AIR TRANSPORT DEPARTMENT

FACULTY OF OPERATION AND ECONOMICS OF TRANSPORT AND COMMUNICATIONS

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Foreword

Prof. Dr. Tony Kazda

Conference Chair

Head of Air Transport Department,
University of Žilina, Slovakia

Dear participants,

it is my great pleasure to welcome you to another edition of INAIR conference, this time organised in cooperation with our partner university, Amsterdam University of Applied Sciences, in famous Amsterdam, Netherlands.

Even if the conference has scientific status, we are trying to invite industry to the discussion in order to understand current industry needs. The INAIR conference is a forum in which Industry and Academia meet to exchange ideas and set up common challenges. The interaction between researchers and industry representatives is a key in order to come up with innovative solutions for the challenges of the future.

Air Transport is nowadays mainly covered in topics like airport planning (infrastructure development); the criteria of success are defined in terms of number of runways, apron stands, terminal facilities etc. Airport capacity shortage requires optimal usage of existing infrastructure. The impact of climate change and resource shortage increases the complexity. Aviation has to optimize its overall capacity usage within even tighter constraints. Resilience of the aviation system is becoming a big issue; reliability of schedules and procedures for all stakeholders involved (including passengers and local communities in the airports neighbourhood) is at stake. Disturbances due to severe weather, technical issues etc. might cause huge delays and costs. Solving these challenges require a mind shift towards changing and optimizing processes, innovation in infrastructure usage, logistics and cooperation between partners.

I believe that papers presented in these proceedings and the follow-up discussion will contribute to suitable solutions for the current needs of aviation sector.

Peer review

All papers in these proceedings were subject to peer review by the members of Scientific Board.

E-mail

inair@fpedas.uniza.sk

kld@fpedas.uniza.sk

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Using Human-Machine Interaction Frequency as a Proxy Measure of Subjective Air Traffic Complexity

Bruno Antulov-Fantulin, Tomislav Radišić
Department of Aeronautics, Faculty of Transport and Traffic Sciences, University of Zagreb
Zagreb, Croatia
bantulov@fpz.hr

Matthieu Rummens
French Air Force Academy
French Air Force
Salon, France

***Abstract*— Subjective air traffic complexity scores have been used previously as a useful measure of air traffic controller workload. There were, however, difficulties in implementing such measurements for real-time workload assessment due to the extent of modifications needed on an operational ATM system. A solution is proposed here which requires only the minimum of HMI data to determine the subjective air traffic complexity. For this paper, an experiment has been conducted with licensed air traffic controllers who assessed air traffic complexity in real-time human-in-the-loop simulations. Simultaneously, basic human-machine interactions were recorded. Analysis of the simulation data showed that the human-machine interactions can be used, with some limitations, to detect increases in air traffic complexity and situations where the controller's workload capacity is exhausted.**

Keywords—HMI, Air Traffic Complexity, Workload Capacity

I. Introduction

The limited efficiency of current air traffic systems will require a next-generation of air traffic systems that are able to help air traffic controllers in their job. Today, systems in air traffic control already have a lot of tools that are helping and making the job of an air traffic controller more efficient and reliable. It is known and it has been researched in other papers that airspace capacity is equal to the workload capacity of the air traffic controller currently working on the airspace [1]. Air traffic controller workload is likely to remain the greatest functional limitation on the capacity of the air traffic management system.

One of the key factors contributing to air traffic controller workload is air traffic complexity. Given predicted traffic increases, as well as corresponding developments in air traffic control procedures and technologies, it is increasingly necessary to understand the abilities of air traffic controllers and to identify the "safe" limits of workload [2]. In the literature on air traffic control complexity, surprisingly few definitions of "complexity" appear to have been given, presumably because the authors assume it is common knowledge. One of the authors defined complexity as a "…measure of the difficulty that a particular traffic situation will present to an air traffic controller…" [3] and went on to describe workload as "…a function of three elements, firstly, the geometrical nature of the air traffic; secondly, the operational procedures and practices used to handle the traffic and thirdly, the characteristics and behaviour of individual controllers (experience, orderliness etc.)….".

Measures of air traffic controller workload are typically based on subjective ratings made by controllers either while controlling air traffic or just afterwards [4]. It is clear that the relationship between air traffic control complexity and workload is an indirect one that is highly mediated by the influence of many individual characteristics, however, increase in complexity always means increased workload for the air traffic controller. A given level of traffic density and aircraft characteristics may create more or less complexity depending on the structure of the sector. Traffic density alone does not define air traffic control complexity, but it is one of the variables that influences complexity and so is a component of complexity. Its contribution to air traffic control complexity partially depends on the features of the sector. Sector and traffic complexity interact to produce air traffic complexity [5].

Although, measurable features of sectors and aircraft may be objective, the concept of air traffic control complexity is subjectively defined by the controller. It is developed from the controller's perception of and interaction with the sector and the air traffic within it [5], and therefore it can only be assessed by controllers using the subjective complexity assessment scores. Complexity is an acute problem in air traffic control and can ultimately limit the safety, capacity and efficiency of the system. The majority of research on air traffic control complexity has been concerned with examining the complexity imparted by the air traffic itself, and not on the overall complexity contributed by the human-machine interaction process [6].

There are several papers worth mention that addresses the same field of research that authors of this paper did. The human-machine interaction or as it is also referred in some other papers as human-computer interaction is very interesting in measuring air traffic control complexity. One of the papers addresses the testing of one of the methods to assess the complexity of air traffic control displays [7]. Also one of the studies worth mentioning is the development of TRACEr. The paper outlines a human error identification technique called TRACEr—technique for the retrospective and predictive analysis of cognitive errors in air traffic control [8]. TRACEr is a valuable aid to design, development and operations in United Kingdom air traffic control, but unfortunately it does not use human-machine interactions to predict errors. One research that uses human-machine interaction states that „...research in the field of human–computer interaction (HCI) has shown that early usability evaluation of human interfaces can reduce operator errors by optimizing functions for a specific population...“ [9]. The most related research paper to this one is by Christos George Tsonis (2006) who used the human-machine interaction with human-in-the-loop simulations [6].

Although very similar methods were used, authors of these paper research air traffic control complexity in a way not measured before. The main hypothesis of this paper is that human-machine interactions can be used to detect increase in air traffic complexity. And with that, a set of new future research can be made to further improve the air traffic systems safety. Authors thought that a new system could be created that records basic human-machine interactions and later on uses that data to detect increase in air traffic complexity and maybe detect if an individual air traffic controller is reaching his/her workload capacity. With that information a system could alert the shift supervisor if the air traffic controller is near his workload capacity and prevent any accidents that might have happened. For this paper, an experiment has been conducted with licensed air traffic controllers who assessed air traffic complexity in real-time human-in-the-loop simulations. Simultaneously, basic human-machine interactions were recorded. Analysis of the simulation data showed that the human-machine interactions can be used, with some limitations, to detect increases in air traffic complexity and situations where the controller's workload capacity is exhausted.

II. Methodology

For this experiment, real-time human-in-the-loop (HITL) simulations were chosen as a method for gathering data because simulations can be performed in a controlled environment which allows repeatable conditions for all participants. Simulations were performed with the ATC research simulator developed and validated at the Department of Aeronautics of the Faculty of Transport and Traffic Sciences, University of Zagreb. This study was part of a larger research project on the effects of trajectory-based operations on air traffic complexity. The scope of the study was narrowed down to only nominal area control operations (en-route airspace) to make it more manageable.

A. Participants

Ten licensed air traffic controllers were recruited from the national air navigation service provider (ANSP). All were, at the time, working daily at the area controller positions. Participants were, on average, relatively young (mean age, 31; age range, 27-34) but with multiple years of experience working their positions (mean experience: 5 years; range, 2-9). Of the ten participants eight were male and two female.

All participants were briefed on the study protocol in broadest terms but no mention was made of the variables which were to be measured. Since there were some small differences between the professional workstations participants used daily during work and the ATC research simulator used in the study, participants were given three one-hour simulator sessions to make them accustomed to the differences. During or after these simulator sessions, all participants strongly affirmed that they thought the research simulator was representative of the actual system and that they felt unhindered in performing their routine tasks.

B. Airspace

To make the research environment as similar as possible to the actual work environment, local airspace was used (Croatia Upper North sector). All participants had multiple years of experience working with this airspace. Aeronautical Information Publications (AIP) were used to gather up-to-date data on local airspace and airspace of neighbouring countries.

Geographically, the sector consists of airspace over northern Croatia and north-western Bosnia and Herzegovina (Fig. 1.). Vertically, the sector, as used in this research, starts at FL 285 and ends at FL 660 (though no flights were flying that high). In reality, due to traffic demand, the sector is often vertically divided into several sub-sectors depending on the traffic loads and in that case 'Upper' is used to describe the sector from FL 325 – FL 355. For this research the complete vertical expanse was used.

The transfer of traffic between neighbouring Area Control Centres (ACC) and Zagreb ACC is regulated by Letters of Agreement (LoA). For this research the relevant parts of LoAs were Flight Level Allocation and Special Procedures sections which state the conditions that have to be met for all flights crossing the boundary of the CTA (called Flight Level Allocation Scheme - FLAS). The purpose of FLASes is to ensure that flights will cross the CTA boundary at required flight levels that enable them to land at the desired airport or to be seamlessly joined with existing traffic. It also states what are the coordination points (COP) or transfer of control (TOC) points. The participants were required to adhere to these procedures during the simulation runs.

C. Traffic

To ensure representativeness of the simulations (and validity of the results in extension), traffic sample needed to be as similar as possible to the real traffic flying through the selected airspace. For this purpose a detailed analysis of the traffic flows and patterns was performed. Historic traffic data was obtained from EUROCONTROL.

Since varying traffic levels were needed to measure HMI frequency at different levels of air traffic complexity, a summer day with high traffic variability was selected as a reference day

Fig. 1. Croatian Upper North Airspace Sector (as used in this research)

(Friday, 30 August 2013). Traffic from off-peak hours was used to create scenarios with low traffic levels, peak hours were used to create high traffic level scenarios, and peak hour traffic augmented with additionally generated traffic was used to create scenarios simulating future traffic levels (as explained in Section 2.D).

As expected, out of the 661 flights that flew through the Zagreb CTA Upper North sector most were commercial medium (approximately 70%) and long-range (approximately 9%) jets. Others were mainly regional turboprops and business jets.

Routes used most frequently during the selected day were those connecting South-East and North-West of Europe. 90% of the flights were in the general east-west direction, with remaining 10% in the north-south. More than 50% of all flights followed one of the five most frequently used routes (Fig. 2).

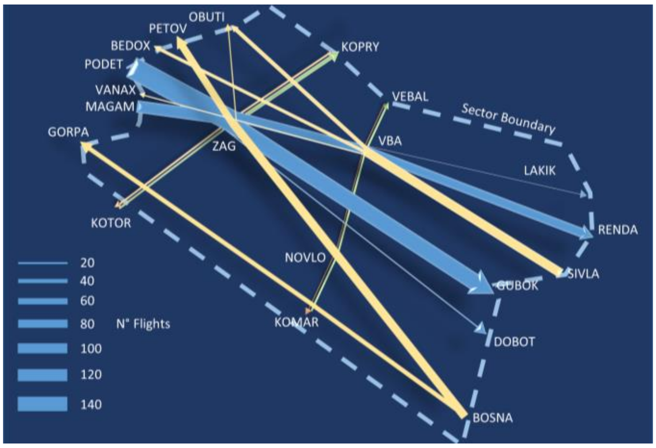

Fig. 2. Most Frequently Used Routes

D. Scenarios

Each participant did nine simulation runs (not counting the simulator preparation training). There were three categories of simulation scenarios according to traffic loads: *Low*, *High*, and *Future*. *Low* and *High* scenarios were developed on the basis of actual traffic data, while *Future* scenarios were based on the peak historic traffic loads which were taken as a starting point and then gradually increased beyond the expected controller's capacity levels. These scenarios had unrealistically high aircraft counts and, to increase air traffic complexity even further, the greater fraction of aircraft were climbing or descending compared to other scenarios. The goal was to increase complexity beyond the levels that could safely be reached with actual traffic and beyond what the controllers experienced during their careers.

To increase complexity above the levels of routine traffic, additional flights were generated in a semi-stochastic manner. Firstly, route was chosen randomly with probability of a given route being chosen equal to the frequency with which it was flown in reality. Secondly, aircraft type was randomly chosen from the actual aircraft distribution for that day. Thirdly, appropriate flight level for that route was chosen with regards to semi-circular system of cruising levels. Finally, time of entry into the sector for that flight was randomly generated until the flight was not in conflict with any other flight in the first few minutes since the entry into the sector (in reality those are solved through coordination between two sector controllers). This was checked by using fast-time simulations. Using this method it was ensured that the artificially generated flights had approximately the same distribution as real ones, without generating un-realistic traffic flow patterns.

Each scenario lasted between 50 and 55 minutes, however, data from the initial 5-10 minutes were discarded because scenarios started with no aircraft initially present in the airspace so there was no data to record. Starting with empty airspace also helped avoid the need to simulate the transfer of responsibility from one controller to another (like in shift changes) which would make the protocol unnecessarily more complicated.

Separation minima for these scenarios were 5 NM horizontally and 1000 ft vertically which was a familiar requirement for the participants because same minima was used during their everyday operations. However, in this experiment the simulation was stopped at the moment that the separation minima infringement occurred because that was, by definition, the maximum air traffic complexity for that controller.

E. Data acquisition

A wealth of information is generated by the simulator during the simulations. All data is stored in real-time to the hard drives at both the controller and pseudo-pilot stations. Stored data can be separated into three main categories:

- Aircraft state data. For each flight all variables pertaining to that aircraft's state are stored at one second interval. These include, but are not limited to: position, speed (TAS, CAS, Mach, GS), heading, track, mass, thrust setting, bank, pitch, drag, ESF, FMS variables, assigned level/heading/speed, etc.
- Human-machine interactions. All mouse events are stored (click, double-click, move, hover, scroll) and all keyboard inputs as well.
- Subjective complexity scores. Subjective complexity scores are collected during the simulation at two minute intervals, with complexity assessment panel sliding into controller's view at the right side of the radar screen, followed by aural notification (without stopping the simulation). They are time-stamped and stored on the hard drive.

To collect subjective complexity scores, modified Air Traffic Workload Input Technique was used (ATWIT) which was previously used to assess complexity by other authors [10][11]. In this study, score descriptors were modified to better reflect the goal of assessing complexity (Table 1).

