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A simulation approach for aircraft cargo loading considering weight and balance constraints

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ABSTRACT

Air cargo transport is a growing industry in parallel with the growth in world trade and e-commerce. The global air cargo transport traffic getting busier, the importance of timely loading with minimum error is increasing. Therefore, digitalization of the air cargo loading process is needed. Assignment of Unit Load Devices (ULDs) to the specific positions on the freighter is performed by loadmasters by manual or semi-manual methods. This study aims to design a simulation model, which performs the ULD assignment automatically by simulating the loading process performed by the experienced loadmasters under the weight and balance constraints. The SEMMA (sample, explore, modify, model, assess) model is used while generating the simulation model. Fifty real-world loading orders were used to assess the performance of the model. The ULD assignment process by the simulation model and the loadmasters using semi-manual loading were compared with regard to time and center of gravity performance indicators. The results demonstrated that the simulation model can 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, the proposed simulation model provides an efficient solution to the ULD assignment problem. However, the base model generated may be improved to address various real-world scenarios.

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). The effects of the COVID-19 pandemic on the air cargo industry has been improving (ICAO, 2021). The CTKs and revenue have reached levels better than the pre-crisis levels (IATA, 2021). Despite the pandemic this industry has continued to grow.

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. Turkey's market place in the air cargo transport industry is expected to grow further with the flag carrier company Turkish Cargo (THY, 2020) and an important international air cargo hub Istanbul Airport (IGA, n.d.). 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.

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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 Unit Load Devices (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.

Can an automatic air cargo loading simulation model load all the ULDs within safety and legal limits, considering the weight and balance constraints, compared to a semi-manual cargo loading process? Can a new model provide better solutions in terms of fuel efficiency?

The main objective is to load all the given sets of ULDs within safety and legal limits by an automatic air cargo loading simulation model, compared to a semi-manual process by a load master that is currently in use. The model will be performed for Airbus 330 cargo air craft and for a single leg flight. The secondary objectives of the study aim to answer the following questions:

i. Can the model load the air craft in a shorter time compared to a semi-manual process?
ii. Can the model load the air craft with a better center of gravity (CG) compared to a semi-manual process? Can the model provide a lower fuel consumption, which can be obtained with a better CG?

In 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, a simulation model, which performs the ULD assignment on to the specific positions on an Airbus 330 Freighter. The simulation madel 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 model. 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.

Literature Review

Theoretical Background

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. Contrasting the 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.

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 weight and balance problems 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 case of 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 find the most profitable selection from a set of cargo to be loaded on an aircraft. Their secondary objective was to optimize the CG, so as to reduce fuel consumption and improve stability, considering real-life issues such as oversized containers, overlapping loading configurations and cargo priority. With case studies they have shown that the model performs within seconds, CG is more preferable, lateral balance is more favorable and no unloaded ULD are left.

Lurkin and Schyns. (2015) have improved the model of Limburg et al. (2014) and they have developed a mixed linear integer model to plan multi-leg 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) integrate palletization and weight and balance aspects in a two-level problem. They assign items to ULDs and ULDs to loading positions, while maximizing the priority of loaded cargo and the total weight. They present a multi-objective particle swarm optimization approach and compare their results to optimal MILP solutions for small instances.

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 (DRGs) and special cargo. And 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.

The literature about air cargo loading problem is summarized in Table 1. Unique ULD assignment or CG restrictions present in all the papers are not shown.

Table 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

Research and Methodology

Method

We propose a simulation-based solution to the problem. We employed SEMMA (sample, explore, modify, model, assess) process model as an overall data mining methodology, which is depicted in Figure 1 (Nie 2014).

