CAN)	1 922 132	1.7	353 848	-17.7
18	18	CHICAGO IL, US (ORD)	1 758 119	-3.8	398 394	-2.4
19	19	LONDON, GB (LHR)	1 672 874	-5.6	351 222	-18.0
20	20	AMSTERDAM, NL (AMS)	1 592 221	-8.4	354 420	-8.7

*Cargo: loaded and unloaded freight and mail in metric tonnes
** includes transit freight

Table 2.3. International Air Freight Traffic and Year-Over-Year Percentage Change (ACI, 2020)

INTERNATIONAL FREIGHT (METRIC TONNES)*						
2019	2018	AIRPORT	2019 total	2019 vs 2018 % change	Q1 2020	Q1 2020 vs Q1 2019 % change
1	1	HONG KONG, HK (HKG)	4 703 589	-6.3	972 000	-10.4
2	2	SHANGHAI, CN (PVG)	2 825 009	-3.1	578 995	-6.5
3	3	INCHEON, KR (ICN)	2 664 005	-6.8	647 106	3.5
4	4	DUBAI, AE (DXB)	2 514 918	-4.8	568 142	-14.3
5	7	DOHA, QA (DOH)	2 173 371	0.5	529 436	4.7
6	5	TAIPEI, TW (TPE)	2 165 216	-6.1	495 048	-0.3
7	6	TOKYO, JP (NRT)	2 039 905	-7.2	484 101	1.1
8	8	SINGAPORE, SG (SIN)	2 014 100	-6.5	453 100	-8.0
9	9	FRANKFURT, DE (FRA)	1 961 460	-4.1	431 005	-11.2
10	10	ANCHORAGE AK, US (ANC)**	1 942 554	-2.5	421 429	-1.3
11	11	PARIS, FR (CDG)	1 888 497	-2.5	390 056	-15.3
12	12	MIAMI FL, US (MIA)	1 706 064	-3.7	398 498	-8.0
13	14	LONDON, GB (LHR)	1 586 865	-5.8	332 468	-18.5
14	13	AMSTERDAM, NL (AMS)	1 570 261	-8.5	349 854	-8.7
15	15	BANGKOK, TH (BKK)	1 293 589	-11.0	302 064	-6.2
16	16	LOS ANGELES CA, US (LAX)	1 272 010	-7.5	277 742	-3.8
17	17	CHICAGO IL, US (ORD)	1 251 111	-8.8	250 550	-8.6
18	19	LEIPZIG, DE (LEJ)	1 147 233	1.8	223 359	-0.5
19	20	GUANGZHOU, CN (CAN)	1 124 224	3.5	196 167	-11.7
20	21	NEW YORK NY, US (JFK)	956 217	-8.7	168 976	-16.2

*International freight loaded and unloaded in metric tonnes

** includes transit freight

2.3.3. Air Cargo Companies

There are three types air cargo service providers: (1) combination airlines (passenger airlines offering cargo services), (2) full-cargo airlines, and (3) integrators. The first two only offer air transport services between airports and work with freight forwarders and ground handlers for the landside logistics. However, integrators offer a door-to-door service to customers. The American FedEx and UPS, and the European DHL are the “threeheaded” kings of the integrators. On the other hand, Amazon Air was established in 2015 and has been growing incredibly with 77 freighters within 6 years (Hayward, 2021).

The list and the capacities of worldwide air cargo companies in 2020 is given in Table 2.4 (IATA 2020). In terms of scheduled cargo tonne-kilometers (CTK), Qatar airways ranked the first regarding international air cargo transport (about 13 billion CTK), whereas FedEx ranked the first in total scheduled CTK (about 17.5 billion CTK) with the addition of its domestic capacity (about 8.5 billion CTK). The Turkish Airlines Cargo ranked the 8th in international, and 9th regarding total scheduled CTK (Table 2.4). In terms of carried scheduled freight tonnes Emirates Airlines ranked the first regarding international transport with about 2.5 million tonnes. However, FedEx ranked the first regarding total scheduled freight carried (about 7.5 million tonnes) with addition of its domestic capacity of 5.2 million tonnes. The Turkish Airlines Cargo ranked the 6th in both the international and the total scheduled freight tonnes carried in 2020 (Table 2.5).

Table 2.4. Scheduled Cargo Tonne-Kilometers in 2020 (IATA, 2020)

Scheduled Cargo Tonne-Kilometers								
International			Domestic			Total		
Rank	Airline	Millions	Rank	Airline	Millions	Rank	Airline	Millions
1	Qatar Airways	13,024	1	Federal Express	8,652	1	Federal Express	17,503
2	Emirates	12,052	2	United Parcel Service	6,614	2	Qatar Airways	13,024
3	Cathay Pacific Airways	10,930	3	China Southern Airlines	1,343	3	United Parcel Service	12,842
4	Fedral Express	8,851	4	Air China	1,116	4	Emirates	12,052
5	Korean Air	7,390	5	Atlas Air	924	5	Cathay Pacific Airways	10,930
6	Luftansa	7,223	6	China Eastern Airlines	826	6	Korean Air	7,412
7	Cargolux	7,180	7	Air Transport International	765	7	Luftansa	7,226
8	Turkish Airlines	7,000	8	SF Airlines	666	8	Cargolux	7,180
9	United Parcel Service	6,228	9	United Airlines	621	9	Turkish Airlines	7,029
10	Singapore Airlines	6,146	10	Shenzhen Airlines	571	10	China Southern Airlines	6,825

Table 2.5. Scheduled Freight Tonnes Carried in 2020 (IATA, 2020)

Scheduled Freight Tonnes Carried								
International			Domestic			Total		
Rank	Airline	Millions	Rank	Airline	Millions	Rank	Airline	Millions
1	Emirates	2,413	1	Federal Express	5,236	1	Federal Express	7,428
2	Qatar Airways	2,281	2	United Parcel Service	3,484	2	United Parcel Service	5,032
3	Fedral Express	2,192	3	China Southern Airlines	777	3	Emirates	2,413
4	Cathay Pacific Airways	1,716	4	Air China	691	4	Qatar Airways	2,282
5	United Parcel Service	1,539	5	China Eastern Airlines	562	5	Cathay Pacific Airways	1,716
6	Turkish Airlines	1,433	6	Hainan Airlines	522	6	Turkish Airlines	1,496
7	Korean Air	1,383	7	SF Airlines	496	7	Korean Air	1,435
8	China Airlines	1,374	8	Atlas Air	471	8	China Southern Airlines	1,416
9	Singapore Airlines	1,115	9	Air Transport International	439	9	China Airlines	1,374
10	Luftansa	911	10	All Nippon Airways	402	10	Air China	1,360

2.4. Air Cargo Load Planning

International air cargo, an operation-intensive industry, involves complex decision-making procedures and numerous players (Brandt & Nickel, 2019). Air cargo has three main stakeholders; (1) the sales department , (2) handling department (built-up unit load devices, ULDs) and (3) the aircraft cargo operations department (aircraft cargo loading).