Description of each subjective complexity level is mostly based on self-assessment of situational awareness which is additionally clarified using aircraft-aircraft or aircraft-airspace interactions. Before using this scale, controllers need to be briefed about the purpose of this technique and meaning behind the words *'complexity'*, *'interaction'*, and *'situational awareness'*.

TABLE 1. AIR TRAFFIC COMPLEXITY RATING SCALE

Complexity Level	Description
1	No complexity – no traffic
2	Very low complexity – very little traffic, no interactions
3	Low complexity – situation and interactions obvious at a glance
4	Somewhat low complexity – firm grasp of the situation, interactions are anticipated and prepared for
5	Somewhat high complexity – aware of the situation, interactions are handled in time
6	High complexity – having trouble staying aware of all interactions, occasionally surprised by unnoticed interactions and conflict alerts
7	Very high complexity – losing situational awareness, unable to track all interactions, responding reactively

III. RESULTS

Before beginning the data analysis it was necessary to prepare the data. First, frequency of each human-machine interaction was calculated for each minute of the simulation. Then, since the subjective complexity scores were entered ideally at two-minute intervals, they needed to be interpolated at one-minute intervals. This issue was further made important by the fact that controllers did not enter their scores at exactly the same moment that the prompt appeared. In worst cases some controllers were late by more than a minute, probably due to heavy workload. For interpolation, the nearest-neighbour method was used. Finally, data from the beginning of each simulation run were discarded because there were no aircraft in the airspace at that time.

Early on, it was found that higher-level HMIs, such as ‘entering assigned altitude into stripless flight progress monitoring system’ or ‘activating range and bearing tool’, could not be used for analysis with any significant result because they occurred very infrequently and sporadically. Therefore, decision was made to analyse only low-level HMIs, such as ‘click’, ‘drag-and-drop’, and ‘hover’. These events occurred with much higher frequency and they also included all of the higher-level interactions which had low frequency by themselves.

Two types of data analysis were performed. First, correlational study was performed on individual and averaged data to detect possible correlation between subjective complexity scores and HMIs. Second, an analysis of predictive power was performed to determine under which conditions the HMIs could be used to infer the probable level of subjective air traffic complexity.

A. *Correlational study*

In this part of the analysis correlation between subjective complexity scores on the one hand and three types of human-machine interactions on the other was tested. Each pair of variables contained data for the whole of the experiment; data from all participants were combined into single variables. There were 515, 487, and 401 data samples for *Low*, *High*, and *Future* scenarios respectively. Lower number of data samples in scenarios with *High* and *Future* traffic levels were due to the fact that the simulation runs were stopped at the moment when separation minima were infringed which happened more often at higher traffic volumes. Sample Pearson’s correlation coefficient (r) for each pair of the variable can be seen in Table 2.

TABLE 2. SAMPLE PEARSON’S CORRELATION COEFFICIENT FOR COMBINED DATA (COMPLEXITY SCORES VS. HMIS)

	Scenario Type		
	Low	*High*	*Future*
Click	0.2224	0.3705	0.5086
Hover	0.0365	0.3585	0.5057
Drag	0.0736	0.3729	0.4223

As can be seen in Table 2, correlation is very weak in scenarios with low traffic volumes whereas it gets stronger with increased traffic volumes. This effect could be attributed to the very low variance of the subjective complexity scores in *Low* scenarios where some participants even assigned the same score (1) to all traffic situations throughout the scenario. Another cause of the low correlation coefficients could be due to the large variance in the complexity scores assigned to the same situation by different controllers. Therefore, another attempt at analysis was performed with data separated per participant. However, in this case data from the different scenario types were combined into single variables. Sample Pearson’s correlation coefficients per participant can be seen in Table 3.

TABLE 3. SAMPLE PEARSON’S CORRELATION COEFFICIENTS FOR PER-PARTICIPANT DATA (COMPLEXITY SCORES VS. HMIS)

	Participants									
	P1’	*P2*	*P3*	*P4*	*P5*	*P6*	*P7*	*P8*	*P9*	*P10*
Click	0.40	0.60	0.41	0.44	0.52	0.48	0.52	0.41	0.66	0.55
Hover	0.48	0.56	0.43	0.62	0.51	0.57	0.51	0.63	0.76	0.66
Drag	0.46	0.68	0.36	0.45	0.55	0.56	0.75	0.58	0.45	0.66

In Table 3, it is visible that the correlation between subjective air traffic complexity and HMIs is much more consistent when it is considered separately for each participant. Also, correlation coefficients hover around 0.5 which can be considered acceptable for some purposes.

One more interesting effect was noticed when mean complexity scores from all participants were used. In this test, for each traffic situation, subjective complexity scores from all participants were used to calculate the mean complexity score for that traffic situation and then the correlation with HMIs was tested. Results can be seen in Table 4.

TABLE 4. COEFFICIENTS OF CORRELATION BETWEEN MEAN AIR TRAFFIC COMPLEXITY AND HMIS

	Scenario Type		
	Low	*High*	*Future*
Click	0.420	0.577	0.735
Hover	0.682	0.883	0.704
Drag	0.832	0.905	0.874

With mean complexity scores, the sample Pearson’s correlation coefficients show much stronger correlation between complexity and frequency of HMIs. This is especially true for *Drag* events which correlate extremely well with the complexity. The source of the increased correlation performance when using mean complexity data might be the well-known 'wisdom of the crowds' effect where mean of scores from independent assessors more accurately predicts some value than the individual scores [12][13]. Possible implications of these results are explored in later section (Discussion).

B. *Predictive power of HMIs*

Linear regression model was created with HMIs as predictors for subjective air traffic complexity. At first, combined data from all participants was used, however regression performance was relatively poor as can be seen in Table 5.

TABLE 5. RESULTS OF LINEAR REGRESSION FOR COMBINED DATA

Scenario Type	Dependent Variable	Predictors	R	R^2	R^2 - adjusted	Std. Error of the Estimate
Low	Complexity Scores	Click, Hover, Drag	0.228	0.052	0.047	0.748
High	Complexity Scores	Click, Hover, Drag	0.497	0.247	0.243	1.088
Future	Complexity Scores	Click, Hover, Drag	0.599	0.358	0.353	1.529

Coefficient of determination (R^2) is lower for scenarios with *Low* traffic volumes which can, again, be attributed to the low variance in subjective complexity scores for these scenarios (many controllers gave lowest score throughout the whole scenario). R^2 increases somewhat with the increase in traffic volume but so does the standard error of the estimate. Similarly to the correlational analysis, regression was attempted again with data separated per participant but combined for all scenario types. Results from these linear regression analyses can be seen in Table 6.

TABLE 6. RESULTS OF LINEAR REGRESSION FOR PER-PARTICIPANT DATA

Par.	Scenario Type	Dependent Variable	Predictors	R	R^2	R^2 - adjusted	Std. Error of the Estimate
1	Low, High, and Future	Complexity Scores	Click, Hover, Drag	0.575	0.330	0.315	0.7809
2	Low, High, and Future	Complexity Scores	Click, Hover, Drag	0.771	0.595	0.586	0.9314
3	Low, High, and Future	Complexity Scores	Click, Hover, Drag	0.587	0.345	0.330	0.8698
4	Low, High, and Future	Complexity Scores	Click, Hover, Drag	0.647	0.418	0.405	1.0441
5	Low, High, and Future	Complexity Scores	Click, Hover, Drag	0.741	0.549	0.539	0.9215
6	Low, High, and Future	Complexity Scores	Click, Hover, Drag	0.718	0.515	0.504	0.6217
7	Low, High, and Future	Complexity Scores	Click, Hover, Drag	0.784	0.614	0.605	0.9904
8	Low, High, and Future	Complexity Scores	Click, Hover, Drag	0.699	0.488	0.476	1.0385
9	Low, High, and Future	Complexity Scores	Click, Hover, Drag	0.800	0.640	0.633	1.0226
10	Low, High, and Future	Complexity Scores	Click, Hover, Drag	0.770	0.593	0.584	0.6272

With the exception of participants 1 and 3, coefficient of multiple correlation (*R*) is between 0.65 and 0.80, which is quite satisfactory when human factors and subjective assessment are involved. Further improvement could be achieved by selecting subset of data with no *Low* scenarios because those scenarios showed poor regression performance in the first analysis, however that was avoided because in real operations controllers do have periods of time with low traffic volumes.

Although the linear regression gave meaningful results, another method of detecting high air traffic complexity was tested. A threshold was set at subjective complexity score of '4'. Those traffic situations which had score below or equal to threshold were considered to be of low or medium complexity and thus not inherently difficult or unsafe, whereas the rest of the traffic situations (with complexity scores above the threshold) were considered very complex and therefore potentially unsafe.

Means of the three HMI indicators were calculated separately for those traffic situations below the threshold and those above it. Results are in Table 7.

TABLE 7. MEAN VALUES OF HMI INDICATORS FOR SITUATIONS BELOW AND ABOVE THE THRESHOLD

HMI Indicator		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Click	***>Thr.***	13.2	14.4	13.6	11.6	12.3	11.7	13.4	10.1	13.8	16.1
	<=Thr.	7.7	6.2	7.3	8.4	6.6	6.2	7.5	6.3	5.9	8.3
Hover	***>Thr.***	384	346	218	397	300	192	208	396	427	373
	<=Thr.	355	211	203	262	249	237	166	249	197	211
Drag	***>Thr.***	18.8	18.6	4.3	9.7	14.3	21.8	10.2	17.1	15.4	20.5
	<=Thr.	17.8	9.2	5.8	9.1	7.8	12.8	4.4	10.5	9.7	11.3

The first noticeable result is that the frequency of HMIs well increases when the complexity is above the threshold compared to less complex situations. It seems possible to choose a threshold of interactions frequency which can be calculated by the computer. If the frequency is above this threshold, the system could react by alerting shift supervisor in order to inform them that the particular controller is currently experiencing heavy workload.

The next step is to evaluate the value of this threshold. However there is another significant tendency in this table. It is noticeable that the ATCOs have different interactions frequencies. Some ATCOs interact much more than others, sometimes three times more faced to the same situation. The HMI interaction rate appears to be dependent on the ATCO. For the same situation, for the same air traffic they do not have the same need to interact with equipment. Due to this fact, the threshold has to be specific to each ATCO and evaluated with a simulation run such as one of scenarios which were used in this research. The threshold has to be evaluated in relative terms, regarding to the lowest number of interactions calculated from the less complex situations, in order to be more adaptive to every ATCO. Each ATCO could have his/her own interactions threshold saved in the system in order to assess whether they are experiencing high workload.

Calculation was performed in order to find the best threshold for this detection of high workload and also to optimize the false alarm rate and the detection probability. Here, the first one means that the ATCO performs a high value of HMI interactions but he/she ranks the complexity below the threshold. This rate has to be as low as possible. The second one means the rate of complex situations (complexity score above the threshold) associated with a number of HMI interactions which is above the threshold. This metric should be high.

Mean values of the below-threshold HMI frequency was selected as a baseline (100%). The threshold was then increased by 10% and false alarm rate and detection probability calculated. Initial results were poor due to high variance in the frequency of the interactions, however once data was smoothed by averaging past three minutes of the simulation, results significantly improved. The following table shows different values of these three figures (Table 8). The statistical rates were calculated by averaging the results from the ten controllers.

TABLE 8. DETECTION AND FALSE ALARM RATES AS A FUNCTION OF THRESHOLD VALUE

Threshold (%) of interaction frequency	Detection rate	False alarm rate
110	0.954	0.323
120	0.920	0.276
130	0.890	0.230
140	0.829	0.179
150	0.774	0.142
160	0.681	0.105
170	0.609	0.080

Setting a threshold depends on the purpose of the system but some trade-off between detection rate and false alarm rate will always be present.

IV. DISCUSSION

There are several lessons to be learned from this research. Generally speaking, it is possible to use human-machine interaction frequency as a proxy measure of subjective air traffic complexity. This conclusion, however, comes with several caveats. Firstly, low-level interaction events are more common and therefore more useful as a measure of HMI frequency. Secondly, humans differ very much in the way they use equipment. Some participants displayed much higher frequency of HMIs than others. Because of this, any attempt of analysis that uses combined data from a number of participants is bound to fail. Thirdly, controllers tend to bunch the complexity scores at the lower end of the scale which makes it difficult to correlate data from scenarios with low traffic volumes with any set of data.

Linear regression can be a useful tool to make a model for predicting air traffic complexity based on HMI frequency. This model, however, needs to be created for each controller individually which makes it somewhat impractical because every controller should do at least three hours of simulator runs while giving complexity scores in order to gather enough data to create a model. Also, such model should probably have to be updated once equipment, airspace or procedures change.

Somewhat simplified method for detecting high complexity by continuously analysing HMI frequency and setting a frequency threshold was presented as well. With this method, a controller workstation could automatically detect peaks in HMI frequency and inform the shift supervisor or store them for later analysis. It could also be used for forensic analysis in the aftermath of an incident or accident.

Perhaps the most unexpected result of the research was very large improvement in correlation between complexity scores and HMI frequency when mean complexity scores were used. Obviously, this type of group judgement can provide new insights into the air traffic complexity. It might be possible to use mean complexity scores from a number of controllers to create a universal model for calculation of baseline complexity score for any given traffic situation. This could then, in turn, be used instead of aircraft count as a measure of air traffic controller workload. Also, prior to the experiment, participants had the concept of complexity explained to them, however, they were not given any pre-scored traffic situations or guidance as to how to determine the complexity based on the features of the traffic situation. This was a conscious choice to avoid influencing controllers in any way but maybe some training with reference scores could be used to give controllers at least some sense of the range of complexity assessment scale that they will use in the experiment.

V. CONCLUSION

This paper presented methodology and results of the research on the correlation between subjective air traffic complexity and human-machine interaction frequency. Through real-time human-in-the-loop simulations ten controllers assessed air traffic complexity. Their scores were then compared with the HMIs gathered by the ATC simulator. Hypothesis that the HMIs can be used to infer air traffic complexity (and workload, by proxy) was confirmed. However, this method comes with several limitations which severely reduce its practical application.

One unexpected and interesting finding of this research was the fact that all HMI indicators correlated very well with mean of complexity scores of all participants (as opposed to the individual participant's scores) which is an interesting target for future research. Similar findings were already published in other fields but authors believe this is the first time such a phenomenon was detected in relation to air traffic complexity.