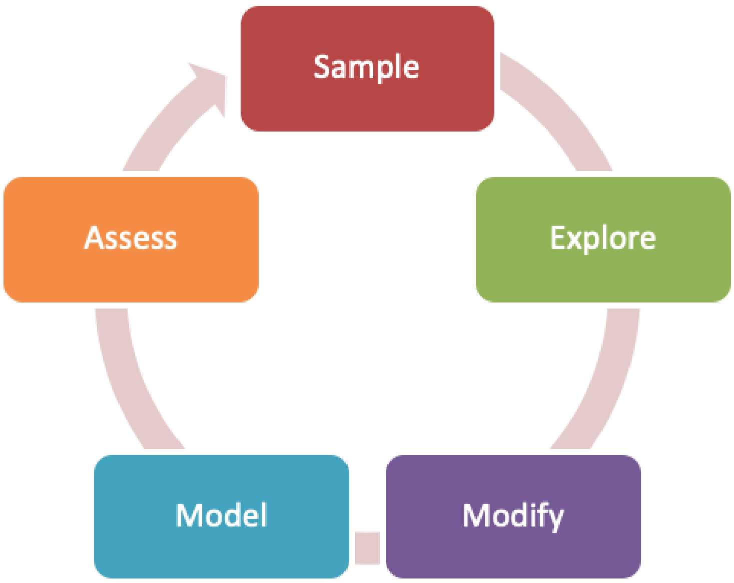

Figure 1: Main steps of SEMMA methodology

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.

Explore

To *explore* the constraints of the weight and balance problem, we have evaluated the given sample data and visualized it (Table 2).

Table 2: 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	

The following constraints were determined and by using these constraints a simulation model was written:

i. Each ULD can be assigned to at most one position slot,
ii. Each position slot can hold at most one ULD,
iii. Each position slot can hold only several types of ULDs and has a maximum weight limit,
iv. The assignment of ULDs to overlapping position slots must be prohibited,
v. The bulk ULDs should be positioned to bulk positions,
vi. Upper and lower deck ULDs are defined and placed accordingly and separately.
vii. 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 it 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).
viii. Cumulative weights of each zone and section are calculated, which should be within limits.
ix. 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.
x. 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 simulation model calculates the dry operation weight (DOW), zero fuel weight (ZFW), take-off weight (TOW), landing weight (LW). By using these data, the model also calculates the allowed payload. Furthermore, the model 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.
xi. Using weight and index values the CG (as % mean aerodynamic cord; %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.
xii. The system also demonstrates the pitch trim value.
xiii. The ULDs that contain DRGs are demonstrated by tags by the simulation model. However, ULD separation constraint is not solved, which must be manually adjusted.
xiv. 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 model.

Modify

In addition, we included the experience of the loadmasters to *modify* the problem constraints. While modeling the simulation model, we considered the following limitations:

i. Manual placement of some special ULDs is needed to be placed before or after the automatic placement of the remaining ULDs by the model.
ii. 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 model.
iii. 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 DRGs, cannot be placed automatically, manual adjustment is needed.

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 simulation model 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 model 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 model as demonstrated on Figure 2. On the figure, the data present in the middle part, which is demonstrated by the red rectangle, need to be entered by the load master. The variables on the right column are calculated by the model and the variables which are out of limit are highlighted by the simulation model automatically.