Before loading the goods into the air craft, cargo is assembled onto palettes or containers called unit load devices (ULDs) (Figure 2.5a). ULDs provide standardized size units for individual pieces of baggage or cargo, which offers rapid loading and unloading. These ULDs are built according to the loading positions of a specific aircraft. Inside the aircraft, these ULDs are placed on designated loading positions and locked into position by latches on the floor (Figure 2.5b) (Brandt&Nickel 2019).

a) b)

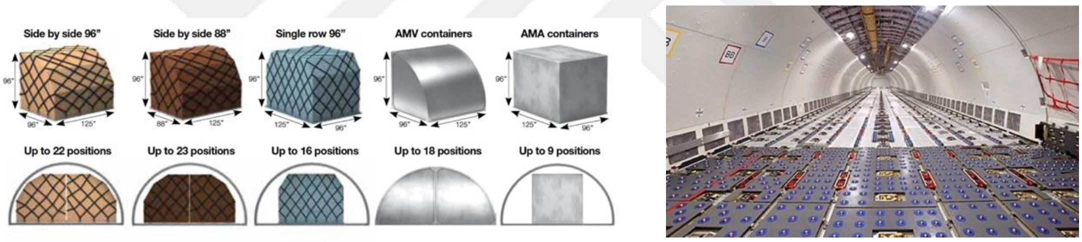


Figure 2.5. a) Cargo Configurations. b) The Slots on the Floor of the Freighter, on Which the ULDs are Locked

Source: Airbus, 2014

There are two types of ULDs as a pallet and a container. ULDs are defined with IATA complimentary codes (Figure 2.5a and Table 2.6). These codes define the type, base measures, shape, conformity and airworthiness factors as well as the carrier company. ULDs have standard size base dimensions and maximum structural weight limits such as PKC 1587 kg, PLA 3174 kg etc.

Some of the most used ULD codes are as follows: PAG, PMC, PGA, PRA for the main deck and AKE, PLA for the lower deck. The first letter indicates the type (either pallet or container) and the second letter indicates the base dimensions and the last letter indicates the contour of the ULD (Table 2.6). In addition to codes the contour of the

ULDs is defined as single row, side-by-side, center and tail, which are also important while loading to specific positions (Figure 2.5a).

Table 2.6. First Letter Indicates the Type and the Second Letter Indicates the Base Dimension of the ULDs

The first letter (type of the ULD)		The second letter (base dimension of the ULD)	
A	Certified aircraft container	A	2235 x 3175 mm / 88 x 125 inch
B	Certified winged aircraft pallet	B	2235 x 2743 mm / 88 x 108 inch
D	Non-certified aircraft container	G	2438 x 6058 mm / 96 x 238.5 inch (20 ft)
F	Non-certified aircraft pallet	K	1534 x 1562 mm / 60.4 x 61.5 inch
G	Non-certified aircraft pallet net	L	1534 x 3175 mm / 60.4 x 125 inch
H	Certified horse stalls	M	2438 x 3175 mm / 96 x 125 inch
J	Thermal non-structural igloo	N	1562 x 2438 mm / 61.5 x 96 inch
K	Certified cattle stalls	P	1198 x 1534 mm / 47 x 60.4 inch
L	Certified multi-contour aircraft container	Q	1534 x 2438 mm / 60.4 x 96 inch
M	Thermal non-certified aircraft container	R	2438 x 4978 mm / 96 x 196 inch (16 ft)
N	Certified aircraft pallet net	S	1562 x 2235 mm / 61.5 x 88 inch
P	Certified aircraft pallet		
Q	Certified hardened aircraft container		
R	Thermal certified aircraft container		
S	Certified multi-modal air/surface container		
U	Non-structural container (igloo)		
V	Automobile transport equipment		
W	Certified ULD for aircraft engine transport		
X	Reserved for airline internal use		
Y	Reserved for airline internal use		
Z	Reserved for airline internal use		

The air craft operations department performs the loading and the fuel of the aircraft. The major aim of the aircraft operations is loading all the built set of ULDs considering safety and legal limits. Secondly, the aim is to operate the flight at minimum cost considering the fuel consumption and boarding operations. For this aim, the load inside the aircraft should be distributed in the best possible way. In the real-world settings, this is performed by experienced load masters as manually or semi-manual (partly computer assisted) manner. This works well in practice; however, it is time-consuming and usually loading is completed at the last possible moment before boarding, which interferes with fine tuning and causes suboptimal loading. Thirdly, for the multileg flights, ULDS should be loaded in a way that the number of reloading of ULDs must be minimum at each stop-over airport to reduce the turnaround time, wear and tear of the aircraft and the damage risk of the cargo. Ultimately, the main objective is maximizing the profit (Brandt&Nickel, 2019).

All these three departments play a role in increasing the efficiency and revenue of each flight; however, the last two departments are the main steps of "air cargo load planning (ACLP)". There are several parameters and constraints, which are referred to as the "Air cargo load planning problem (ACLPP)". The ACLPP consists of the union of the following four subproblems.

a) Air craft configuration problem; selecting the type and the number of ULDs to be built.

b) Built-up scheduling problem; timing of built-up process.

c) Air cargo palletization problem; assignment of items to ULDs.

d) Weight and balance problem (WBP); assignment of ULDs onto the loading positions considering the weight, balance and center of gravity constraints.

2.5. Weight and Balance Problem Theoretical Background

Two issues are vital in the weight and balance considerations of an aircraft.

• The total weight of the aircraft must be lower than the maximum weight allowed by the manufacturer for the type of aircraft.

• The center of gravity (CG); the point at which all of the weight of the aircraft is considered to be concentrated, must be maintained within the allowable range for the operational weight of the aircraft. While allocating the load positions, the following issues must be taken into account as possible constraints (Brandt&Nickel, 2019):

a. ULD assignment: Each ULD must either be assigned to one specific loading position. Depending on the ULD's type, contour, weight, or contained dangerous goods, it might not be loadable at certain positions.

b. Loading position assignment: On each flight leg each loading position can load at most one ULD except bulk position.

c. Overlapping positions: In freighters there are two decks; main (upper) and lower decks. There are several combinations of positions for ULDs (Figure 2.6). For example, a PAG ULD can be loaded onto 40 different positions. Several loading positions can overlap and mutually exclude each other from being used.

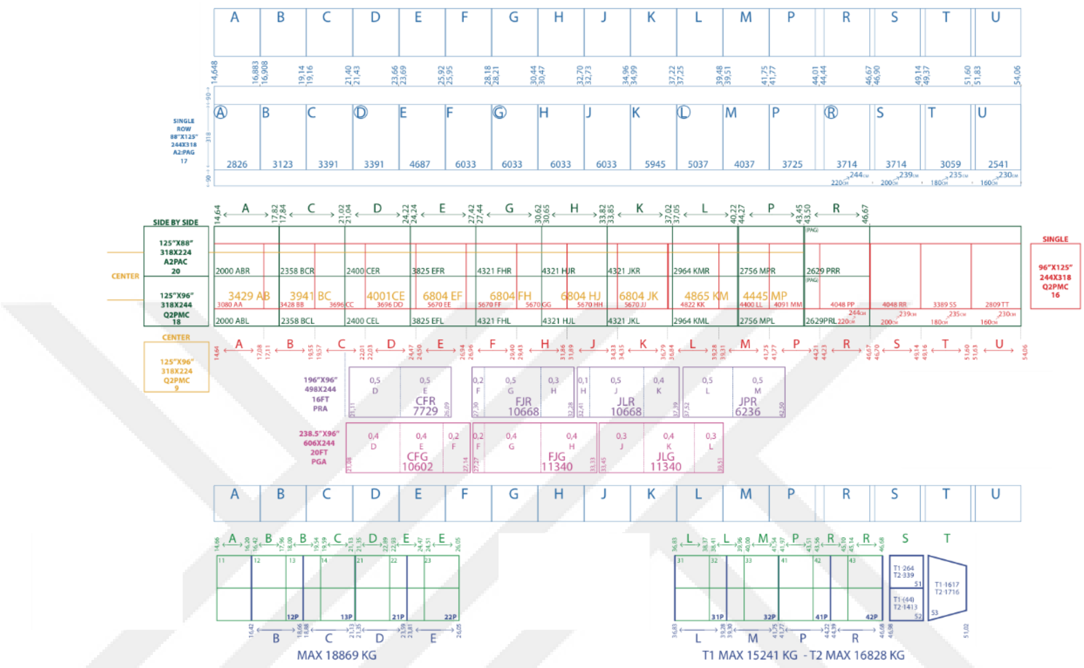


Figure 2.6. The Different Combinations of Positions Where the ULDs Can Be Loaded According to Shape, Contour and Weight Limits.

d. Weight limits: The aircraft has several specific defined weights limits on each flight leg, which are explained bellow. The weight of the aircraft at several stages of the flight (as weight of the fuel decreases throughout the flight) must be considered. There are maximum limits for zero fuel weight, take-off weight and landing weight, which change according to weight variant that are certified at A330. There are three modes of weight variant for A330F: range, payload and dynamic modes.