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The Effects Of Demographic Factors On CRM Perception On Pilots: Turkey Example

M. Onur Balkan
Inonu University Civil Aviation Academy
Malatya Turkey
onur.balkan@inonu.edu.tr

Semih Soran
Ozyegin University School of Aviation
Istanbul Turkey
Semih.soran@ozyegin.edu.tr

Emin Serin
Inonu University Civil Aviation Academy
Malatya Turkey
eminserin@hotmail.com

Abstract— Aviation industry has become aware of the significance of human errors and human factor in the accidents 30 years ago and developed programs known as CRM intended for the diminution of the known errors and increase of effectiveness [1]. The aim of this research is to understand the relationship between the demographical factors and perception of CRM on pilots. In order to reach this aim we conducted a survey on pilots at government and airline. We reached totally 1000 pilots but only 301 of them filled the survey but due to missed items and filling failures we could use 225 of them. We used SPSS 21.0 statistical package program for analysis. We made reliability analysis, factor analysis for structural validity, correlation and linear regression analyses for hypothesis tests. After the reliability analysis we found that overall Cronbach alpha coefficient was 0.701. Also we found that scale established 4 factors structure. After the regression analyses we found that age, tenure had a negative impact on CRM perception, total flight year, total flight hours, tenure, position and statue had a positive impact on CRM perception.

Keywords— CRM, Demographics, Aviation

Introduction

John K. Lauber (1984), a psychologist member of the National Transportation Safety Board (NTSB), has defined CRM as ‘‘using all available resources and information, equipment, and peopled to achieve safe and efficient flight operations’’ [1]. CRM includes optimizing not only the person–machine interface and the attainment of timely, suitable information, but also interpersonal actions including leadership, effective team formation and maintenance, problem-solving, decision-making, and maintaining situation awareness [2]. Here is the definition of CRM from FAA: "*CRM can be broadly defined as the utilization of all available human, informational, and equipment resources toward the goal of safe and efficient flight. CRM is an active process by crewmembers to identify significant threats, to communicate them, and to develop, communicate, and carry out a plan and actions to avoid or mitigate each threat. CRM also deals directly with the avoidance of human errors and the management and mitigation of those errors that occur. CRM reflects the application of human factor knowledge to the special case of flight crews and their interactions with each other, with other groups and with the technology in the system*"[3]. Main goal is not getting people to 'work together better' but to reduce 'the frequency and severity of errors that are crew based'. This is achieved by training crews to 'avoid, trap or alleviate the cost of error by making better use of human resources.

LITERATURE REVIEW

A. CRM

The purpose of CRM (Crew Resource Management) is enabling the best possible utilization of the available resources [4]. CRM is found at the implementation stage of decision-making process of multiple team flights. The question of "is CRM enough?" was dealt with in 1979 in a study conducted by NASA and new models related to the effective usage of all the available resources and team coordination were developed [5]. Aviation industry has become aware of the importance of human errors and human factor in the accidents 30 years ago and developed programs known as CRM directed at the reduction of the known errors and increase of efficiency [6].

CRM has gone in the course of a number of evolutions. The first generation focused on enhancing the effectiveness of managerial staff and correcting shortcomings in pilot behavior, tyranny by captains. In 1986, CRM training shifted to focal point of cockpit group dynamics. Training became more aviation-based with regard to flight operations and focused on team-based concepts such as team decision making. Third-generation CRM training broadened to reflect the environment in which crewmembers function, which included organizational culture and groups. By 1994, the fourth generation of CRM had come about, and its focus was on the addition of specific CRM behaviors to checklists, specialization of curriculum, and special training for those who instruct, certify, and evaluate crews in full mission simulations. The fifth generation CRM evolved to error management. The foundation of this generation is the fact that human error is unavoidable. Whereas previous CRM programs trained crewmembers to avoid errors, they are now being trained to recover from errors and to manage those errors that are inevitable [4].

So how will we use CRM as a tool for flight safety? Many researchers investigate the issue and established a training program regarding CRM. CRM is the most commonly used technique educating the aviation sector's personnel on team work and this technique attracted the attention of other sectors dealing with high risk in the recent years [7]. The idea suggesting that the errors originating from human factor could be avoided in some way with trainings, led experts to initiate a series of training activities aimed at giving cockpit team attitudes, behaviors and beliefs that could prevent the errors. Effectively of the trainings was measured by way of evaluations processes conducted before and after the training activities which started under the title of CRM and directed at preventing the errors, and trainings were observed to have a positive contribution to the prevention of errors [8].

CRM training programs allow the trainers to focus mainly on human- human dealings as well as to emphasize the concepts such as communication, leadership, team work and coordination [9]. These programs include a lot of modules that aim at improving skills such as leadership, team spirit, decision-making and situational awareness; ensuring coordination among team members; more effective stress, workload and conflict management; and establishing a human-automation harmony [10]. Consequently, it will be likely to reduce the human errors and their negative effects by using the resources such as human, hardware and knowledge more efficiently thanks to CRM training programs [11].

Although many airline companies established training programs they could not achieved as they desired. Later on, a new research topic emerged. Why the training programs had functioned well? Researchers focused on culture and personal differences. In 1970s, the research conducted by NASA reported the significance of human-human communication in aviation. The interviews done with an airline named Pan AM pilots exposed that they received high quality training on aircraft systems and operations; though, they reported that they face problems in definite issues such as leadership, communication and decision-making [9]. Cooper, White and Lauber, in their detailed study on aircraft accidents that occurred between 1968 and 1976, concluded that most of those accidents were due to the problems in “giving orders”, “communication” and “coordination” among the crew. Likewise, the simulator studies done by Ruffell-Smith discovered the magnitude of management skills in cockpit [12]. Under the light of these findings, CRM training programs were considered to extend non-technical skills such as communication, leadership, team work, decision making, situational awareness, work load and stress management. Even though CRM training programs are extensively used by airlines all over the world, they are not as thriving as those applied in the USA. Helmreich and Merritt, in their studies, argue that the factor which accounts for this difference in achievement is the existence of different cultural contexts [9].Helmreich and Merritt, in their study on determining the attitudes of pilots in certain scales, found out that their attitudes are influenced, to a great extent, by national culture. Also Salas et.al conducted a research about individual differences such as, personal selection and national culture. According to this work, when selecting pilots, CRM tests should be conducted to the candidates to measure their tendency to work as team. Also they had taken into account the culture factor [13].

Researchers explained the situation with the hypotheses proposing that CRM implementations could be effected by various factors and they continued their research by including different factors in their studies [11]. Besides the cultural differences, we tried to investigate the demographical differences among the flight crew. The scope of our work was narrowed by the aim. The researches could be found in the literature regarding culture [3][11], behavior markings [14] and Non-technical skills [15]. But we could not find any specific work emphasizing the demographics. Some of the researches mentioned the demographics but not as a sole topic. We investigate demographics such as: age, tenure, education, total flight time, total flight year, aircraft experience, position, and statue. Our main objective was to seek a relation between these factors and CRM understanding.

II. METHODOLOHY

A. *Research Goal*

The aim of this research is to understand the relationship between the demographical factors and perception of CRM on pilots. In order to achieve this aim we developed these hypotheses:

H1: There is a correlation between demographic factors and CRM factors.

H2: Demographic factor had an impact on CRM factors.

B. *Sample and Data Collection*

The subjects of this study are Turkish pilots working for both government and commercial airline companies operating in Turkey. According the data obtained from Turkish Airline Pilots Association (TALPA) and government pilots who working for them, the number being 3000 in 2015. Within the scope of this study, a sample of 1000 pilots was taken from this population by using “basic random sampling” method. 300 of them returned, due to failed filling and missing answers 225 of them analyzed.

Table 1 Demographics

Demographics	
Age	20-24 10.7% 25-34 63.6% 35-44 25.8%
Education	University 88% Master 12%
Tenure	Less than 1 year 6.2% 1-3 6.2% 3-10 46.2% Less than 10 41.3%
Aircraft experience	Less than 1 year 7.6 % 1-3 16.4% 3-8 36.9% 8+ 39.1%
Total Flight year	Less than 10 year 59.6% 10-15 26.2% 15-20 13.8% 20+ 0.4%
Pozition	Captain 65.8% First Officer 34.2 %
Statue	Pilot 75.6% Instructor 18.2% Examiner 6.2%
Total Flight Hour	Less than 1500 hr 49.8% 1500-3000 39.6% 3000-6000 10.7%

According to Table-1 most of the pilots were 25-34 years old (63.7%) and 88% of them graduated from a university. Nearly 60 percent of the sample was a flyer less than 10 year and half of them had 1500 flight hours and less.

C. *Analyses and Results*

The Data produced in this study were collected by survey. The survey consisted of two measures. In the first part questions about the demographic characteristics of pilots; in the other part questions designed to measure CRM perception were asked.

The CRM perception was measured by a scale taken from Helmreich and Merritt, but we update the scale to fit our country. We use previous researches conducted in Turkey. The measure included 20 items, each item was answered through a five-point Likert scale ranging from “1=strongly disagree” to “5=strongly agree.” In the present study, the Cronbach's α coefficient for the scale was 0.70.

The Validity of the Measures: To ensure the validity and reliability of the study variables, explanatory factor analysis was conducted by using SPSS software.

The CRM perception measure produced four factors upon factor analysis. The first factor named “CRM Training”, explained 21.78% of the total variance (We received numbers of CRM training) . The second factor was named “Decision Making” and it explained 13.47% of the variance (My decision making ability as good as in emergencies as in routine flying conditions, A truly professional crewmember can leave his/her personal problems behind when flying). “Stress” the third factor with a variance of 10.37 % (I am less effective when stressed or fatigued), was followed by “Command” (8.94%) (Except for total incapacitation of the captain, the first officer should never assume command of the aircraft). The factors all together explained 68.80% of the variance. KMO Bartlett's Test of Sphericity was 0.747.

Table-2: Factor analysis results for CRM

CRM	CRM Training	DM	Stress	Command
Q1	0.812			
Q4	0.746			
Q5	0.729			
Q3	0.715			
Q7	0.678			
Q9	0.645			
Q11		0.703		
Q13		0.618		
Q14			0.779	
Q15			0.750	
Q17				0.712
Q19				0.661
Total Explained Variance for CRM 54,58 %				

DM: Decision Making, OR: Obeying the Rules

As a result of correlation analyses we found that, there were a negative correlation between “CRM Training” and tenure ($r=-0.17$, $p<0.01$), age ($r=-0.14$, $p<0.05$), aircraft experience ($r=-0.23$, $p<0.01$), total flight year ($r=-0.16$, $p<0.05$) and positive correlation with position ($r=0.18$, $p<0.05$). Also we found that there were a positive correlation between “Decision making” and tenure ($r=0.13$, $p<0.05$), aircraft experience ($r=0.14$, $p<0.05$), total flight year ($r=0.15$, $p<0.05$), total flight time ($r=0.17$, $p<0.01$) and statue ($r=0.15$, $p<0.05$). According to these results H1 partially accepted.

Table 3 Regression Analyses

	CRM training	DM	Stress	Command
	β	β	β	β
Age	-,049	,109	-,158	-,130
Education	,118	-,050	,085	-,030
Tenure	,054	**-,305***	,054	,066
Aircraft experience	-,251	,143	,076	-,167
Total Flight year	,089	,043	,101	,108
Total Flight Hour	-,081	-,017	,075	-,057
Statue	,070	-,041	-,063	-,003
Position	,018	-,089	,066	**-,287****
ΔR^2	0.077	0.029	0,065	0,046
ΔF	1.999	0.717	1,652	1,140

To explore whether the independent variables had a significant impact on the dependent variables, hierarchical regression analyzes were conducted. Table-3 shows the regression analysis results for each CRM dimension. Results showed that tenure had a negative impact on decision making and position had a negative impact on command factor. In the regression analysis, demographic variables: age, education, aircraft experience, total flight year, total flight hour and position had no significant impact on CRM factors. According to these results H2 partially accepted.

III. CONCLUSION

Human error in Aviation was the subject of researchers for many years. After the quantum leaps in the aviation human could not catch the technology as desired. At the beginning of the aviation history, pilots had tolerated the aircraft errors but after the 1960's the current turned to opposite way. Even though the technology has helped to human, it is not enough to prevent accidents. We mentioned the evolution of the CRM above. CRM turned to be most used technique within the airlines. CRM training helped the airlines to educate their crew for cooperation in the aircraft.

The aim of this research is to investigate the relation between demographic differences on CRM perception among the pilots. Most of the academic researches focused on cultural differences on CRM but demographics were not the focus of them.

In order to achieve this aim we cunducted a survey on pilots in Turkey. We use SPSS program to evaluate the results of survey. The results showed that the reliability of the scale was 0.701. We cunducted factor analyses for structural validity. The scale gave us four factor structure. The factors named as follows: the first factor "CRM training", second one "Decision making", third one "Stress" and the last one named "Obeying the rules". This structure was shown similarities between Helmreichs', Flinn and Şekerlis' works. As a result of correlation analyses we found that, there were a negative correlation between "CRM Training" and tenure ($r=-0.17$, $p<0.01$), age ($r=-0.14$, $p<0.05$), aircraft experience ($r=-0.23$, $p<0.01$), total flight year ($r=-0.16$, $p<0.05$) and positive correlation with position ($r=0.18$, $p<0.05$). These results may indicate that, younger and inexperienced pilots could not understand the importance of CRM training or they did not pay enough attention to the issue. Only the captains approached the training positively. Also we found that there were a positive correlation between "Decision making" and tenure ($r=0.13$, $p<0.05$), aircraft experience ($r=0.14$, $p<0.05$), total flight year ($r=0.15$, $p<0.05$), total flight time ($r=0.17$, $p<0.01$) and statue ($r=0.15$, $p<0.05$). These results tell us that, experienced pilots had more healthy decision making process.

As a result of the regression analyses, we found that that tenure had a negative impact on decision making and position had a negative impact on command factor. These results indicated that decision making affected by experience. When the experience level increased the decision making effectiveness increased as well. Above the 10 years or more experienced pilots showed more attention to decision process, they were aware of fatigue could decrease their level of attention and also they were well aware of personal problems could impair their decision making process. Another finding of our research is the position factor had a negative effect on command factor. Command factor (or we can say as Obeying the rules) as the Helmreich argued before, was one of the critical point of cooperation within the cockpit. First officers did not question the orders of captain but they obey them. FO's accepts captain's decisions without doubt and they think that unless the captain became incapacitated, they have to obey. But in aviation history there were many accidents caused by the captain's individual mistakes. The main reason behind the CRM is that. According to Helmreich and Hostefede this problem pops up mainly in the eastern cultures or societies which had high power distance.