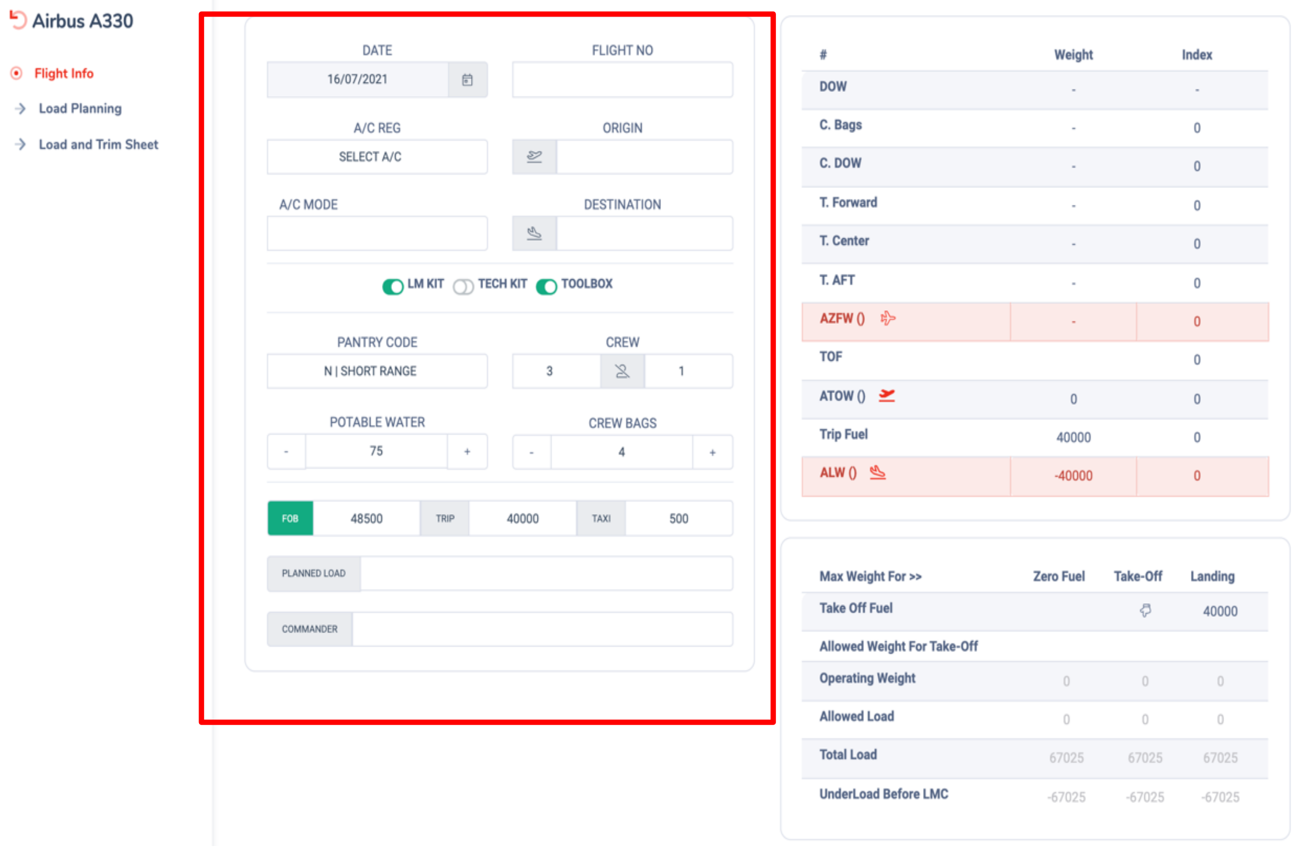

Figure 2: The First Page of the Air Cargo Loading (ACL) simulation model.

The second step is to upload the ULD list from the excel sheet (Figure 3a) into the model as demonstrated in Figure 3b.

	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	

Figure 3(a): An Example ULD List of the simulation model.

Figure 3(b): the ULD List Uploading Page (b) of the simulation model.

The third step is to start automatic loading by one click as demonstrated on the Figure 4. On the Figure 4a, the uploaded ULD list is shown in the area demonstrated in the big red square. And the model 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 4b.