• Basic weight: Standard empty weight of an airplane.

• Dry operation weight (DOW): The empty weight of the aircraft in addition to the weight of the crew and other standard items, such as potable water and meals.

• Corrected dry operation weight: Dry operation weight plus crew baggage and optional equipment such as technical kit and load master (LM) kit.

• Payload: The weight of occupants, baggage and cargo.

• Zero fuel weight (ZFW): The sum of corrected dry operation weight and payload without fuel.

• Take-off weight (TOW): The weight of an aircraft just before beginning the takeoff . It is the ramp weight minus the weight of the fuel burned during start and taxi.

• Landing weight (LW): The takeoff weight of an aircraft excluding the fuel burned and/or dumped en route.

e. Cumulative weights: Each aircraft has structural weight limits for each individual loading position, each zone, each section (forward, center and aft) and for total weight (Figure 2.6 and 2.7).

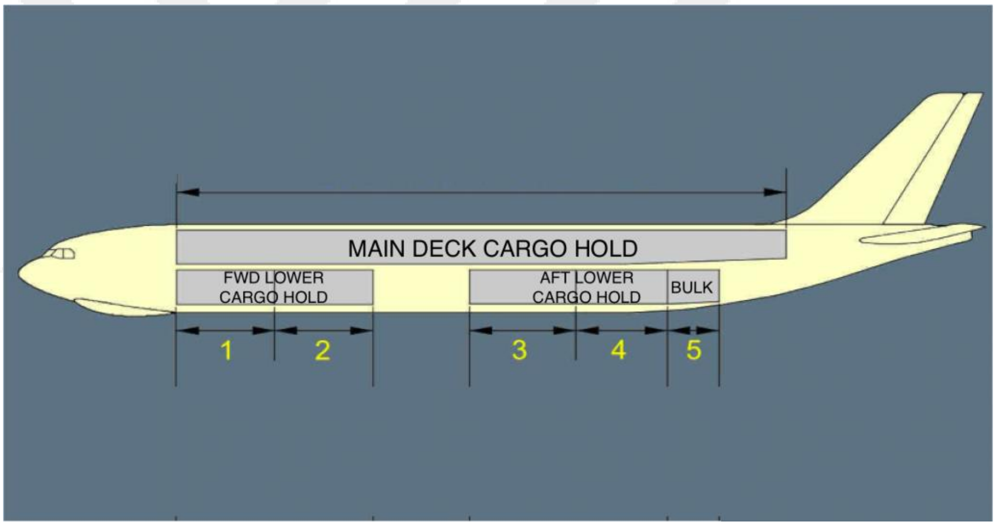


Figure 2.7. ULD Loading Sections of a Cargo Aircraft.

f. The Balance Theory and the Center of Gravity (CG): The WBP are based on the physical law of the lever. According to this law, a lever is balanced when the sum of the moments about the fulcrum is zero. Figure 2.8 demonstrates the law of lever. To establish a balance the sum of (-) and (+) moments should be zero which means (A*Arm C) should be equal to (B*Arm D).

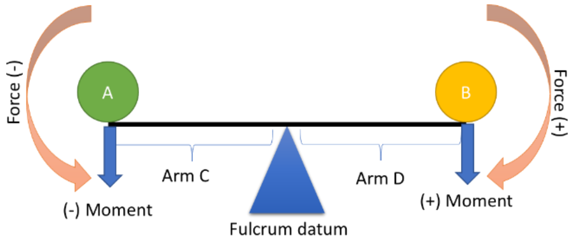


Figure 2.8. Law of Lever. Moment= Weight * Arm (the Distance From the Fulcrum Datum).

The weight and balance have an impact on the stability and maneuverability of the aircraft. The CG is the balance point of an airplane. If total moment is divided by the total weight of the aircraft, the distance between the datum and the CG can be calculated. The CG is the theoretical point, where the total weight of the airplane is assumed to be concentrated. It may be expressed in the distance (inches) from the reference datum or in % of MAC (mean aerodynamic cord) (Figure 2.9 and 2.10).

a)

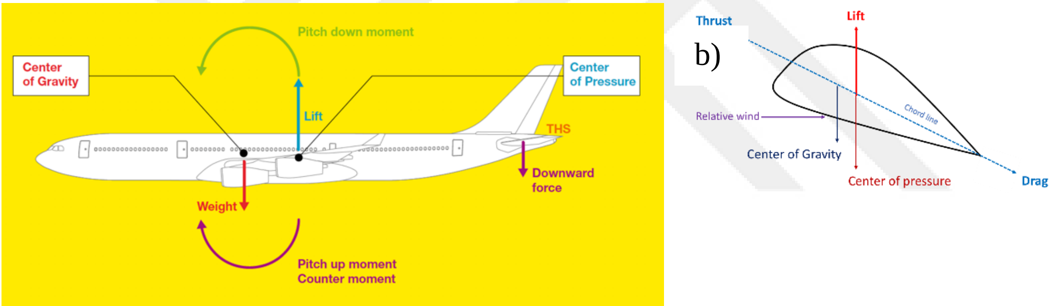
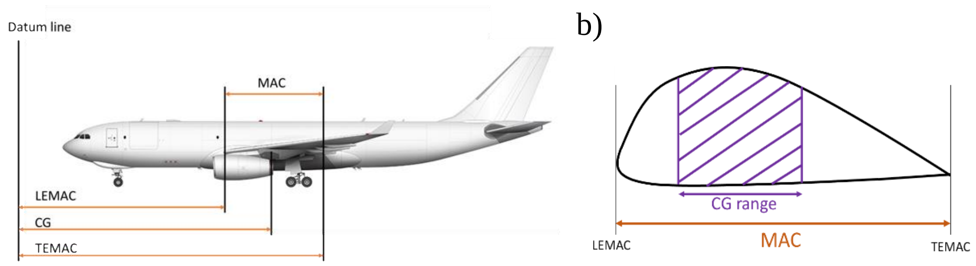


Figure 2.9. (a) The Presentation of the Forces on an Aircraft and (B) on the Wing While Flying.

For the stability of an airplane, the CG is located more forward than the CP. Therefore, the distance between the CG and the CP creates a pitch down moment, which is compensated by a downward force of Trimmable Horizontal Stabilizer (THS) (Figure 2.9).

a) b)



MAC (the width of the wing)=TEMAC-LEMAC
Distance from LEMAC = CG – LEMAC
CG as %MAC= (Distance from the LEMAC*100) / MAC

Figure 2.10. Presentation of Mean Aerodynamic Chord (MAC) and the Center of Gravity (CG) on an Aircraft (a) and the Wing (b).

Both longitudinal and lateral balances are important, however the main concern is longitudinal balance, which is determined by the location of the CG. The CG must be located within the specific limits (the CG range of the aircraft) for the stability, maneuverability of the aircraft and for a safe flight (Figure 2.10b).