We suggest that airline companies or the government agencies should pay attention to composition of flight crew. And especially the captain and FO relations regarding flight safety, also they may highlight the importance of cooperation within the flight deck. Captains' decisions should not be unquestionable but of course this should not led harm the chain of command. Another suggestion regarding the results, companies or the government agencies should train the pilots whose experience were 3 years or less about the dangers of fatigue and conditions which could impair their ability to decide well. To achieve these objectives companies could revise their CRM training programs or they can highlight the importance of the training. Also training managers should be careful about the cultural differences and should adopt the program to avoid this kind of situations.

All these findings aside, we have to indicate that our study had some limitations in itself as well. The first one of these limitations is an issue that could arise in the generalization of the findings obtained. Since the sample used in the present study majorly consists of public and private sector pilots flying in general aviation industry. Therefore, the studies that could bear healthier results would be the studies with wider sample groups with a separation of public and private sector pilots. Another limitation is that the data reflects only people's own assessments. The following studies could especially address the cultural differences among the flight crew and how to avoid from that.

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Innovative Baggage Delivery for Sustainable Air Transport

Pavel Loskot
Swansea University, Swansea, SA2 8PP, UK
E-mail: p.loskot@swan.ac.uk

Peter Ball
Zafire Ltd., Manor Park, Banbury OX16 3TB, UK
E-mail: pball@zafire.com

***Abstract*—The passenger travel processes in Air Transport (AT) have not changed for the past 40 years. Here we contribute to the IATA visions of Simplifying the Business (StB) and improving the passenger experience by proposing to dissociate passenger travel and baggage delivery. This innovative aspect has profound positive consequences on the AT logistics and economies. Even though it requires a significant change in the current AT regulations, the proposed improvement is likely to be phased-in and eventually adopted by the airlines as well as the aircraft manufacturers. Our analysis shows that dissociating passenger and baggage flows can be vital for maintaining sustainability of AT. Moreover, the enabling technologies supporting this change either already exist, or are being developed.**

***Index Terms*—Air Transport, Baggage delivery, Passenger experience, Simplifying the Business, Sustainability.**

1. Air Transport and IATA Visions

The infrastructure, processes and systems in AT have not changed for over 40 years, so they are dated, inefficient and complex. Some of the main challenges are passenger queuing at various check and service points at the airport, mishandled bags, and unexpected service disruptions, for example, due to a bad weather or aircraft maintenance. These problems are causing excessive delays and costs, and they are exacerbated as the passenger numbers and the cargo volumes grow faster than the system capacity [1], [2]. For instance, the number of passengers worldwide has increased from 1.89 billions in 2003 to 3.3 in 2014 (i.e., a 75% increase).

The airlines and the airports have been well aware of these problems. The IATA (International Air Transport Association) established several programs to accommodate the growing demand for the AT services [3]. These programs are structured around three main objectives: 1. Airline products with new distribution capabilities and e-services, 2. Real-time interactions, and 3. Seamless and hassle-free services. The latter objective concerns the relevant themes such as Smart Security, Baggage Services, Security Access and Egress, Automated Border Control and Fast Travel. In simple terms, the overall aim is to simplify the processes and improve the passenger experience while enhancing the security, safety, and the utilization efficiency of space, staff and other assets. The passenger experience is improved by providing them with more autonomy which have focused so far on baggage self-tagging, baggage self-drop-off, and self-checking services.

2. Air Transport of PAX, Baggage and Cargo

The AT network realizes the delivery of passengers, their baggage and cargo. This delivery is a very complex process consisting of many integrated services and supporting sub-processes. The aircraft serving as the AT carriers have finite volumetric and weight load capacities which are usually optimized to maximize the delivery efficiency [4], [5], [6]. Such efficiency can be measured as a revenue for the operator (e.g., an airline, or an airport), and increasingly also in terms of the generated CO_2 emissions [7], [8]. For the long-term average seat occupancy of about 80%, the long-haul flights generate a modest \$6 profit per passenger, however, a substantial profit of \$2.40 per kilogram of cargo [1], [3]; it is clear that cargo delivery is critical for the airline financial viability [9].

A typical commercial airliner trades-off the payload with its operational range as shown in Fig. 1. The payload-range trade-off curve also depends on the particular aircraft configuration (e.g., whether using the winglets) and the engine parameters. The payload only represents passengers, their baggage and cargo; the dry operating weight (DOW) includes everything else except the fuel [7], [8]. The maximum take-off weight (MTOW) is limiting for longer flights whereas the maximum landing weight (MLW) is a concern for shorter flights. The maximum zero-fuel weight (MZFW) becomes limiting when the payload and fuel are optimized for a given range. In Fig. 1, R_1 is the maximum range with the maximum payload. The ranges between R_1 and R_2 require to trade-off the payload for fuel. The maximum range R_2 achievable with full fuel tanks can be exceeded if the payload is further reduced to make the aircraft more fuel efficient. The payload-range trade-off of the new aircraft designs corresponds to R_3 (see Section 4).

The average passenger weight (combined male and female) is 73-75kg and the child 34-36kg [10], [7]. The hand (carry-on) luggage and checked-in luggage allowances differ per airline and the travel class: an economy class passenger on a long-haul flight is usually allowed to carry up to 7kg single luggage on board, and to check-in one piece of luggage up to 23kg for free. The maximum seating capacity of an aircraft decreases with the number of travel classes offered. A long-haul airliner typically carries: 240-520 passengers (80% occupancy) with 7kg average hand luggage per passenger, average checked-in luggage of 23kg (80% of travelers) and 2×23kg (remaining 20% of passengers) which amount to:

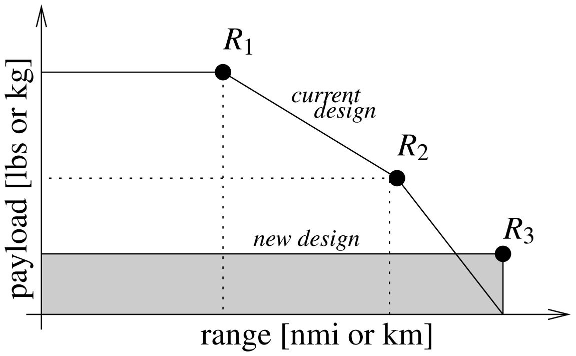

Figure 1. A typical payload-range characteristic of the current and future aircraft.

20-33	tons of passengers with hand luggage;
7-15	tons of checked-in luggage;
23-28	tons of cargo;
50-76	tons of the total payload.

The variants of the new Airbus A350 aircraft report the volumetric and structural cargo payloads of up to 52 tons [7], in addition to passengers and baggage. The purposely modified airliners known as the freighters can increase the maximum total payload of cargo to as much as 140 tons [7], [8].

The cargo is consolidated by the 3rd party forwarders (e.g., UPC, TNT, DHL) from the shippers and suppliers, usually into unit load devices (UDLs). The cargo delivery is optimized for efficient routing, loading and unloading and priority handling [5], [6]. The air cargo tariffs and premiums are determined to manage the demand against the available transportation capacity [3]. The average revenue per one kilogram of cargo delivery is calculated as [4]:

$$\mathrm{TRF}\ [\$/kg] = \frac{\sum_i \mathrm{CW}_i\ \times\ \mathrm{TRF}_i}{\sum_i \mathrm{CW}_i}$$

where $\mathrm{CW}_1 < \mathrm{CW}_2 < \ldots$ are cargo weights, and $\mathrm{TRF}_1 > \mathrm{TRF}_2 > \ldots$ are the corresponding tariffs. The tariffs can be determined through bids for the available carrier capacity.

A. Dissociating Passenger Travel and Baggage Delivery

Passenger travel as well as baggage handling and delivery is regulated by the IATA regulations. The IATA's General Conditions of Carriage [3] recommends that:

"*... checked baggage will be carried on the same aircraft as the passenger unless Carrier decides that this is impractical, in which case Carrier will carry the checked baggage on Carrier's next flight on which space is available.*"

Moreover, most airlines operate the policy that luggage of checked-in passengers who fail to board the flight must be off-loaded for the security reasons. Thus, currently only a small number of bags are delivered on the next flight, and the affected passengers will not be notified until they attempt to collect their luggage at the destination airport. Provided that most or all of the bags are allowed to be delivered on flights other than the passengers' flight, many significant improvements to the AT delivery services can be devised as we will discuss in the rest of the paper. Specifically, the implementation aspects of dissociating passenger travel and baggage delivery are considered in Section 3, and the benefits and future trends are summarized in Section 4.

Consider a single passenger travel from the point of origin (usually the passenger's home, work place, or a hotel in the return journey) to the destination (a hotel, or home in the return journey). The passenger leaves the origin at time T_0 for the departure at time T_1. After the flight of duration $(T_2 - T_1)$, the passenger arrives to the destination at time T_3. Associated to these events at times T_0, T_1, T_2 and T_3 are additional events E_0, E_1, E_2 and E_3 occurring at times $T_0 + \Delta T_0$, $T_1 + \Delta T_1$, $T_2 + \Delta T_2$ and $T_3 + \Delta T_3$, respectively, as depicted in Fig. 2. The events E_i represent:

- E_0: baggage sent from the origin to departure airport;
- E_1: baggage is delivered to the departure airport;
- E_2: baggage is delivered to the arrival airport;
- E_3: baggage is collected by the passenger.

In the conventional (current) system, passenger travel and baggage delivery are coupled (synchronized), so that $\Delta T_i = 0$, for all $i = 0, 1, 2, 3$. However, once these two processes become separated, the events E_i, $i = 0, 1, 2, 3$ generally occur before or after the corresponding times T_i (i.e., $\Delta T_i \neq 0$) which allows to consider entirely new AT services with the significantly improved passenger experience.

B. Baggage Delivery Strategies

Even though dissociation of passenger travel and baggage delivery is conceptually simple, its implementation is rather non-trivial, since it is constrained by the strict AT regulations, especially those involving the AT safety and security. Importantly, at all times, baggage ownership has to be defined. In particular, the passengers hand over their baggage to the airline or the airport baggage service before the departure, and then take over their baggage back upon the arrival. Other baggage ownership handovers frequently occur during baggage handling and delivery (e.g., loading and unloading).

Passenger travel involves three segments: journey to and from the airport (ground segments), and the air travel between the departure and destination airports. The passenger and baggage dissociation for the ground segments is specific as it does not involve the air travel. Hence, the 3rd parties may provide a new travel service to deliver passenger baggage to and from the airport. Prior to the departure, the passengers can either drop their luggage off at a dedicated collection point (established, e.g., at a post office, central bus or railway station, by large supermarkets and similar such sites), or their luggage is conveniently collected from their premises. This enables hassle-free passenger travel to the departure airport, encouraging the use of more efficient and ecological public transport. At the destination airport, instead of collecting baggage from the belt in the arrival hall, the 3rd party can again provide a new delivery service for baggage to the selected destination (typically, a hotel) which simplifies passenger

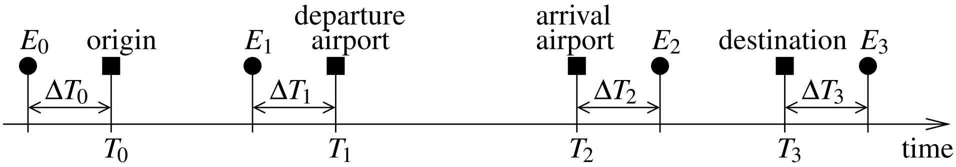

Figure 2. The time axis of passenger travel and baggage delivery between an origin and a destination.

travel from the airport. For instance, the Manchester airport in the UK is experiencing over 40,000 vehicle movements daily, so any consolidation of the travel to and from this airport by means of public buses and trains can greatly contribute to its sustainability.

Dissociating passenger travel and baggage delivery within the air segment is the most complex as it requires changes to the current airline and airport procedures and regulations. On the other hand, unlike baggage dissociation over the ground segment, the required technology and infrastructure is already available at the airports, so the changes are mainly related to baggage handling and logistics. In particular, let $\Delta T_0 = \Delta T_1 = 0$, i.e., the passenger delivers his/her luggage to the departure airport, and check it in with the airline. The airline schedules luggage delivery to the arrival airport. The passenger is notified about the most likely collection time, for example, during the check-in, or even during the air-ticket booking prior to his/her travel to the departure airport. Since luggage is likely to be delivered after the passenger arrival, the airline agrees with the passenger the collection method at the destination. The airline can exploit the delayed luggage delivery to better optimize the profit-paying cargo delivery, especially if sufficient number of passengers sign up for the delayed luggage service, and there is a premium for the expedited cargo delivery. The incentives (e.g., extra travel miles) can be used to manage the demand for this new baggage service. For instance, the passengers can be encouraged to send their luggage to the airport early prior to their travel; according to the airline operational procedures, luggage is usually loaded to the aircraft at least 0.5 hours prior to the departure.

C. Aircraft Load Optimization

In order to assess the feasibility of the proposed dissociated baggage delivery, we consider an AT network segment consisting of an origin airport, a destination airport and a single stopover airport. Similar analysis can be performed for more complex AT network topology having multiple (e.g., stopover) airports by iteratively expanding the model in Fig. 3.

Let there be p passengers traveling from the origin to a destination airport with p_1 passengers on the direct flight, and $p_2 = p - p_1$ stopover passengers. The corresponding baggage volume (e.g., expressed as weight in kilograms) is denoted as $b = b_1 + b_2$, and the cargo volume as $c = c_1 + c_2$. We assume that the passenger numbers p_1 and p_2 on the respective flights are fixed. Provided that the passengers and their baggage can be dissociated, our goal is to optimize loading of each flight.