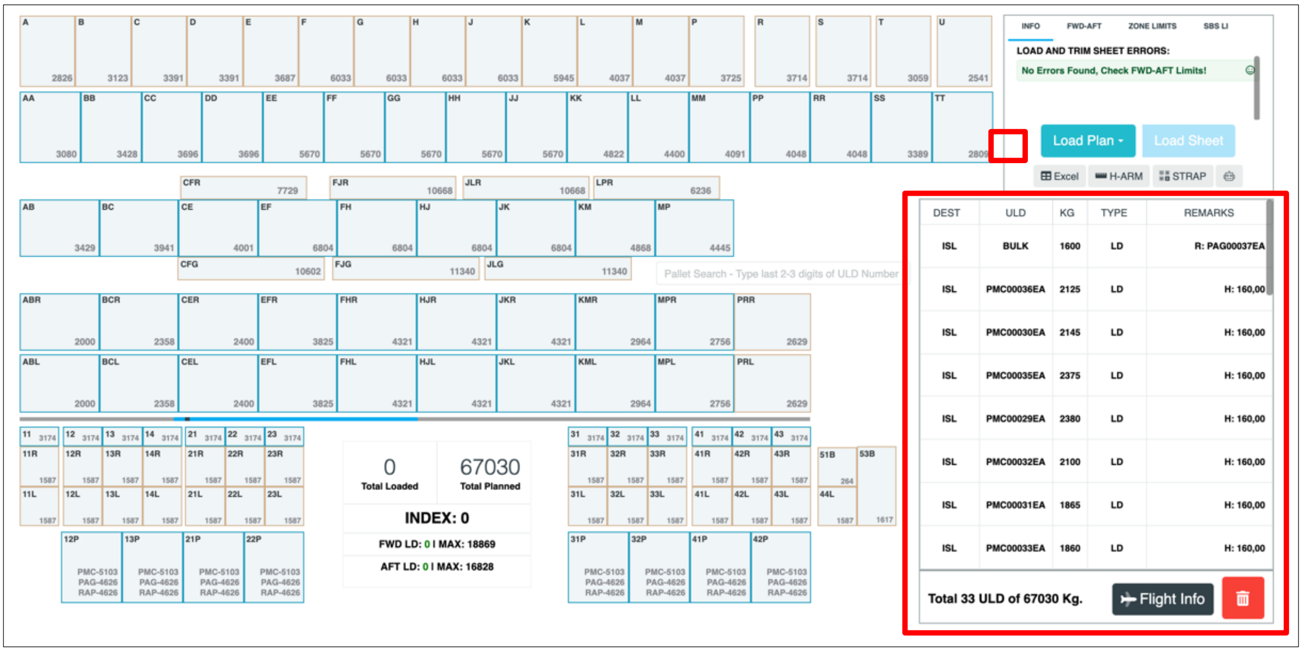

Figure 4(a): The Load Sheet Page of the ACL simulation model, before the Loading is Completed.

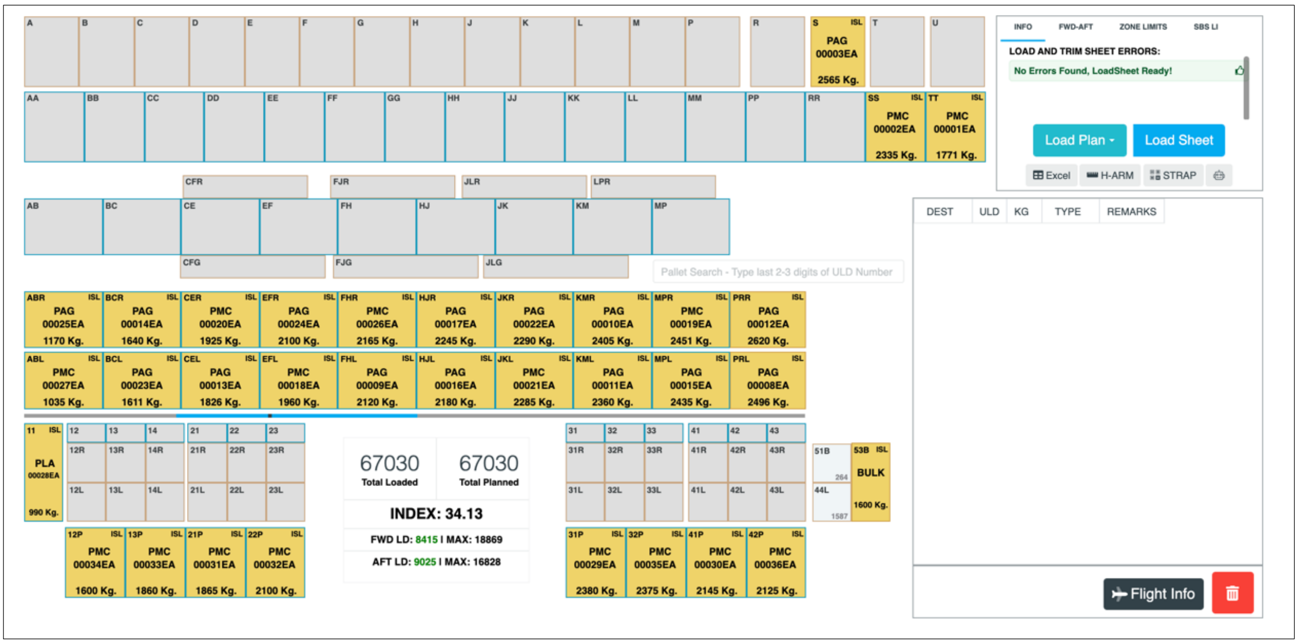

Figure 4: The Load Sheet Page of the ACL simulation model after the Loading is Completed.

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 5. The program automatically calculates and demonstrates the CG, pitch trim value in addition to all the weights and position indexes.