Moments are calculated by multiplying the weight of each component by its arm. As the results are large in number and may mathematical errors, moment indexes (moment/reduction factor) are used. For each zone of the aircraft the manufacturers express the moment index, and the sum of these indexes is used to calculate the CG. The manufacturers also express a graphical representation (graphical envelope) (Figure 2.11). The moment indexes are used to determine the CG on the graphical envelope. Using diagonal lines from total moment index and total weight, the CG is demonstrated without using mathematical calculations. This visual envelope also defines the CG and weight limits of the air craft at TOW and ZFW. The figure 2.11 illustrates the visual envelope. Vertical values are the total weight, the first horizontal values are the total moment index and the second horizontal values are the CG expressed in %MAC. ATOW: actual take-off weight, AZFW: actual zero fuel weight.

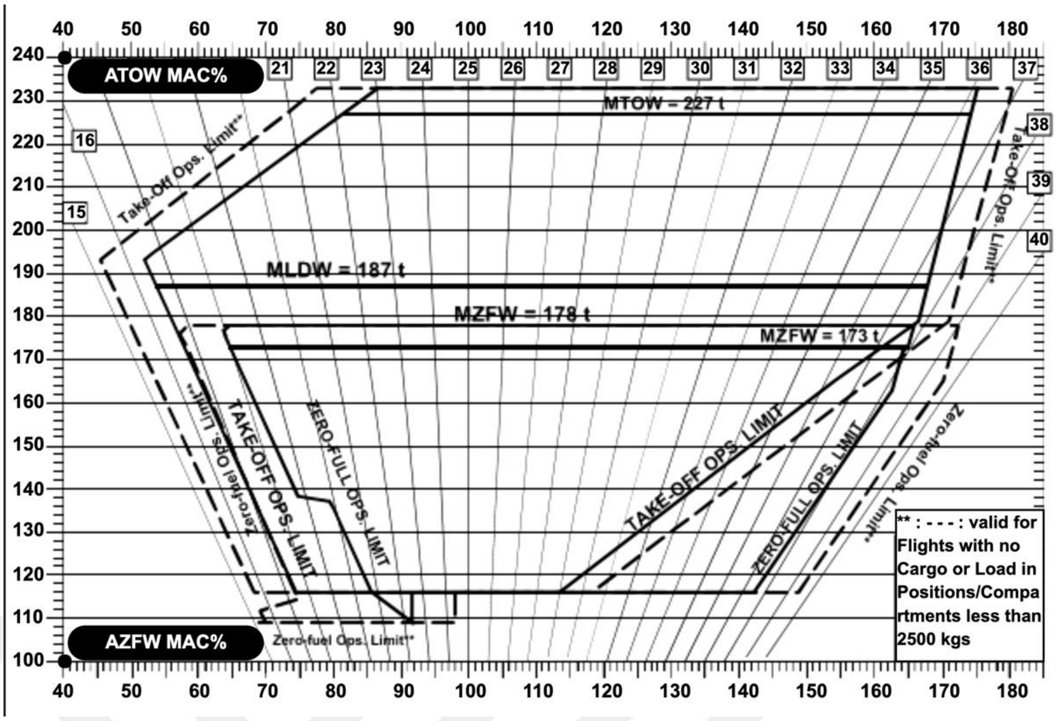


Figure 2.11. The Graphical Envelope of the A330 Aircraft.

Besides being in the safe limits of the graphical envelope, a ‘perfect’ CG reduces drag, which leads less engine power and fuel consumption during flight to maintain speed (Limburg, 2012). As an example, displacement of CG of less than 75 cm, saves 4000 kg of fuel over a 10000 km flight (Mongeau and Bes, 2003).

Some definitions needed to present the problem are given below:

• Datum: An imaginary vertical plane or line from which all measurements of arms are taken. The datum is established by the manufacturer. Once the datum has been selected, all moment arms and the location of CG range are measured from this point.

• Chord line: A straight line distance across a wing from leading edge to trailing edge.

• Center of gravity (CG): The point at which an airplane would balance if suspended. Its distance from the reference datum is determined by dividing the total moment by the total weight of the airplane. It is the mass center of the aircraft, or the theoretical point at which the entire weight of the aircraft is assumed to be concentrated. It may be expressed in percent of MAC (mean aerodynamic cord) or in inches from the reference datum.

• LEMAC: Leading edge of the mean aerodynamic chord. A reference point for measurements, and specified in inches from the datum to allow computations to relate percent MAC to the datum.

• TEMAC: Trailing edge of the mean aerodynamic chord.

• Mean aerodynamic chord (MAC): The width of the wing. The average distance from the leading edge to the trailing edge of the wing.

• Percent MAC (%MAC): The distance in inches of the CG from LEMAC divided by the MAC. It is a good standard for CG location in airplanes because it permits a standard weight and balance program for different types of airplanes.

• CG arm: The arm obtained by adding the airplane's individual moments and dividing the sum by the total weight.

• CG limits envelope: An enclosed area on a graph of the airplane loaded weight and the CG location. If lines drawn from the weight and CG cross within this envelope, the airplane is properly loaded.

• CG moment envelope: An enclosed area on a graph of the airplane loaded weight and loaded moment. If lines drawn from the weight and loaded moment cross within this envelope, the airplane is properly loaded.

g. Moment of inertia: Heavier ULDs should be loaded close to the CG. The aircraft's maneuverability decreases with a higher moment of inertia. In real world practice not all air crafts are fully loaded as cargo load factor has been reported as lower than 50% in 2019 (IATA 2019). In that situation moment of inertia becomes important.

h. Loading dependencies: Some loading positions must be used as a couple such as two ULDs–one with the cutout and the other with the overhang must be placed next to each other.

i. ULD separation: The ULDs containing incompatible goods such as dangerous goods must be loaded with a certain distance apart. The DRGs may include explosives, flammable liquids and solids, toxic and infectious substances, oxidizing substances and organic peroxides, corrosives and radioactive substance. There are several rules while loading those DRGs such as loading apart from foods or loading apart from each other for a defined distance. Radioactive material must be placed away from the crew.

j. Loading operations: In multileg flights the ULDs on the way to a door must be removed before a ULD can be loaded. Likewise the ULDs that will be unloaded in the first stop, must be assigned to a position close to the door. Some ULDs can also be prioritized that must be transported in that flight.

CHAPTER III

LITERATURE REVIEW

Unlike air passenger transportation, the air cargo transportation has not been that much digitalized to increase the profitability and efficiency. There are scarce literature including several mathematical models addressing each steps of air cargo load planning problems. The literature about air cargo loading problem is summarized in Table 3.1. The CG and the ULD assignment restrictions present in all the papers and are not shown.

Table 3.1. Literature Summary About Weight and Balance Problems With ULDs.

Author	Year	Optional loading	Cumulative weights	Overlapping positions	Moments of inertia	ULD separation	Number of legs	Objective
Brosh	1981	+	-	-	-	-	1	Max load
Mongeau	2003	+	-	+	-	-	1	Max load
Limbourg	2012	-	+	+	+	-	1	Min moment of inertia
Vancroonenburg	2014	+	+	+	-	+	1	Min center of gravity offset
Lurkin	2015	-	+	+	-	+	N	Min cost
Dahmani	2016	+	-	-	-	-	1	Max load, max priority

Source: Brandt&Nickel, 2018

Mongeau and Bes. (2003) proposed a model to select the most profitable set of ULDs for an aircraft. Limbourg et al. (2012) have created a mixed linear program based on real-world problems submitted by a professional partner to reduce WBP as well as to decrease the fuel cost. The main goal was optimally loading a set of pallets and containers considering the safety and technical constraints, such as control of the lateral and longitudinal balance, combined and cumulative weight, feasibility envelopes in addition to a restricted version of the cumulative aft body weight constraint, which is important for the Boeing 747 aircraft. In addition, the model optimally positioned the CG and concentrate-package the weight starting around the CG (moment of inertia), both of which cause reduction of fuel cost and increase safety. They have tested the model with real-world data and have demonstrated the time consumed is within minutes and meets all the described safety and technical constraints. The model also allows the input of new constraints.