Denote as L_1 the maximum available load (capacity) for $c_1 + b_1$ on the direct flight, and as L_{21} and L_{22} the maximum

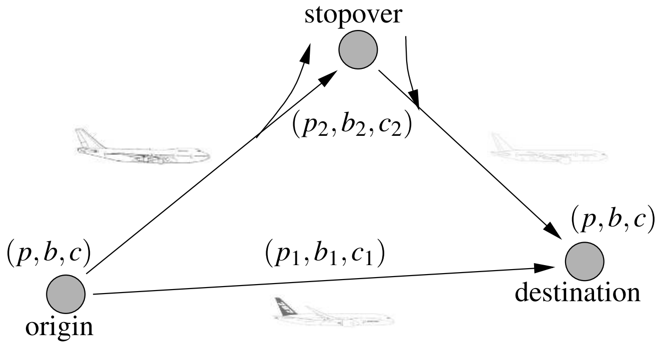

Figure 3. A single origin and destination segment of the AT network with the indicated quantities of passengers (PAX), baggage and cargo.

available loads for $c_2 + b_2$ on the two indirect flights. Note that there is likely to be more passengers and more load transported on the flights from the origin to the stopover, and from the stopover to the destination than (p_2, b_2, c_2), however, these additional passengers and loads are not included in L_{21} and L_{22}. Thus, we have the constrained loads,

$$\begin{aligned} b_1 + c_1 &\leq L_1 \\ b_2 + c_2 &\leq \min(L_{21}, L_{22}). \end{aligned}$$

If α_1, α_2, β_1 and β_2 denote the unit transport costs (tariffs per kilogram of weight) of b_1, b_2, c_1 and c_2, respectively, on the corresponding flight segments, we want to minimize the total transport cost:

$$\begin{aligned} & \min\left(\alpha_1 b_1 + \alpha_2 b_2 + \beta_1 c_1 + \beta_2 c_2\right) \\ = \; & \min\left(\underbrace{\alpha_2 b + \beta_2 c}_{\text{const}} + b_1 \underbrace{(\alpha_1 - \alpha_2)}_{\Delta\alpha_{12}} + c_1 \underbrace{(\beta_1 - \beta_2)}_{\Delta\beta_{12}}\right) \\ = \; & \min\left(b_1 \Delta\alpha_{12} + c_1 \Delta\beta_{12}\right) = \min M(b_1, c_1) \qquad (1) \\ & \text{s.t. } L_2 \leq (b_1 + c_1) \leq L_1 \end{aligned}$$

where we denoted $L_2 = c + b - \min(L_{21}, L_{22})$. We further assume that the load capacity $L_1 > L_2$, and that the transport costs $\Delta\alpha_{12} < 0$ and $\Delta\beta_{12} < 0$ to meet the transport demands as indicated above.

The problem (1) is a simple linear program with two decision variables b_1 and c_1 given the transport capacities L_1 and L_2, the loads c and b, and the set of costs $\{\alpha_1, \alpha_2, \beta_1, \beta_2\}$. This problem can be readily solved graphically. In particular, the feasible region of decisions (b_1, c_1) satisfying the load constraints is shown as a shaded area in Fig. 4. Provided that $|\Delta\alpha_{12}| < |\Delta\beta_{12}|$, i.e., the tariff differential for baggage

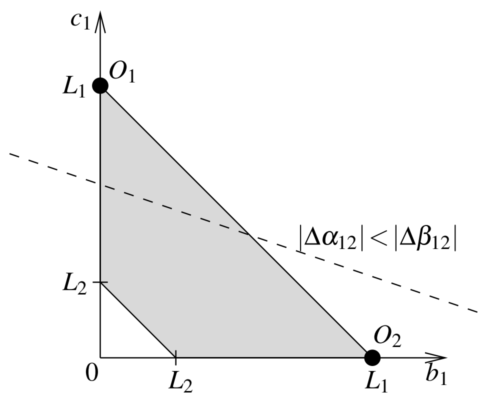

Figure 4. The payload optimization for the direct and stopover delivery in Fig. 3.

delivery between the direct and indirect flights is smaller than the tariff differential for cargo delivery, the optimum solution minimizing the transport cost corresponds to the point O_1 in Fig. 4. The dashed line in Fig. 4 is defined by the expression:

$$c_1 = -\frac{\Delta\alpha_{12}}{\Delta\beta_{12}} b_1 + \frac{M}{\Delta\beta_{12}}$$

and the minimum cost is given by the minimum value of M. On the other hand, if the tariff differentials are such that $|\Delta\alpha_{12}| > |\Delta\beta_{12}|$, the dashed line in Fig. 4 would have the gradient smaller than -1, and the optimum is given by the point O_2. Finally, if $|\Delta\alpha_{12}| = |\Delta\beta_{12}|$, i.e., both types of the loads have the same differential cost, the dashed line in Fig. 4 would have the gradient equal to -1, and any decision contained on the line between the end-points O_1 and O_2 is optimum. However, in practice, the tariffs for baggage and cargo delivery are likely to differ significantly [3]. If the transport capacity $L_1 > c_1$ and the optimum load is given by O_1, the remaining capacity $(L_1 - c_1)$ on the direct flight is used for transporting baggage b or cargo c_2, depending whether the costs $\alpha_1 < \beta_2$ or $\alpha_1 > \beta_2$, respectively. Similar conclusions applies for the optimum O_2 and the non-zero transport capacity $(L_1 - b_1)$.

We can readily generalize the load optimization problem in (1) to more types of cargo. The cargo types are defined by their different transportation tariffs. As shown in the solution of (1), the loads with larger tariff differential are more important and should be considered before the other loads. While still assuming only a single origin and a single destination, we can further generalize the load optimization problem to the case of multiple stopovers. We then minimize the total cost $\sum_{ij} \alpha_{ij} c_{ij}$ over all origin-destination routes i with the cargo loading c_{ij}, for a given set of costs $\{\alpha_{ij}\}$.

Consequently, by dissociating passenger travel from baggage delivery, we can consider baggage to be another type of cargo. This brings a great flexibility to optimize the aircraft loading, since baggage delivery is currently provided on most flights of the commercial airlines.

Table I
SOME FLIGHT STATISTICS BETWEEN SELECTED AIRPORTS

Orig.	Dest.	dur.	direct	1 stop	2 stops	total
EDI	PEK	$<$ 24h	0	42	94	136
DUB	PEK	$<$ 24h	0	49	62	111
LHR	PEK	$<$ 24h	3	103	21	127
EDI	FCO	$<$ 12h	1	27	15	43
DUB	FCO	$<$ 12h	2	43	10	55
LHR	FCO	$<$ 12h	3	80	2	85
EDI	DXB	$<$ 12h	0	52	6	58
DUB	DXB	$<$ 12h	4	63	7	74
LHR	DXB	$<$ 12h	20	102	5	127
EDI	JFK	$<$ 18h	0	89	23	112
DUB	JFK	$<$ 18h	8	66	9	83
LHR	JFK	$<$ 18h	69	141	11	221
EDI	PIT	$<$ 18h	0	4	51	55
DUB	PIT	$<$ 18h	0	30	61	91
LHR	PIT	$<$ 18h	0	156	51	207
EDI	GIG	$<$ 24h	0	9	35	44
DUB	GIG	$<$ 24h	0	7	52	59
LHR	GIG	$<$ 24h	1	42	33	76
EDI	SYD	$<$ 32h	0	6	104	110
DUB	SYD	$<$ 32h	0	17	44	61
LHR	SYD	$<$ 32h	0	93	65	158

D. Initial Implementation Strategy

We consider dissociation of baggage delivery for the air travel segment only in order to outline an initial implementation strategy. We propose to deliver baggage on the flights with the minimum number of hops (stopover airports). Specifically, all baggage should be delivered on the direct flights between the airport hubs, and baggage delivery on the flights with one stopover is preferred to the flights with two stopovers and so on. Tab. I contains the typical numbers of daily flights with up to 2 stopovers, given the maximum overall journey duration (in hours) between the given origin and destination airports denoted by their 3-letter IATA codes[1]. For the three selected origin airports in the UK and Ireland (EDI, LHR and DUB), the destination airports are chosen in the different continents.

As indicated above, we assume a typical airline load of 7-15 tons of checked-in baggage which represents about $1/3$ to $1/2$ of the overall cargo load of 23-28 tons. Consequently, in order to estimate the average number of flights N_{B} required to aggregate baggage delivery (i.e., the baggage load on these flights has priority over the cargo load) over one day, we denote as B the average baggage load per (origin-to-destination) flight, and as C the same quantity, but for the cargo load. Then, $B = \alpha \cdot C$ where typically, the fraction $\frac{1}{3} \leq \alpha \leq \frac{1}{2}$ (i.e., the higher the average passenger flight occupancy, the larger α), and the flight average load excluding the passengers is, $B + C = (1+\alpha)C$. For the total number of daily flights N_{tot} considered, we have that, $N_{\mathrm{tot}} \cdot B \approx N_{\mathrm{B}}(B + C)$, and thus,

$$N_{\mathrm{B}} \approx N_{\mathrm{tot}} \cdot \frac{\alpha}{1+\alpha}$$

where the function $f(\alpha) = \alpha/(1+\alpha)$ is strictly increasing. For example, $f(1/2) = 1/3$, so about $1/3$ of the daily flights

[1]Data collected manually from skyscanner.net for a typical week day in November.

between the given origin and destination airports can be used to carry all the daily baggage volume on the remaining $2/3$ of the flights reserved for the cargo (no baggage) delivery. More importantly, these $1/3$ daily flights for the aggregated baggage delivery should be allocated over the routes with the minimum number of hops (stopovers). Moreover, since the flights between the origin and destination airports are usually scheduled over the whole day (except a period after the midnight, say, 12am till 5am), the maximum baggage delivery delay (after the passenger's arrival to the destination airport) is approximately $(24-5)/3 \doteq 6.3$ hours which is acceptable. In practice, this maximum delay is likely to be smaller, for example, when baggage is delivered on the direct flight while the passenger travel includes one stopover. Note also that we assume that the airlines fully collaborate (beyond the current flight share schemes) to better utilize the aggregated baggage transport capacity between the origin and destination airports.

In summary, delivering baggage over the flights with smaller number of stopovers (ideally, via the direct flights only), relieves the baggage load congestion, and thus, increases the load throughput at the stopover airports. We recommend to route baggage over the direct flights only whenever possible (i.e., when the aggregated load on the direct flights is sufficient), and especially when the destination airport is a large air travel hub.

3. Implementation Aspects

In general, the implementation strategy is critical to overcome many challenges. The main challenge to enable dissociation of passenger travel and baggage delivery is the security, especially when the 3rd parties become involved by offering new baggage delivery services. The modern X-ray scans can reliably detect any suspicious or prohibited luggage content, so they are nowadays used immediately after the baggage check-in at the airports. However, to resolve the luggage content issue requires on-site presence of the passenger. This may constrain baggage delivery to the departure airport either together with the passenger arrival or earlier, but not later. The X-ray scans at the departure airport are also expected to be used for the remote customs clearances under the import regulations of the destination country [3]. The 3rd party baggage delivery to/from the airport requires additional measures to prevent unauthorized tampering with luggage such as the use of secure lockable transport containers.

The provisioning of the passenger services in AT is often shared by the airport authorities, the airlines and the other 3rd parties. Thus, their coordination using well-defined communication and data sharing protocols and models is important. The added flexibility of the proposed baggage delivery creates opportunities to utilize assets, resources and the infrastructure more efficiently. However, the changes in baggage handling procedures also necessitate new service level definitions (e.g., on-time delivery guarantees and penalty for late delivery), new business models (e.g., new incentives, costs and infrastructure sharing strategies) as well as new supporting services (e.g., real-time anywhere baggage tracking, insurance of the luggage contents and of the agreed on-time delivery).

Dissociation of passenger travel and baggage delivery is likely to be implemented in several phases following the current IATA's phased approaches and roadmaps to significant upgrades of the AT infrastructures and procedures. For instance, Checkpoint of the Future program [3] defines the risk assessment and the required technology and operations for the three implementation phases to be completed by 2014, 2017 and 2020, respectively. The Fast Travel and Bags Ready-to-Go programs of the IATA [11] aim to improve the airport passenger throughput and capacity, especially by focusing to speed-up the baggage check-in processes. Hence, the proposed dissociated baggage delivery is highly relevant to these two programs. In particular, the home check-in is now widely adopted by the airlines and passengers, however, the innovations in the baggage check-in processes have not been considered until recently. Many airlines already have self-check-in kiosks allowing the passengers to print their own bag-tag in order to speed-up the baggage drop-off. Some airlines (e.g., KLM and Qantas) are subsidizing the programmable electronic bag-tags [12], [13], [14]. The electronic bag-tags are reusable, allow smartphone programming, and to some extent a real-time localization of the baggage. Other airlines (e.g., British Airways and Air France) are trialing the cost-effective home-printed bag-tags. These solutions lower operational costs, and provides new revenue incomes to the AT service providers.

The ICCT (Information, Communication and Computing Technologies) are the key enabler of these improvements by providing accurate and trusted information in real-time to wherever it is needed for the timely operational decision making. It is recognized that as much as 97% of the passengers are now traveling with their smartphones [2]. Particularly over the ground segments (to/from the airports), dissociation of passenger travel from baggage delivery is fundamentally dependent on real-time tracking of baggage location. This increases security, enables efficient management of the baggage flows (especially during the unplanned service disruptions), and creates the piece of mind for the passengers. The baggage tracking is likely to be realized as a multi-tier network of tracking devices:

- The low-cost RFID-type chips containing a newly introduced UUID (Universally Unique Identifier) [2] attached to luggage seek as well as can be queried by the nearby access points.
- The access points are aware of their location; they exploit GPS-type tracking when they are mobile (e.g., mounted on the baggage delivery vehicles). The portable (hand-held) access points can be used in case the manual baggage handling becomes necessary.
- The access points periodically report all baggage they have authenticated to the tracking center.

Furthermore, the IATA requires that the airlines track and record all baggage process steps (e.g., delivery, acquisition, transfer, handover, aircraft loading and unloading) since 2018.

4. Benefits and Future Trends

The proposed dissociation of passenger travel and baggage delivery contributes directly to the IATA InBag program which is concerned with the baggage processes across the industry [3]. The main objectives are to increase the airport throughput (especially at large busy airport hubs) and improve the passenger experience, and ultimately, baggage dissociation should be over the whole journey (door-to-door). The airport throughput is increased by simplifying and automating the processes and reducing their response times. In fact, the trend of automating the processes in AT is a strong driver supporting the proposed idea of baggage dissociation. The passenger experience is improved by making the services more reliable, more intuitive and more user-friendly while providing the passengers with more autonomy and control. Baggage dissociated from the passengers can be routed more directly to the destination which streamlines its delivery over the AT network. The airlines may collaborate to deliver all luggage several times a day on the dedicated cargo flights, for example, at least among the major airport hubs.