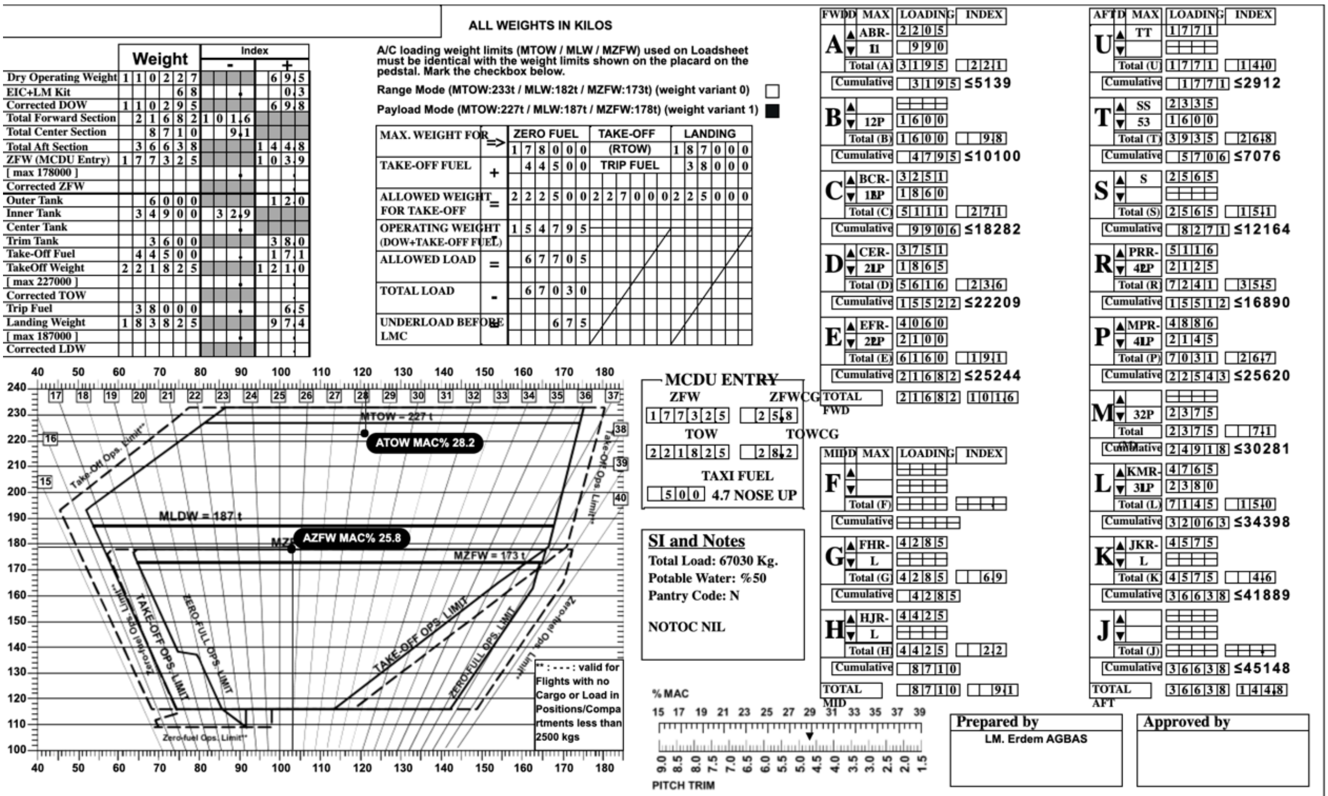

Figure 5: The Load and Trim Sheet Page of the ACL Simulation Model.

Assess

To *assess* the efficiency of the model (i.e. the automatic cargo loading simulator) we used 50 sets of real-world data (*loading orders*). The solutions of the model were compared to those obtained by an experienced load masters who uses a semi-automated model based on their individual experience. We considered the following criteria for comparison purpose:

i. All ULDs must be loaded.

ii. The stability and safety constraints must be met.
iii. Time consumed must be minimized.
iv. The optimal or near optimal CG (considering the fuel consumption) is achieved.

The SPSS software version 20.0 (SPSS, Inc., Chicago, IL, USA) was used in the analysis. Continuous data were given as median (minimum-maximum) and compared by using Mann Whitney U test. 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.