Vancroonenburg et al. (2014) employed a model to determine the most profitable set of cargo to be loaded from a list of cargoes. Their secondary objective was to optimize the center of gravity (stability and consumption of fuel) considering real-life issues such as oversized containers, cargo priority and overlapping loading configurations. Case studies have shown that the model performs within seconds, produces more favorable CG and lateral balance, and leaves no unloaded ULD.

Lurkin and Schyns. (2015) have improved the model of Limburg et al. (2014) and they have developed a mixed linear integer model to plan multileg flights. While meeting all the technical and safety constraints (weight and balance, optimum CG), their second aim was to reduce ground handling time by planning cargo loading for each leg. In addition, they have included hazardous goods and oversized ULDs in the model.

Dahmani and Krichen (2016) studied two steps of ACLP, palletization and WBP. First step was the assignment of items to ULDs and the second step was to assign the ULDs to the loading positions. They present a multi-objective particle swarm optimization approach and compare their results to optimal MILP solutions.

Wong et al. (2020) performed a Cave Automatic Virtual Environment (CAVE)-based virtual reality system to visualize and experiment with the loading procedures. They assessed the impact of the digital twin system on the daily operations of an air cargo terminal, especially the allocation of dangerous goods and special cargo. They proposed that load planners can master complex air cargo load planning through the system with optimal solutions generated and the operations of cargo assembly and security screening with digital twins could be further developed for future development.

CHAPTER IV

METHODOLOGY & APPLICATION

4.1. Analysis of the Current Practice and the Literature

Currently, the common practice is to load the ULDs to the specific positions on the freighters by loadmasters with manual, semi-manual or heuristic methods. For a safe flight, many constraints regarding safety and stability must be taken into account while assigning of each ULD to a specific position. Most of the time, the loading is completed at the last moment, without fine-tuning. For the case-study, we observed the loading process performed by the experienced loadmasters and used their experience to develop the simulation model.

We also performed the literature review and observed that there were a few studies about the digitalization of the air cargo loading process. The main concern was the safety and stability constraints of the WBP.

Based on the experience of the loadmasters and the literature review, we designed a simulation model.

4.2. The Methodology Used and the Simulation Model

We propose a simulation-based solution to the problem and a SEMMA model was used as an overall data mining method (Nie, 2014).

The SEMMA is an acronym of Sample, Explore, Modify, Model and Assess. It comprises a list of sequential steps developed by the software producer SAS Institute.

Sample: In this step, an appropriate portion of a vast dataset is chosen, which must include the significant information but also it must be easy to manipulate quickly. The aim of this step is to identify variables or factors (both dependent and independent), which influence the process.

Explore: The univariate analyzes are performed, and the data are visualized with graphics. In univariate analysis, the individual associations between variables are assessed. The significant associations are further evaluated by multivariate analysis to determine the independent factors, influencing the dependent variable (outcome).

Modify: After exploring the sampled data, the lessons learned are derived with the application of business logic. In other words, the data is parsed and cleaned, being then passed onto the modeling stage, and it is explored if the data requires refinement and transformation.

Model: The modeling step applies a variety of data mining techniques in order to produce a projected model of how this data achieves the final, desired outcome of the process. Modeling techniques in data mining include neural networks, tree-based models, logistic models, and other statistical models such as time series analysis, memory-based reasoning, and principal components. Each type of model has particular strengths, and is appropriate within specific data mining situations depending on the data.

Assess: Finally, the reliability and usefulness of the model is evaluated.

After each stage of SEMMA, the results may raise new questions. To model these new questions you may need to proceed back to the exploration step to refine the data.

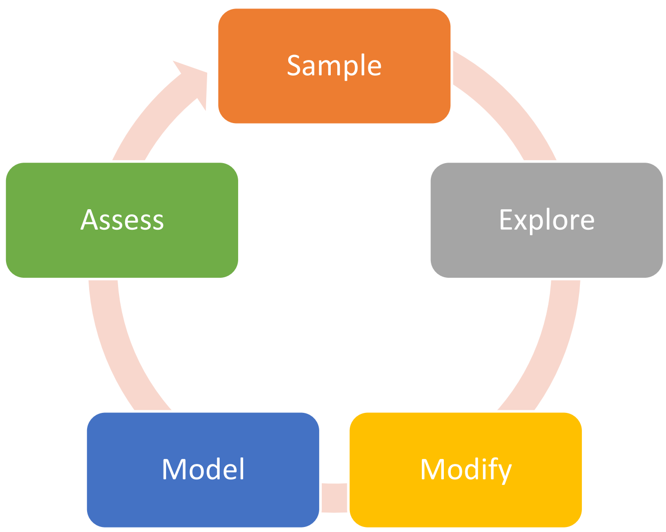


Figure 4.1. The Main Steps of the SEMMA Model.

4.2.1. Sample

The model was performed for the Airbus 330 freighter. A total of 50 sets of real-world data were used. These data were: registration of the aircraft (e.g.TC-JDO), the weight variant (range, payload and dynamic modes for A330), crew number (cockpit, crew), pantry code, water amount (%), crew baggage (amount), fuel on board (kg), trip fuel (kg), taxi fuel (kg), planned payload (kg), in addition to list of ULDs.

4.2.2. Explore

To *explore* the constraints of the weight and balance problem, we have evaluated the given sample data and visualized it (Table 4.1).

Table 4.1. Characteristics of the Loaded Cargo of 50 Different Flights

Variables	Median (minimum-maximum) (n=50)
Total ULD number	31 (7-35)
Total payload, kg	51,650 (9,215-66,730)
Allowed payload, kg	67,680 (50,290-68,198)
Load factor,%	77.5 (13.6-99.4)
ZFW, kg	161,554 (119,535-177,091)
TOW, kg	192,599 (145,360-226,700)
Take-off fuel, kg	26,934 (17,580-66,390)
ULD, unit load device; ZFW, zero fuel weight; CG, center of gravity; TOW, take-off weight	

4.2.3 Modify

In addition, we included the experience of the loadmasters to *modify* the constraints. The following constraints were determined, and by using these constraints, a simulation program was written as a *model*.

1- Each ULD can be assigned to at most one position slot,
2- Each position slot can hold at most one ULD,
3- Each position slot can hold only several types of ULDs and has a maximum weight limit,
4- The assignment of ULDs to overlapping position slots must be prohibited,
5- The bulk ULDs should be positioned to bulk positions,
6- Upper and lower deck ULDs are defined and placed accordingly and separately.

7- The lateral balance should be maintained: only three cases may occur: either a position is on the left-hand side, on the right-hand side, or covers the whole section. The total weight difference between left- and right-hand side ULDs should not exceed the limits (The lateral imbalance of the aircraft due to asymmetric loading of Cargo and fuel must not exceed the limit).
8- Cumulative weights of each zone and section are calculated, which should be within limits.
9- The airline company has already decided which ULDs have to be loaded and a position must be found for each of the ULDs on the list.
10- By entering the data regarding registration of the aircraft (e.g.TC-JDO), the weight variant (range, payload and dynamic modes for A330), crew number (cockpit, crew), panitry code, water amount (%), crew baggage (amount), fuel on board (kg), trip fuel (kg), taxi fuel (kg), planned payload (kg), the program calculates the DOW, ZFW, TOW, LW. By using these data, the program also calculates the allowed payload. Furthermore, the program warns the user if the maximum limit of ZFW, TOW, LW are exceeded. In addition, it warns the user if the planned load is higher than the allowed load.
11- Using weight and index values the CG (as %MAC) is calculated and demonstrated on the graphical envelope for both ZFW and TOW. Also, the system warns when the CG is out of safe limits.
12- The system also demonstrates the pitch trim value.
13- The ULDs that contain DRGs are demonstrated by tags by the program. However, ULD separation constraint is not solved, which must be manually adjusted.
14- The ULD with an overhang can be demonstrated on the program by tagging manually on the system. However, the loading dependencies constraint is not solved by the program.