The airlines (the IATA) as well as the airports are likely to support delivery of baggage to and from the airports by the 3rd party forwarders. Such service could be integrated with the existing cargo and parcel AT delivery to exploit the existing infrastructure. This greatly simplifies the check-in process and fully avoids the baggage drop-off at the departure airport. The baggage-free passengers are then much more likely to use public transport to and from the airports, thus relieving the airport traffic congestion. The new baggage delivery is likely to differentiate among several service levels and fee options, for example, to manage delivery priorities. Furthermore, once the dissociated baggage delivery is fully implemented, one has to wonder whether the regulation would require that the passenger travel and their baggage is delivered from the same departure airport to the same destination airport, even though possibly at different times. If such requirement is not adopted, the baggage delivery service will be completely independent of passenger travel (who may well decide not to travel at all), and it will then resemble a courier or parcel delivery service.

The large busy airports now operate close to their capacity while the demand for AT is continuously increasing [2]. Hence, there is a need to completely reconsider the airport designs to reflect the growing demands, and to better accommodate the new regulations and processes as they are being introduced by the IATA [3]. For instance, the new airport design may have passenger-only and baggage-only terminals with the supporting infrastructure optimized accordingly.

Baggage dissociation is also likely to encourage new aircraft designs. The passenger-only aircraft are faster to load and unload, they can either accommodate more passengers, or provide more room for the passengers (i.e., contribute to the passenger experience), and at the same time, they are lighter, and thus faster and more fuel efficient. Such new aircraft designs represent multi-billion opportunities for the aircraft manufacturers such as Airbus and Boeing. Recently, Airbus filed several relevant patents on the new aircraft designs supporting these ideas [15], [16].

Independent baggage delivery can be aligned with the recent proposal on the Physical Internet [17]. The Physical Internet mimics the delivery of data packets by proposing to physically deliver things in the standardized containers. Hence, it is likely that future luggage will be standardized including the shape, size, materials, and accessories (e.g., the wheels and handles for easy moving, loading and storage). Such standardized luggage will have integrated sensors (location, temperature, acceleration) and the recording of the sensor outputs.

Moreover, many sensors will be deployed in the realization of the current IATA programs and visions. Such sensor networks can be considered to support the roll-out of the emerging Internet of Things (IoT).

We conclude that our study outlined in this paper indicates that dissociating passenger travel and baggage delivery is a promising step towards more sustainable future Air Transport.

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An Optimization Approach for Airport Ground Operations with A Shortest Path Algorithm

Orhan Eroglu, Zafer Altug Sayar
TUBITAK BILGEM, BTE
Smart Transport Systems, Senior Researcher
Kocaeli, Turkey
orhan.eroglu@tubitak.gov.tr, zafer.sayar@tubitak.gov.tr

Guray Yilmaz
Turkish Air Force Academy, ASTIN
Computer Engineering Department, Chair
Istanbul, Turkey
g.yilmaz@hho.edu.tr

***Abstract*—Tower and ground controls take significant role as much as arrival and transit traffic management on aeronautics. Both the safety of the vehicles and livings on the airport, and minimization requirement for flight costs with the help of optimizations on ground operations point out the importance of tower and ground controls. Especially the recent improvements on air transport have resulted in a drastic increase in air traffic intensity. As an inherent consequence of this progress, ground traffic volume must be diminished starting from modification on behaviors of air traffic controllers. Optimization of ground movements of vehicles by means of advanced algorithms is taken into consideration in this study.**

The study aims to compute the shortest paths for vehicles from apron or their current position to especially runway thresholds, taxi endpoints or any position and to report the results to controllers. Although such reports cannot be restrictive, those can be significantly usable decision support alternatives for controllers.

In order to implement the system under consideration, Floyd-Warshall shortest path algorithm has been utilized. This node-based algorithm has been chosen since the ground routings in an airport are performed by controllers using virtual node points defined on the taxiways. The system created with the help of this algorithm is named "Floyd-Warshall Ground Route Optimization System" (FLOW-GRO). In the FLOW-GRO system, the minimum taxi-time between each node in the airport is taken as the weight of that edge since the maximum taxi speed on each taxiway segment may vary. Algorithm is fed by a start and an end point as inputs, and returns a list of nodes as an output that represents the shortest way. The application of the FLOW-GRO System has been examined in a well-working Air Traffic Management Simulation System (ATCTRSIM) that has been developed by TUBITAK BILGEM.

As an inevitable conclusion of this study may be that, ground traffic controllers can be continuously helped with shortest path suggestions generated by a decision support system. Therefore, controllers may acquire a tendency to create vehicle routes in the shortest possible way in the long run, thanks to the system. A potential future phase of the study may be the evaluation of the routing performance of traffic controllers over the ground movements with the help of the system. In addition, conflict avoidance in a dynamic manner can be examined.

Keywords—Shortest path, Floyd Warshall, optimization, ground controllers, FLOW-GRO.

I. INTRODUCTION

In recent years, whole the world faces the increasing demand for air transport and respectively increasing air traffic loads. Air traffic is seen to going to be twice or three times the current density, in 2020's by authorities [1].

Tower control and ground traffic management include the traffic movements performed on the parking bays in airports, taxiways and runway thresholds, and on the runways throughout the takeoff. If the fact that, even the current load on the ground traffic significantly exhausts traffic controllers in tower control is taken into consideration; any increase in the ground traffic will lead the control and management of ground traffic to become more difficult.

Very initial ones of precautions in order to cope with tower control and ground traffic that get harder day by day, may be listed as revision and optimization of traffic control procedures and standards, improving monitoring abilities by development of new traffic surveillance and communication technologies, and hardening the practices of air traffic controllers. In addition, new decision support systems usable for controllers to manage ground traffic may be developed. Decision support systems are computer-based systems that basically suggest varying potentially useful directives for human operators or users before or during any decision [2].

One of the major handicaps about airports, which have high ground traffic load, is that route conflicts and routing delays may occur more often when taxiing of vehicles is not performed in the shortest possible way [3]. Therefore, a computer supported decision system that can continuously suggest the shortest route between a start and a destination position for the sake of managing taxiing operations on the airport may play a significant role on diminishing the ground traffic load.

In this study, a computer system is proposed, which is developed for the aim of generating the shortest path between two points during the taxi procedures of ground traffics. It is assumed that aprons, taxiways and lineup areas in airports all construct a graph structure including a number of nodes. Therefore, Floyd-Warshall shortest path algorithm [4] is utilized to form the shortest taxiway between any two points in such a graph. Implementing this algorithm, the FLOW-GRO system, which can act as a decision support system for the aim of generating the optimum taxiways, is created. The FLOW-GRO system has been examined and tested by tens of different taxi routings using the node-based taxiway graphs of a set of airports form Turkey, and results have been reported.

II. Floyd-Warshall Shortest Path Algorithm

The base of the Floyd-Warshall algorithm stands on a simple formulation, actually. If a graph consists of X, Y and Z nodes and the shortest distance between X and Z is depicted as min(distance(X,Z), then this distance is equal to the sum of the distance between X and Y (distance(X,Y)) and the distance between Y and Z (distance(Y,Z)). The algorithm is the systematic application of this process for the whole graph.

The pseudo-code of the Floyd-Warshall algorithm is shown in the **Fig. 1**. The algorithm takes advantage of two matrices: The D matrix includes the distances between each connected node-pair, and the S matrix includes the sequential relationship between nodes, i.e. it holds the last node before the terminal one, if it exists, in the shortest path between two nodes. The indices ***k*** stands for the current iteration number, ***i*** stand for the row number of the matrices and ***j*** stands for the column number of the matrices. The algorithm iterates one minus the number of nodes and updates the matrices in each iteration. At the end of all the iterations, there exist two matrices keeping the shortest distances and neighborhood information about all the nodes [5].

In order to make the description of the algorithm easier, a simple graph given in the **Fig. 2** is used to show iterations step by step. For example, the distance and sequentiality matrices are created. Since the distance matrix is composed of direct distance between nodes, the very first distance value between two nodes is taken as infinity if they are not directly connected. The sequentiality matrix is initially an empty matrix and its values are generated throughout iterations. However, the each value of columns for the shortest paths of a value in each row may be used for the initial values, i.e. it means a direct connection between any node-pair to exist. The initial case of the D and S matrices (D_0 and S_0) are shown in the **Fig. 3**

```
procedure [array] FloydWarshall(D, S)
for k in 1 to n do
for i in 1 to n do
for j in 1 to n do
if D[i][j] > D[i][k] + D[k][j] then
D[i][j] = D[i][k] + D[k][j]
S[i][j] = S[k][j]
Return S
```

Fig. 1 Floyd-Warshall Algorithm

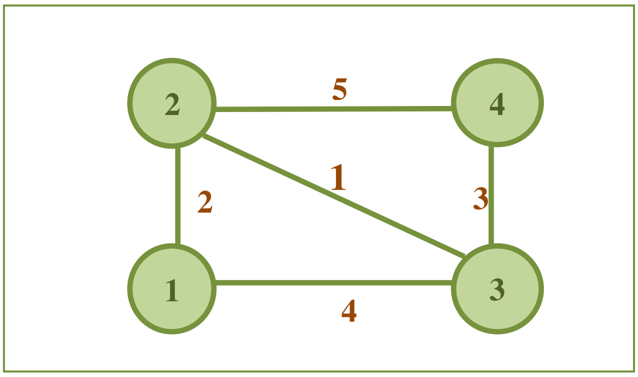

Fig. 2 A demonstration

D_0	1	2	3	4
1	-	2	4	∞
2	2	-	1	5
3	4	1	-	3
4	∞	5	3	-

S_0	1	2	3	4
1	-	2	3	4
2	1	-	3	4
3	1	2	-	4
4	1	2	3	-

Fig. 3 D_0 and S_0 matrices

The given pseudo-code of the algorithm simply means that, if the sum of new distances between i^{th} and j^{th} nodes when the k^{th} node is placed between them is smaller than the older distance, then the k^{th} node must be placed in the corresponding index in the S matrix the corresponding distance value in the D matrix must be updated with the new value.

The algorithm then iterates and generates D_1 and S_1 matrices (given in the **Fig. 4**) from D_0 and S_0 matrices, D_2 and S_2 matrices from D_1 and S_1 matrices, and eventually D_{n-1} and S_{n-1} matrices from D_{n-2} and S_{n-2} matrices. Basically, the procedure operates as follows: The iteration number ***k*** is also the index of the matrices (D_k and S_k) generated at the end of the iteration. In each iteration, the new values of D_k is obtained updating the D_{k-1} with respect to the node id in the index k. For instance, at the first iteration (***k*** = 1), values in the first row and the first column of D_0 matrix in the **Fig. 3** are used to update the other values in the matrix, respectively.

Sample runs of the pseudo code given in the **Fig. 1** and updates on the matrices are as follows:

<u>For k=1, i=2, j=3:</u>

If $D_0(2,3) > D_0(2,1) + D_0(1,3)$ then

$D_1(2,3) = D_0(2,1) + D_0(1,3)$

If the values in the D matrix are to be used:

Since $1 < 2 + 4$, then no update is performed.

<u>For k=1, i=3, j=4:</u>

If $D_0(3,4) > D_0(3,1) + D_0(1,4)$ then

$D_1(3,4) = D_0(3,1) + D_0(1,4)$

If the values in the D matrix are to be used:

Since $3 < 4 + \infty$, then no update is performed.

Matrices after the first iteration are given in the **Fig. 4**.

D_1	1	2	3	4
1	-	2	4	∞
2	2	-	1	5
3	4	1	-	3
4	∞	5	3	-

S_1	1	2	3	4
1	-	2	3	4
2	1	-	3	4
3	1	2	-	4
4	1	2	3	-

Fig. 4 D_1 and S_1 matrices

After the generation of D_1 and S_1 matrices, the next iteration starts. Since iteration index ***k=2***, matrix updates are to be performed on the indices excluding ***i=2*** and ***j=2***.

A sample run of the second iteration and updates on the matrices are as follows:

For k=2, i=1, j=3:

If $D_1(1,3) > D_1(1,2) + D_1(2,3)$ then

$D_2(1,3) = D_1(1,2) + D_1(2,3)$

If the values in the D matrix are to be used:

Since 4 > 2 + 1, then update is performed and

$D_2(1,3) = 2 + 1 = 3$, and

$D_2(3,1) = D_2(1,3)$ since the matrix is symmetric, and

$S_2(1,3) = S_2(3,1) = 2$ since the new fact is acquired that the shortest path between the 1^{st} and the 3^{rd} nodes contain the 2^{nd} node.

After performing all the updates of the iteration with the index ***k = 2***, the D and S matrices have a form as shown in the **Fig. 5**.

Similarly, ***k=3*** and ***k=4*** iterations finally create the eventual matrices given in the **Fig. 6**.

The shortest path between two nodes can be easily observed from the D_4 matrix in the final phase. Additionally, the S_4 matrix holds the sequence of the shortest path between two nodes. For example, the distance between the nodes 1 and 2 is equal to 2 as shown in D_4. In addition, the fact that $S_4(1,2)$ is equal to 2 and $S_4(2,1)$ is equal to 1 shows that the nodes 1 and 2 are directly connected.

As a counter example, the path between the nodes 1 and 4 can be considered. The total distance between two nodes is equal to 6, as shown in the matrix D. When the S matrix is regarded in addition, the fact that path between these two nodes points out the node 3 can be observed. The path is currently 1→3→4 and the sub-path between the nodes 1 and 3 must be concerned. If this process is continued through the step in which there exist no new node in the path, the shortest path between two nodes is found to be 1→2→3→4.

D_2	1	2	3	4
1	-	2	3	7
2	2	-	1	5
3	3	1	-	3
4	7	5	3	-

S_2	1	2	3	4
1	-	2	2	2
2	1	-	3	4
3	2	2	-	4
4	2	2	3	-

Fig. 5 D_2 and S_2 matrices

D_4	1	2	3	4
1	-	2	3	6
2	2	-	1	4
3	3	1	-	3
4	6	4	3	-

S_4	1	2	3	4
1	-	2	2	3
2	1	-	3	3
3	2	2	-	4
4	3	3	3	-

Fig. 6 D_4 and S_4 matrices

III. THE FLOW-GRO SYSTEM

The Floyd-Warshall algorithm offers a significantly favorable solution for optimization phenomena in airport ground operations since it works well on problem spaces including node-based graphs. Parking bays, taxiway segments, lineup areas and even runway points on airports can be represented by node points in order to construct the graph model of an airport [6], as shown in **Fig. 7** and **Fig. 8**. Line segments that connect these nodes form the whole taxiway of airports and these segments may be assumed to be edges in the graph model. Therefore, the modeled airport graph, which consists of nodes and edges, suggests a suitable model for Floyd-Warshall algorithm to be executed on.