Results and Discussion

A total of 50 sets of real-world data were used to compare air cargo loading by automatic air cargo loading simulator 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 2 above.

According to the results of conducted experiments, all ULDs were successfully loaded with the simulation model and also with the semi-manual automatic cargo loading (ACL) method by the loadmaster. The comparison of semi-manual and automatic ACL is given in Table 3. The automatic ACL took significantly shorter time compared to semi-manual ACL (p<00.1) (Figure 6). The automated ACL methods loaded the freighter within about one minute whereas it was about 12 minutes by semi-manual ACL. For comparison it must be stated that loading time takes at least 60 minutes when fully manually loaded. All the CGs were in safety limits for both the semi-manual and the automatic ACL methods furthermore the CG were not significantly different between the methods. As the CG were similar between semi-manual loading and the automatic loading, we did not evaluate the fuel consumption.

Table 3: 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.

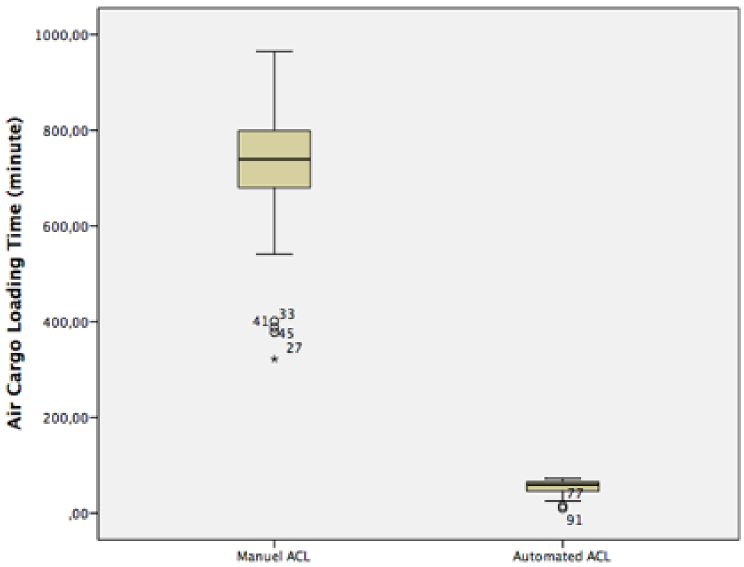

Figure 6: Air Cargo Loading (ACL)

Table 4: 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 model has also the property that the loadmaster can load specific ULDs manually on the model, such as the ones that must be placed next to each other like the overhang and the other with the cut-out. Afterwards the model places the rest of the ULDs automatically.

An unstructured interview was done with the loadmasters who used aircraft cargo loading simulator. The majority of the loadmasters declared that the simulation model 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 simulation model is suitable for those changes, which allows fine-tunning of the loading. 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 simulation model is possible. The main aim was loading of all the given set of ULDs considering the weight and balance constraints. The simulation model was able to load all the given set of ULDs. The median load factor of the sample was 77% which is substantially higher compared to the mean international cargo load factor i.e. 65% recorded up until May 2021. The time consumed was about 1 minute by the proposed ACL simulation model 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 the loading is performed by semi-manual systems and multiple loadings may be performed per day. For instance, Turkish Cargo performed about 8500 flights during last year, which is about 23 flights per day. The company employs about 100 load masters. These data demonstrate the high traffic of air cargo loading. 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. The model met all the determined objectives except fuel cost. As the CG was similar the fuel cost was expected to be similar. Lastly, all the load masters declared that using this simulation model substantially decreased the pressure and stress on the loadmasters. Therefore, there will be more room for fine-tunning 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 rapidly improved due to its high responsiveness to last minute orders. 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 model 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.

Conclusions

Air cargo transport is a growing area in parallel with global economic growth. One of the major components of the air cargo transport is the loading of the ULDs to specific positions, which is performed by the load masters by manual or semi-manual methods. Air cargo transport is a dynamic process and several factors are considered while loading an air craft, 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.

Automatic air cargo loading by a simulation software is possible and handy. The simulation model can perform loading of all given set of ULDs within safety and stability limits with a shorter time. Although the model allows for user manual adjustments, it should be improved to include other constraints such as loading dependencies, loading separation or multileg flights. As 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 models would be wise to increase the safety and efficacy of the air cargo transport.

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