While modeling the simulation program, we considered the following limitations:

1. Manual placement of some special ULDs must be placed before or after the program's automatic placement of the remaining ULDs.
2. Loading dependencies constraint is not solved in the model. The ULDs that must be placed next to each other such as one with the overhang and the other with the cut-out, should be placed manually on the program.

3. ULD separation constraint is not solved in the model. Two ULDs that contain incompatible items must be loaded at positions that are a certain minimum distance apart, especially for dangerous goods (DRGs), which cannot be placed automatically; manual adjustment is needed.

4.2.4 The Model

A software in Java script was written to perform automatic air cargo loading based on the weight and balance constraints as mentioned above. The program is designed for Airbus 330 and works with a predetermined list of ULDs. The base dimensions, weight and the contour of the ULDs should be given on this list. The program can extract and upload all ULD data from a PDF or excel sheet automatically, whereas in the current semi-manual system each ULD data has to be written manually into the semi-manual programs.

The first step is to enter all the technical data about the flight including the flight registration data on to the program as demonstrated on Figure 4.2. On the figure, the data present in the middle part, demonstrated by the red rectangle, needs to be entered by the loadmaster. The program calculates the variables on the right column and the variables which are out of limit are highlighted by the program automatically.

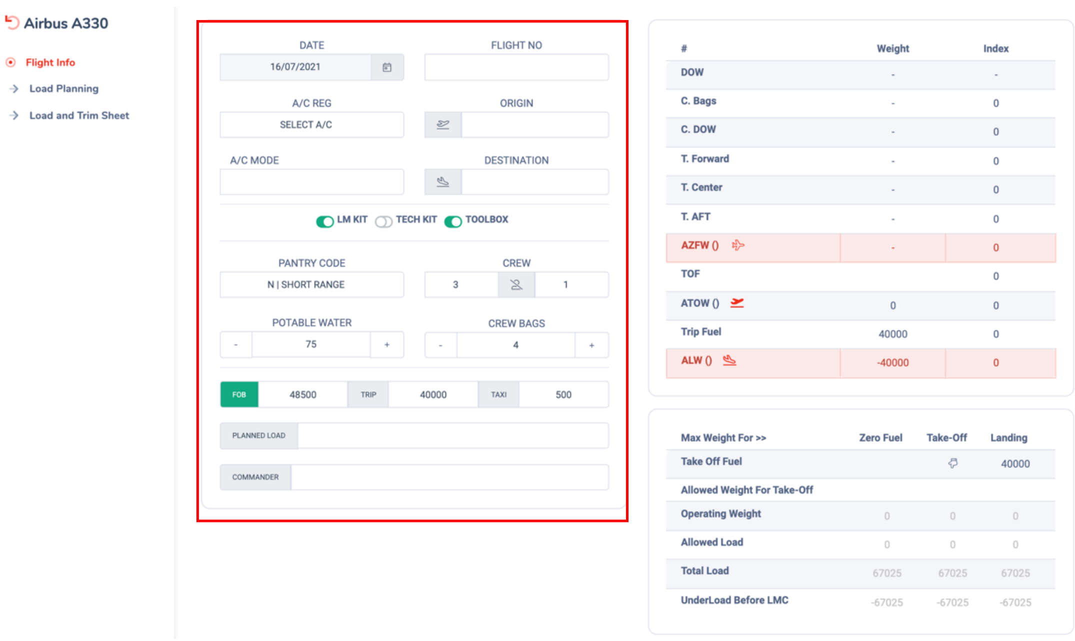


Figure 4.2. The First Page of the Air Cargo Loading (ACL) Program.

The second step is to upload the ULD list from the excel sheet (Figure 4.3a) into the program as demonstrated in Figure 4.3b.

a)

	MAIN DECK COMPARTMENTS				
	DEST	ULD NUMBER	WEIGHT	HEIGHT	REMARKS
1	ISL	PMC00001EA	1.771	160,00	t1
2	ISL	PMC00002EA	2.335	160,00	t2
3	ISL	PAG00003EA	2.565	200,00	t3
4	ISL	PAG00008EA	2.496	240,00	SS
5	ISL	PAG00009EA	2.120	240,00	SS
6	ISL	PAG00010EA	2.405	240,00	SS
7	ISL	PAG00011EA	2.360	240,00	SS
8	ISL	PAG00012EA	2.620	240,00	SS
9	ISL	PAG00013EA	1.826	235,00	SS
10	ISL	PAG00014EA	1.640	235,00	SS
11	ISL	PAG00015EA	2.435	240,00	SS
12	ISL	PAG00016EA	2.180	240,00	SS
13	ISL	PAG00017EA	2.245	240,00	SS
14	ISL	PMC00018EA	1.960	240,00	SS
15	ISL	PMC00019EA	2.451	220,00	SS
16	ISL	PMC00020EA	1.925	220,00	SS
17	ISL	PMC00021EA	2.285	230,00	SS
18	ISL	PAG00022EA	2.290	240,00	SS
19	ISL	PAG00023EA	1.611	200,00	SS
20	ISL	PAG00024EA	2.100	240,00	SS
21	ISL	PAG00025EA	1.170	210,00	SS
22	ISL	PMC00026EA	2.165	210,00	SS
23	ISL	PMC00027EA	1.035	150,00	SS
	LOWER DECK COMPARTMENTS				
	DEST	ULD NUMBER	WEIGHT	HEIGHT	
1	ISL	PLA00028EA	990	160,00	
2	ISL	PMC00029EA	2.380	160,00	
3	ISL	PMC00030EA	2.145	160,00	
4	ISL	PMC00031EA	1.865	160,00	
5	ISL	PMC00032EA	2.100	160,00	
6	ISL	PMC00033EA	1.860	160,00	
7	ISL	PMC00034EA	1.600	160,00	
8	ISL	PMC00035EA	2.375	160,00	
9	ISL	PMC00036EA	2.125	160,00	
		BULK			
	DEST	AWB	WEIGHT		
1	ISL		1600		
2					
3					
TOTAL WEIGHT				67.030	

b)

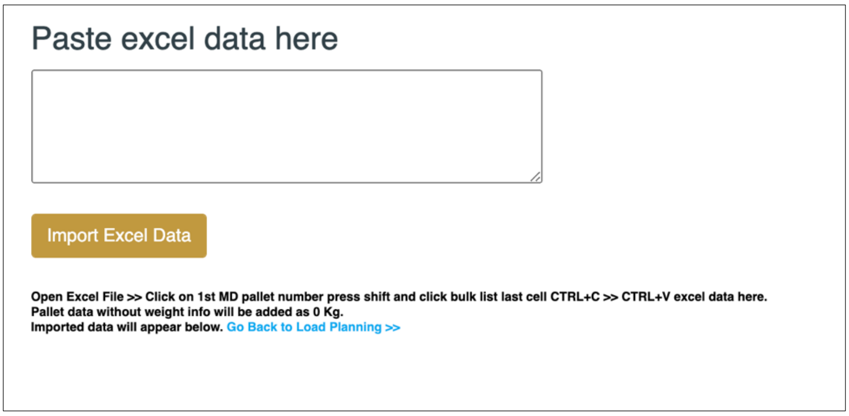
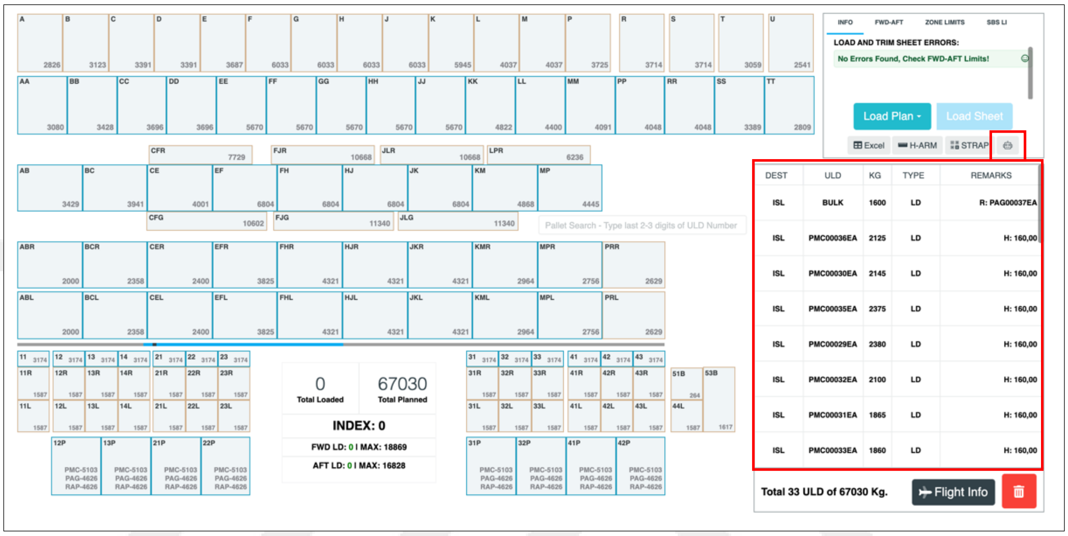