Performing the Floyd-Warshall algorithm on an airport graph, finding the shortest taxiway between any two airport nodes is guaranteed mathematically. In order to acquire this functionality, The FLOW-GRO system, which can take any node-based airport data as input, has been developed.

The most interesting proposal of the FLOW-GRO system arises on deciding the edge weights. In general, Euclidean distance is the very first option to be used as edge weight since any two taxiway nodes have Euclidean distance between them. On the other hand, the Euclidean distance may be inappropriate in several cases in ground traffic management because taxiway speeds may vary. The main challenge stems from this variation and another parameter should be placed in order to be utilized as edge weight. Thus, the minimum taxiing-time of each edge, which can be calculated by dividing the edge distance by the maximum allowed taxi speed, is chosen for the edge weight.

Fig. 7 Airport graph model from TUBITAK ATM simulation

Fig. 8 Airport graph model of TUBITAK (Detailed view)

The FLOW-GRO system has been examined several times in the ATM simulation system that is developed by TUBITAK-BILGEM (The Scientific and Technological Research Council of Turkey – Informatics and Information Security Research Center). This simulation system includes 4 different airports in Turkey and each of them consists of hundreds of alternative, varying speed taxiways.

IV. CONCLUSION AND FUTURE WORK

The study do not cope with the hardest challenges, beside it proposes the usage of a well-known method for a common problem in air traffic management: optimization of taxiway routings. It is a simple application work of a node-based algorithm in a domain of more complex computational problems.

As an inevitable future work of this study, the ability of performing conflict avoidance dynamically should be given to the system. In addition to static computation of the shortest taxiways, the system may also determine whether conflict exists between different traffics dynamically, and it may also propose the next possible shortest path for the conflicting ground vehicles.

Another exciting potential of the FLOW-GRO system is that it can be exploited for the sake of evaluating the ability of traffic controllers to generate the most appropriate taxiing routes over the ground movements.

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Identification of a Cessna Citation X Aero-Propulsive Model in Climb Regime from Flight Tests

Georges Ghazi, Ruxandra M. Botez and Magdalena Tudor
École de Technologie Supérieure – University of Quebec
Laboratory of Applied Research in Active Controls, Avionics and AeroServoElasticity
Montreal, Quebec, Canada
http://www.larcase.etsmtl.ca / ruxandra.botez@etsmtl.ca

***Abstract*—During aircraft development, several mathematical models are created from our knowledge of fundamental physical laws. Those models are used in order to make decision at all development stages. In this paper, a methodology to design an aero-propulsive model for the Cessna Citation X in climb regime from flight test identification to model identification is presented. The aircraft's model was built by identifying a general aircraft mathematical model in climbing flight. A professional level D flight simulator was used as a flight test aircraft and a total of 70 flight tests were performed at different flight points within the aircraft flight envelope. The obtained aero-propulsive model was next interpolated to provide a performance database model within the whole aircraft flight envelope. Results showed that the proposed methodology gives an excellent estimation of the aircraft performance with a success rate of 100% for both identification and validation process.**

Keywords—Aero-Propulsive model; Cessna Citation X; Level D Flight Simulator; Flight Tests; System Identification

I. INTRODUCTION

Since 1980, the airplane has become the most common way to travel great distances. According to the Air Transport Action Group (ATAG) [1], in 2014, more than three billion passengers boarded an aircraft in order to travel somewhere on earth. Although this mobility has a beneficial impact on the global economy and international trade between countries [2], it partly contributes to global warming. According to the ATAG [3], in 2011, the airline operations were responsible of around 2% of carbon dioxide (CO_2) global emissions. Even if this percentage is still relatively low compared to other transports, the aerospace industry aims to reduce by 50% its carbon footprint in 2050 [1].

Over the last years, several researches and techniques have been elaborated in order to improve aircraft performances. According to Okamoto *et al.* in [4], a 20% reduction in airplane drag can reduce up to 18% on fuel consumption. Such drag reduction can be achieved through the implementation of winglets wingtip devices on current commercial aircraft [5, 6]. According to Boeing, this improvement led to increase the new Boeing 737 MAX fuel efficiency by 1.8%. Similarly, morphing wing technologies can be used to reduce the airplane drag, and thus reduce the fuel consumption. According to Gabor *et al.* in [7-9], a local modification of the aircraft wing shape could improve the aerodynamic characteristics of the wing in flight, and therefore reduce the airplane drag. Improving the engine efficiency is also an ongoing effort of engine manufacturers. For example, the new Airbus 320 NEO (New Engine Option) has been equipped with new CFM International Engines more powerful and *sharklets* (winglets). According to Airbus [5], these improvements will reduce the fuel consumption by 15% compared to a conventional Airbus A320. Biofuel also is a very promising alternative to reduce CO_2 emissions [10].

All these examples highlight the efforts provided by the aerospace industry to reduce its overall carbon footprint. However, althought these techniques are promising, they cannot be implemented on aircrafts that are currently in service. It is therefore of interest to find other alternatives. According to Jesen *et al.* in [11, 12], most of aircraft in the United State do not flight at their optimal trajectories. This is the reason why, these last years, the aerospace industry and several researchers have focused their studies on trajectories optimization [13-19]. By reducing both flight distance and flight time, trajectories optimization leads to reduce the fuel consumption, and so the CO_2 emissions.

Trajectory optimization in vertical or lateral profile is the main function of the Flight Management System (FMS) [20]. The FMS is an airborne device used by the pilot or the airline to predict the optimal trajectory that minimizes the flight cost expressed in terms of flight time and total fuel burned. To estimate the aircraft performances and compute the optimal trajectory, the FMS needs a mathematical representation of the aircraft [21, 22]. Such a representation can be obtained from a set of nonlinear equations also called Equations of Motion (EoM). For example, Ghazi and Botez in [23, 24] presented a full nonlinear model of the Cessna Citation X business aircraft that can be used to estimate and analyze the aircraft performance for any flight phase. However, because of limited processing capacity, a FMS cannot support an aircraft model based on EoM. It is therefore of interest to build another aircraft model, which is more adapted to the FMS' architecture.

Sibin *et al.* in [25] described a methodology to develop an aircraft performance model for the flight management system using data obtained from a flight simulator prototype. The obtained model provided good performance data such as aerodynamic forces or engine thrust, and can be therefore used to describe the aircraft behavior within its flight envelope. However, as some aircraft manufacturers are conservative to provide complete aero-propulsive data, having access to the aircraft data required to create such a model can be very difficult.

Murrieta *et al.* in [26] presented a methodology to create an aircraft Performance Database (PDB) using a Citation X Level D flight simulator. Based on several flight tests, the aircraft fuel flow was sampled during the cruise phase for different constant altitudes and speeds. The aircraft mass was also considered constant. The results were next prepared and formatted into lookup table in order to be used by an in-house algorithm that can predict the fuel burn during cruise. However, the methodology proposed by Murrieta et al. did not provide enough information about the aircraft aerodynamic parameters, which are usually necessary for aircraft performance analysis or for flight control system design purpose.

The main objective of this paper is to present a methodology for deriving an aero-propulsive model of the Cessna Citation X from flight tests that will allow to have a better estimation of the aircraft performance in climb regime. Such a model could be useful to support the researchers in order to validate their algorithms for trajectory optimization [21, 22, 27] and/or flight control system [28-31]. The flight tests were performed on a professional Cessna Citation X level D aircraft research flight simulator (see Fig. 1) designed and manufactured by CAE Inc. According to the Federal Aviation Administration (FAA, AC 120-40B), the level D is the highest certification level for the flight dynamics modeling.

This paper is organized as follows. In Section 2, the aero-propulsive performance model structure and the problem statement are presented. Section 3 deals with the methodology used to build the aero-propulsive model. Section 4 presents the results of a case study in which the methodology was applied to predict the aircraft performance of the Cessna Citation X during climb. Finally, the paper ends with conclusions and future work remarks.

II. Aero-Propulsive Model and Climb Trajectory Prediction

This section first introduces a description of an aero-propulsive model. Then, after a presentation of the different mathematical equations that define the aero-propulsive model, the algorithm used to predict the aircraft trajectory is shown.

Fig. 1. Level D Cessna Citation X Flight Simulator

A. Aero-Propulsive Mathematical Model

By definition, an aero-propulsive model is used to predict the force acting on an aircraft under specific flight conditions and for a given aircraft configuration. In general, an aero-propulsive model consists of two sub-models: one sub-model is used to predict the aerodynamic drag force, while the other is used to estimate the propulsive thrust force.

As illustrated in Fig. 2, an aero-propulsive model can be compared to a black box with multiple inputs and outputs. The choice of these inputs and outputs depends mainly on the study of interest. As show in many studies [17, 26], the main parameters that affect the aircraft behavior in climb regime are the gross weight, the center of gravity position, the altitude, the speed and the ISA (International Standard Atmosphere) temperature deviation, while the outputs of interest are usually the drag and engine thrust forces. Therefore, an aero-propulsive model can be represented in a more mathematical form by the following general equation:

$$\left[D, T, T_{sfc}\right] = \mathbf{f}\left(GW, X_{cg}, IAS, h, \Delta ISA\right) \tag{1}$$

where D is the drag force, T is the engine thrust force, T_{sfc} is the engine specific fuel consumption, GW is the gross weight, Xcg is the center of gravity position, IAS is the indicated airspeed, h is the altitude, ΔISA is the temperature deviation and $\mathbf{f}: \mathbb{R}^5 \longmapsto \mathbb{R}^3$ is the mathematical representation of the aircraft performance (i.e. the aero-propulsive model).

1) Aircraft Equations of Motion in Climbing Flight

The development of the aero-propulsive mathematical model starts with the kinetic equations of motion. Based on the Newton's second law, namely

$$\frac{W}{g}\mathbf{a} = \Sigma\mathbf{F} \tag{2}$$

where $\mathbf{\Sigma F}$ is net force applied to the aircraft and $\mathbf{a}$ is the aircraft acceleration relative to the inertial frame, the kinetic equations of motion for an aircraft in climbing flight can be written in the stability axes as follows:

$$\frac{W}{g}\left[\frac{dV}{dt}\right] = T - D - W\sin(\gamma) \tag{3}$$

$$\frac{W}{g}\left[\frac{d\gamma}{dt}\right]V = -L + W\cos(\gamma) \tag{4}$$

where, g is the acceleration due to gravity, V is the aircraft true airspeed and γ is the aircraft climb path angle.

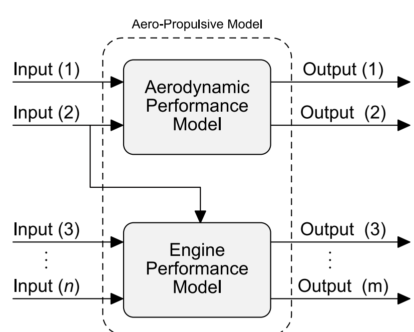

Fig. 2. Aircraft Aero-Propulsive Model Inputs and Outputs

Equations (3) and (4) have the advantage to describe the complete aircraft longitudinal motion. According to these equations, if the forces acting on the aircraft (i.e. lift, drag and thrust) are known, therefore the aircraft trajectory can be estimated. Conversely, if the aircraft trajectory is known, therefore the forces can be determined. In others words, using sampled data from flight tests for different flight conditions and aircraft configurations, a model for the forces can be identified. Then, using this same model, the aircraft trajectory in climb can then be predicted for any flight condition and aircraft configuration within the aircraft flight envelope.

2) Lift and Drag Forces Estimation

According to several references in aircraft flight mechanics [32-36], the two components of the aerodynamic forces L and D can be expressed with non-dimensional coefficients C_L and C_D such as:

$$D = qSC_D \tag{5}$$

$$L = qSC_L \tag{6}$$

where $q = 1/2\rho V^2$ is the dynamic pressure and S is the reference wing area. The lift force L can be easily obtained from Eq. (4) as follows:

$$L = W\cos(\gamma) - \frac{W}{g}\left[\frac{d\gamma}{dt}\right]V \tag{7}$$

Then, by combining Eq. (11) and Eq. (12), the lift coefficient C_L can be determined with the next equation:

$$C_L = \frac{1}{qS}\left(W\cos(\gamma) - \frac{W}{g}\left[\frac{d\gamma}{dt}\right]V\right) \tag{8}$$

Finally, based on the result in Eq. (8), the drag aerodynamic coefficient can be therefore estimated from the drag polar equation of a cambered wing [33, 35, 36], which states that:

$$C_D = CD_{min} + \frac{C_L^2}{\pi ARe\sqrt{1-M^2}} \tag{9}$$

where CD_{min} is the minimum drag coefficient, AR is the aircraft aspect ratio, e is the Oswald efficiency factor and M is the aircraft Mach number.

3) Engine Thrust and Specific Fuel Comsumption Estimation

Using the estimation of the drag force obtained in the previous section, the thrust force can be therefore determined from Eq. (3) such as:

$$T = \frac{W}{g}\left[\frac{dV}{dt}\right] + D + W\sin(\gamma) \tag{10}$$

Then, the engine specific fuel consumption coefficient T_{sfc} can be estimated from Eq. (11),

$$T_{sfc} = \frac{\dot{W}_f}{T} \tag{11}$$

where $\dot{W}_f$ is the engine fuel flow defined by:

$$\dot{W}_f = \frac{dFB}{dt} \tag{12}$$

and FB is the fuel burn.

This last equation concludes the aircraft aero-propulsive mathematical model. In the next section, the algorithm used to predict the aircraft climb trajectory is presented.

B. Climb Trajectory Prediction

To predict the aircraft trajectory, two parameters must be computed: the altitude and the horizontal distance. However, both parameters depend mainly on the rate of climb. Thus, it is first necessary to find a way to express the rate of climb.