Figure 4.3. An Example ULD List (a) and the ULD List Uploading Page (b) of the Program.

The third step is to start automatic loading by one click as demonstrated on the Figure 4.4. On the Figure 4.4a, the uploaded ULD list is shown in the area demonstrated in the big red square. And the program automatically performs the assignment of the ULDs onto the specific position with one click onto the small red square. Finally, the completed loading schema is demonstrated as in Figure 4.4b.

a)



b)

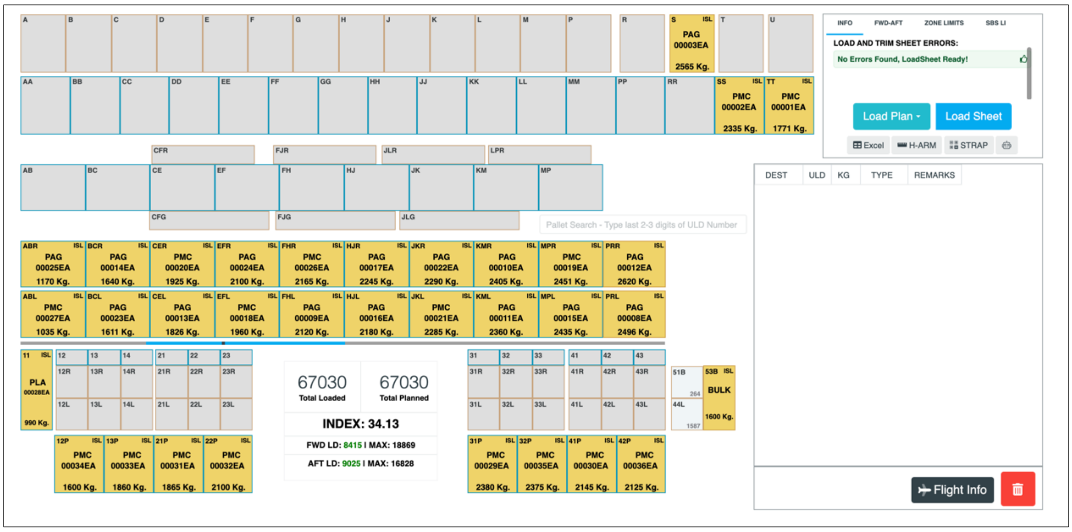


Figure 4.4. The Load Sheet Page of the ACL Program, Before (a) and After (b) the Loading is Completed.

The fourth step is to check the info box on the right upper corner of the page regarding errors. The fifth step is to check the Load and Trim Sheet page, which is demonstrated in Figure 4.5. The program automatically calculates and demonstrates the CG, pitch trim value in addition to all the weights and position indexes.

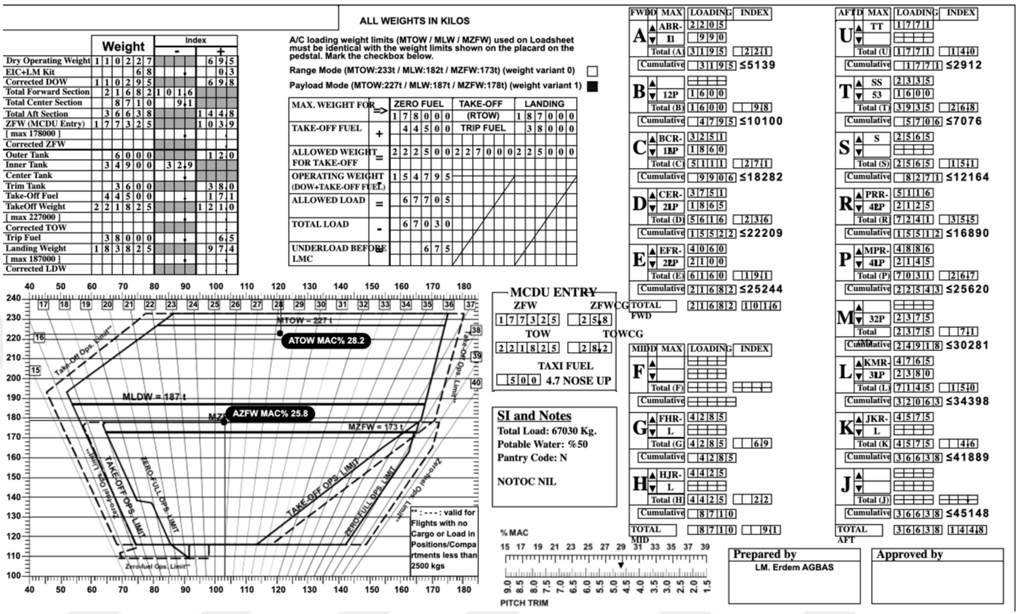


Figure 4.5. The Load and Trim Sheet Page of the ACL Program.

4.2.5 Assess

To *assess* the efficiency of the model (i.e. the automatic cargo loading program) we used 50 sets of real-world data (*sample*). The solutions of the model were compared to those obtained by an experienced load masters who uses a semi-automated model in terms of loading all the ULDs, meeting the stability and safety constraints, time consumed, and meeting the optimal CG (considering the fuel consumption). The normality of the data was assessed by.

The SPSS software version 20.0 (SPSS, Inc., Chicago, IL, USA) was used in the analysis. As the data were not normally distributed therefore continuous, data were given as median (minimum-maximum). To compare the medians, a nonparametric Mann Whitney U test was used. The Spearman's rank correlation test was used to analyze the associations of loading time. All parameters that showed a p value of ≤ 0.1

in the univariate analysis were tested using the multivariable linear regression analysis. A two-tailed p value of ≤ 0.05 was defined as statistically significant.

4.3. Comparison of the Simulation Model with the Current Method in Use

A total of 50 sets of real-world data were used to compare air cargo loading by automatic air cargo loading program and semi-manual air cargo loading by an experienced load master. All flights were one-leg flights.
The median ULD number was 31 and the load factor was about 80%. The details of the freights and the flights are given in Table 4.1 above.

All ULDs were successfully loaded with the automatic program and also with the semi-manual ACL method by the load master. The comparison of semi-manual and automatic ACL is given in Table 4.2. The automatic ACL took significantly shorter time compared to semi-manual ACL (p<00.1) (Figure 4.6). The automated ACL methods loaded the freighter within about one minute, whereas semi-manual ACL was about 12 minutes. For comparison, it must be stated that loading time takes at least 60 minutes when fully manually loaded. All the CGs were within safety limits for both the semi-manual and the automatic ACL methods furthermore the CG was not significantly different between the methods. As the CGs were similar between semi-manual and automatic loading, we did not evaluate fuel consumption.

Table 4.2. Comparison of Manual and Automated Air Cargo Loading

	Semi-manual ACL	Automated ACL	p value*
Time (seconds)	739 (322-965)	59.5 (10-72)	<0.001
ZFW index	105 (89.2-135.2)	108 (88.8-145)	0.32
ZFW CG (as %MAC)	26.2 (22.4-33.1)	26.9 (22.1-34.6)	0.18
TOW index	120 (91-154)	123 (90-164)	0.33
TOW CG (as %MAC)	28.7 (23.4-34.1)	29 (23.1-35.7)	0.34

Data are shown as median (minimum-maximum) and compared with Mann Whitney U test. ZFW, zero fuel weight; CG, center of gravity; TOW, take-off weight

When we evaluated the factors effecting the loading time by automated ACL method, we observed that the total ULD number was the only independent factor. The associations of loading time are given in Table 4.3.

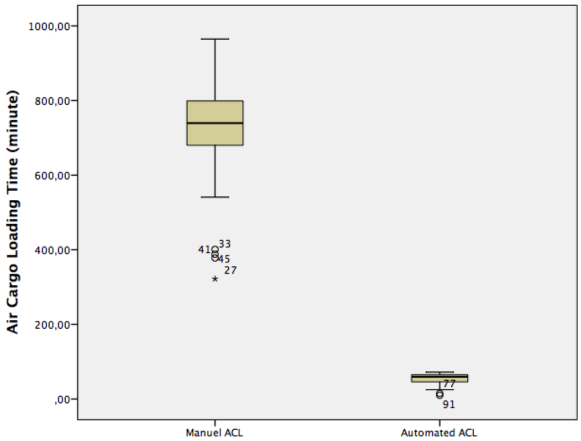


Figure 4.6. Air Cargo Loading (ACL) Time. Automated ACL Was Significantly Shorter Than Manual ACL (p<0.001).

Table 4.3. Correlations and Independent Predictors of Automated Air Cargo Loading Time.

	P	r	ß	CI for 95%
Total ULD number	<0.001	0.921	0.983	1,93-2.16
Total payload, kg	<0.001	0.629		
Load factor,%	<0.001	0.592		
ZFW, kg	<0.001	0.628		
TOW, kg	<0.001	0.485		

Our new program has also the property that the loadmaster can load specific ULDs manually on the program, such as the ones that must be placed next to each other like the overhang and the other with the cut-out. Afterwards the program places the rest of the ULDs automatically.

A questionnaire was performed between the loadmasters who used our new automatic aircraft cargo loading program. The majority of the loadmasters declared that the program was useful regarding decreasing loading time, risk of errors and stress. The aircraft cargo loading is a dynamic procedure. Last minute changes are not uncommon and our program is suitable for those changes, which allows fine-tunning of the loading.

4.3. Discussion

The assignment of the ULDs to a specific position is performed by considering several constraints. Weight and balance limits are the main constraints. There are many weight limits per each defined section of the aircraft. Also, the CG, the point where the weight of the air craft is concentrated, should be within several limits. Location of heavy ULDs to the center, loading dependencies, ULD separation and loading operations (multileg flights, prioritized ULDs) were the other issues that should be considered while loading an air craft. All of these constraints must be satisfied for a safe flight. Furthermore, within these safety limits, fine tuning can be made to increase the efficiency of the flight, in terms of fuel consumption, and ease and total time of the operation.

In daily practice the air cargo loading is performed by the load masters in a semi-manual manner. There are several studies on automatic air cargo loading. Some of the studies focused on the built-up of ULDs whereas others were designed for the loading of readily built ULDs to an aircraft.

In our study we have shown that automatic air cargo loading by a software is possible. The program could load all the given ULDs with a similar CG compared to an experienced load master. In addition, the time consumed was about 1 minute by the proposed ACL software compared to 12 minutes by semi-manual CL. The difference was statistically significant however one could think that this will not make too much difference for a single flight. However, in daily practice, semi-manual systems perform the loading, and multiple loadings may be performed per day. For instance, Turkish Cargo performed about 8500 flights last year, about 23 flights per day. The company employs about 100 loadmasters. These data demonstrate the high traffic of air cargo loading. Not only time consumed per loading decreases, but also the stress and pressure on the loadmasters decreases by a well-designed automatic program. Therefore, there will be more room for fine-tuning of the loading.

After COVID-19 pandemic, there had been a steep decrease in both air passenger and cargo traffic. However, while passenger traffic was still low, air cargo traffic improved rapidly as the global trade recovered and e-commerce increased. By May 2021, air cargo traffic was even higher than the pre-crisis levels. Before the crisis, half of the air cargo was carried by the passenger aircraft belly while the other half was carried by freighters. As the passenger traffic decreased steeply, the importance of freighters has been increased, and most air cargo has been carried by freighters, especially the fragile and valuable cargo. This caused an increased load factor of the freighters in addition to increased air cargo traffic. After having considered all the data, it is clear that air cargo traffic and load factor have increased substantially after the COVID-19 pandemic. Therefore, timely operations with minimum error have become more important, emphasizing the need for digitalization in the air cargo loading process.

On the other hand, the present program does not cover all the constraints such as DRGs or assignment of ULDs that should be located next to each other. Also, the software should be improved to perform multileg flights.

CHAPTER V

CONCLUSIONS

Air cargo transport is a growing area in parallel with global economic growth. Although air cargo represents less than 1% of global trade by volume, in terms of value it represents about one-third, which is above 6.7 trillion USD (IATA, 2020). Furthermore, within the next 20 years, world air cargo traffic is expected to grow by 4.2% and the world freighter fleet is expected to grow by 70% from 1770 to 3010 airplanes (IATA, 2020).

One of the major components of air cargo transport is loading the ULDs to specific positions, which is performed by the loadmasters by manual or semi-manual methods. Air cargo transport is a dynamic process, and several factors are considered while loading an aircraft, from timing to multileg flights or loading prioritized ULDs. As the air cargo traffic is expected to increase, to decrease the errors and loading time, digitalization of the air cargo loading is needed. Therefore, investments for the automatic air cargo loading programs would be wise to increase the safety and efficacy of the air cargo transport.

With this study, we simulate the air cargo loading by the loadmasters with a written computer program. The main aim was loading all the given set of ULDs considering the weight and balance constraints. The program was able to load all the ordered ULDs within about one minute. The median load factor of the sample was 77%, which is substantially higher than the mean international cargo load factor, i.e. 65% recorded until May 2021. Secondly, the model could perform the loading considering the weight and balance constraints, including all the weight limits. In addition, the CG was within appropriate limits and similar to the loading performed by the loadmasters. Thirdly, in terms of time, the loading was performed within a shorter time compared to loadmasters. The program met all the determined objectives except fuel cost. As the CG was similar the fuel cost was expected to be similar. Lastly, all the loadmasters declared that using this program substantially decreased the pressure and stress on the loadmasters. Although the program allows for user manual adjustments, it should be improved to include other constraints such as loading dependencies, loading separation or multileg flights.

In conclusion, automatic air cargo loading by a simulation software is possible and handy. The program can perform the loading of all given sets of ULDs within safety and stability limits with a shorter time. As air cargo traffic is expected to increase, digitalization of the air cargo loading is needed to decrease the errors and loading time. Therefore, investments for the automatic air cargo loading programs would be wise to increase the safety and efficacy of air cargo transport.

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