Equation (3) is rearranged as follows:

$$\frac{T-D}{W} = \sin(\gamma) + \frac{1}{g}\left[\frac{dV}{dt}\right] \tag{13}$$

Then by noticing that:

$$\frac{dV}{dt} = \frac{dV}{dh}\frac{dh}{dt} \quad \text{and} \quad \frac{dh}{dt} = V\sin(\gamma) \tag{14}$$

and by replacing Eq. (14) into Eq. (13), the following Eq. (15) is obtained:

$$\frac{T-D}{W} = \left(1 + \frac{V}{g}\frac{dV}{dh}\right)\frac{\dot{h}}{V} \tag{15}$$

Finally, from Eq. (15), the rate of climb $\dot{\boldsymbol{h}}$ can be expressed as follows:

$$\dot{h} = \frac{\left(\frac{T-D}{W}\right)V}{(1+AF)} \tag{16}$$

where AF is the acceleration factor defined by:

$$AF = \frac{V}{g}\frac{dV}{dh} \tag{17}$$

The altitude h can be therefore obtained by integrating the result in Eq. (16). However, to performed numerical integration, the aircraft trajectory should be divided into N-1 sub-segments separated by $\Delta h = 1{,}000$ ft as shown in Fig. 3. Thus, for each sub-segment Δh, the drag and thrust forces are first computed using the identified aero-propulsive model. Then, based on these estimations, the average rate of climb for each sub-segment is estimated. Finally, the flight path angle γ is computed using the Eq. (14).

In parallel, the engine fuel flow is also estimated using the engine specific fuel consumption parameter (see Eq. (18)).

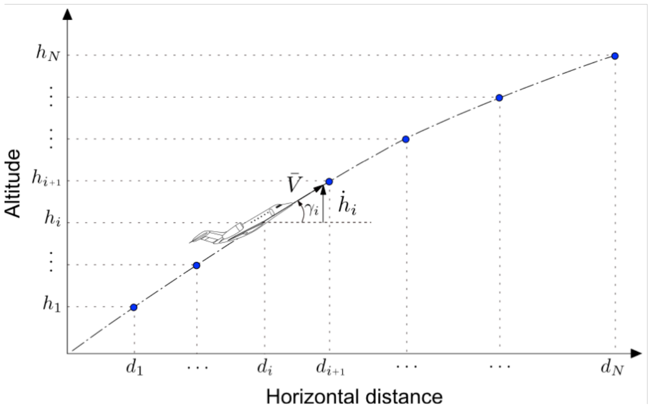

Fig. 3. Discritized Aircraft Trajectory

Equation (18) shows the complete procedure to estimate all the aircraft parameters for a given sub-segment,

$$(S) = \begin{cases} \dot{h}_i = \dfrac{\left[\dfrac{T_i - D_i}{W_i}\right] V_i}{1 + AF_i} \\ \gamma_i = \operatorname{asin}\left[\dfrac{\dot{h}_i}{\bar{V}}\right] \\ \overline{GS}_i = \bar{V}\cos(\gamma_i) \\ \dot{W}_{f_i} = T_i \times T_{sfc_i} \end{cases} \quad (18)$$

where $\overline{GS}_i$ is the average ground speed for a sub-segment defined by the altitudes h_i and h_{i+1}, $i \in [\![1, N]\!]$.

Finally, the aircraft horizontal distance *HD* traveled and the fuel burn *FB* were determined using an Euler integration method as follows:

$$HD_{i+1} = HD_i + \overline{GS}_i \Delta t_i \quad (19)$$

$$FB_{i+1} = FB_i + \dot{W}_{f_i} \Delta t_i \quad (20)$$

where Δt_i is the time to climb between two consecutive altitudes.

III. System Identification and Parameter Estimation Algorithm

According to Zadeh [37], "system identification is the determination, on the basis of observation of input and output, of a system within a specified class of system to which the system under test is equivalent". As shown in Fig. 4, system identification includes the model structure definition based on mathematical equations and the estimation of parameters defining the model.

Based on these observations, the proposed methodology to identify an aero-propulsive model from flight tests consists of two steps. In a first step, several flight tests have to be performed in order to sample the inputs and outputs required to describe the aircraft performance. Then, in a second step, a procedure that automatically tunes the parameters defining the model according to the study in ***Section II*** must be developed.

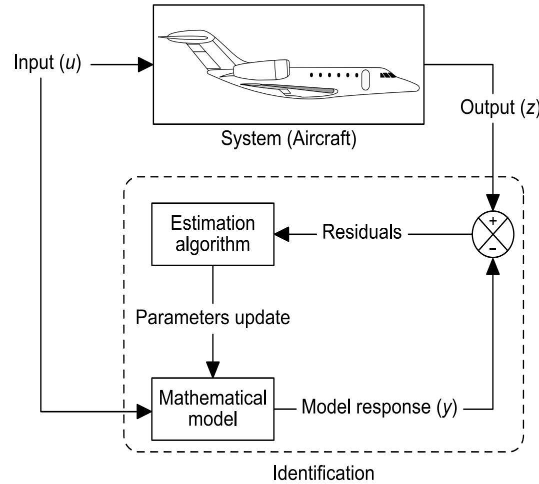

Fig. 4. System Identification Illustration

A. Flight tests Description

To estimate the aircraft performance for different flight conditions and aircraft configuration, 70 flight tests within the aircraft flight envelope were performed with the level D Cessna Citation X flight simulator. Each flight test was performed according to the procedure described in Fig. 5. It should be noted that all the 70 flight tests were not only used for the identification process. Indeed, flight tests were divided into two categories: identification and validation. The first category aimed to identify the aero-propulsive model, while the second category was used to validate the obtained model. However, to minimize the number of flight tests, the choice of the number of flight tests for the identification process should be done carefully.

As it can be seen in Fig. 5, the procedure consists in take-off with the aircraft following by a level-off at 1,000 ft. At this altitude, the test pilot prepares the aircraft configuration by retracting the landing gears, selecting the flaps position and maintaining the aircraf indicated airspeed. Then, once the gross weight is closed to the requiered value, a climb is performed. During the climb phase, the airspeed is maintained constant by controlling the aircraft pitch angle or by engaging the Flight Level Change (FLC) mode from the autopilot panel.

Once the flight test was done, the data recorded during the climb were exported from the flight simulator in the form of .csv files, so they can be used in Matlab® and formatted according to the structure shown in Table 1.

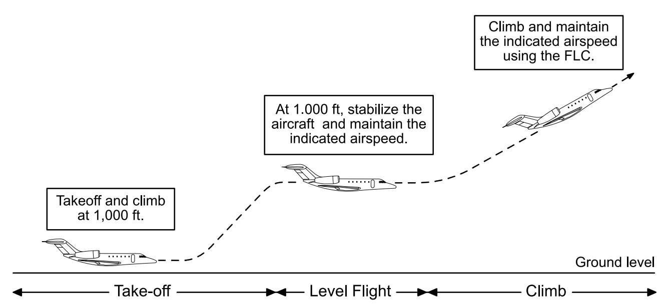

Fig. 5. Flight Test Procedure

TABLE I. SAMPLE CLIMB DATA

GW: 25,000 lbs || Xcg: 17% || ΔISA = 0		
Altitude (ft)	Fuel Burn (lbs)	Horizontal Distance (nm)
1,000	0	0
2,000	25.55	2.29
3,000	50.76	4.61
.	.	.
.	.	.
33,000	722.44	96.49
34,000	743.80	100.27
35,000	765.42	104.12

B. Parameter Estimation Algorithm

The aero-propulsive model is derived by determining a combination of thrust and drag forces that best estimates the rate of climb. Thus, for each sub-segment, the climb path angle, the rate of climb, the time to climb and the engine fuel flow were computed using Eqs. (21) to (24):

$$\gamma_i = \text{atan}\left(\frac{h_{i+1} - h_i}{d_{i+1} - d_i}\right) \tag{21}$$

$$\dot{h}_i = \bar{V} sin(\gamma_i) \tag{22}$$

$$\Delta t_i = \frac{h_{i+1} - h_i}{\dot{h}_i} \tag{23}$$

$$\dot{W}_{f_i} = \frac{FB_{i+1} - FB_i}{\Delta t_i} \tag{24}$$

where $\bar{V}$ is the average true airspeed along a sub-segment, Δt_i is the time to climb from h_i to h_{i+1} and $\dot{W}_{f_i}$ is the average engine fuel flow along the sub-segment. In the same way, the acceleration factor AF and the Mach number were also determined along each sub-segment. As all these values are computed directly using the sampled data in Table 1, they are assumed to represent the real state of the aircraft.

In parallel, using a first initialization for the minimum drag coefficient CD_{min} and the Oswald efficiency factor e, the drag and the thrust forces were calculated from Eqs. (5), (9) and (10). These results allow to find a first estimation of the rate of climb using Eq. (16). A minimization routine based on the Nelder-Mead algorithm [38] was next used to adjust the minimum drag coefficient, the Oswald efficiency factor and the thrust in order to minimize the error between the estimated rate of climb obtained with Eq. (16) and the rate of climb computed with Eq. (22). Then, the engine specific fuel consumption coefficient T_{sfc} was computed using the optimal thrust and rate of climb resulting from the minimization, and Eqs. (11) and (12) such as:

$$T_{sfc} = \frac{\dot{h}\, \Delta FB}{T \Delta h} \tag{25}$$

where ΔFB is the difference of fuel burn between two altitudes of a sub-segment.

The complete procedure of the estimation algorithm applied for one flight test (i.e. for one aircraft configuration) is shown in Fig. 6.

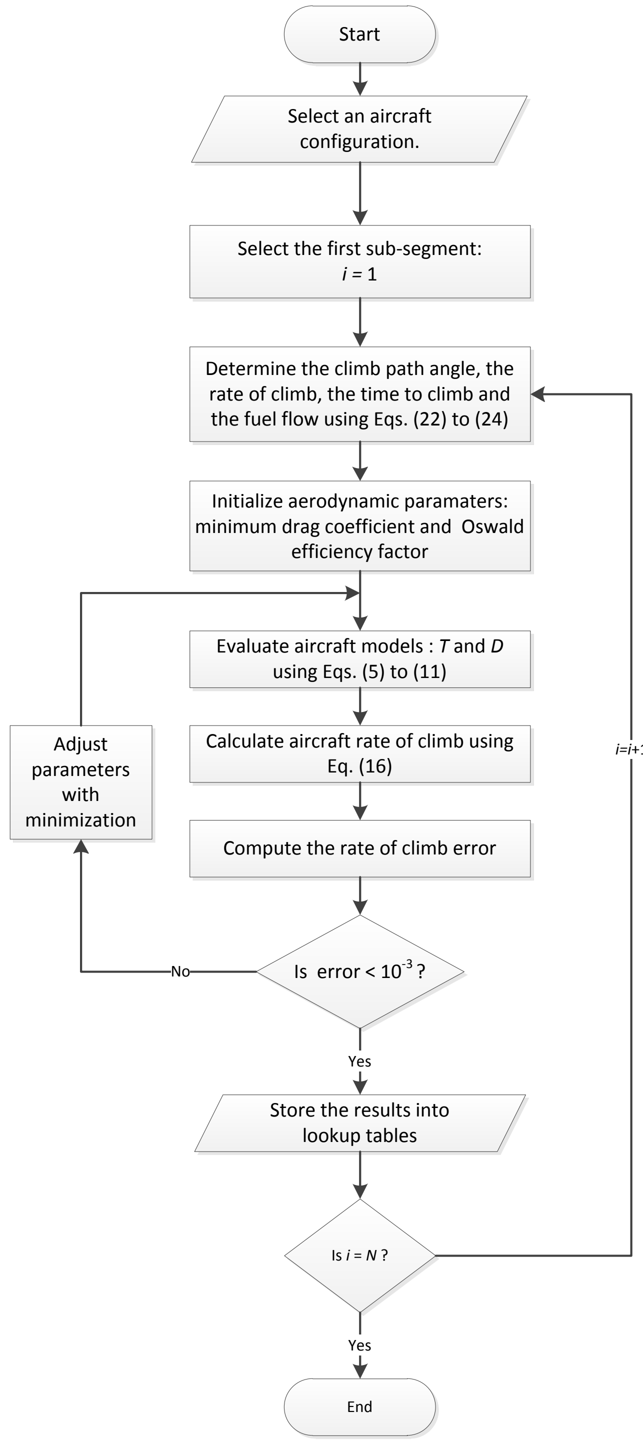

Fig. 6. Parameter Estimation Algorithm Procedure

The procedure shown in Fig. 6 was applied on 9 of the 70 flight tests performed with the level D simulator. For each flight test, the drag force *D*, the thrust force *T*, and the thrust specific fuel consumption coefficient T_{sfc} resulting from the minimization routine were stored and formatted into different 3-D lookup tables as shown in Fig.7,

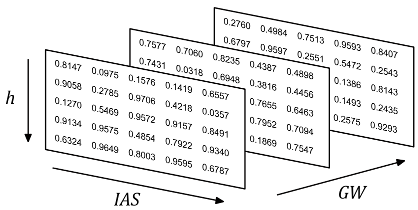

Fig. 7. 3-D Lookup Table Illustration

or in a more mathematically form as follows:

$$\begin{aligned} [D] &= f_{TD}(GW, IAS, h) \\ [T] &= f_T(GW, IAS, h) \\ [T_{sfc}] &= f_{sfc}(GW, IAS, h) \end{aligned} \qquad (26)$$

Finally, using a 3D linear interpolation, the three parameters defining the aero-propulsive model in Eq. (26) were interpolated in order to predict the aircraft trajectory for all the remaining 61 flight tests according to the procedure described in section ***Climb Trajectory Prediction***.

IV. Results

To validate the aero-propulsive model developed in this paper, 70 flight tests were performed using the level D Cessna Citation X flight simulator. Then, as mentioned in the section ***Flight Tests Description***, these flights were divided into two categories. Only 9 flight tests were selected for the identification process, while the remaining 61 flight tests were used to validate the obtained model within the Cessna Citation X flight envelope (see Table 2).

To conclude about the efficiency of the proposed methodology, each flight test was compared against the Level D flight simulator. To do that, the horizontal distance traveled and the fuel burn were first computed from data measured with the flight simulator. In parallel, the same flight test was evaluated using the aero-propulsive model and the procedure described in section ***Aircraft Trajectory Prediction***. The fuel burn and the horizontal distance traveled were next compared in order to conclude about the accuracy of the model. If the maximum error between the two models was less than 5%, then the flight test was considered as successfully identified or estimated. To illustrate the way in which each flight test was validated against experimental data, an example of three successful cases is given in Figures 8 and 9.

TABLE II. Flight Tests Envelope Limits

Parameter	***Min***	***Max***
Altitude	0 ft	35,000 ft
Speed (IAS)	140 kts	350 kts
Gross Weight	25,000 lbs	33,000 lbs
Xcg	17%	32%

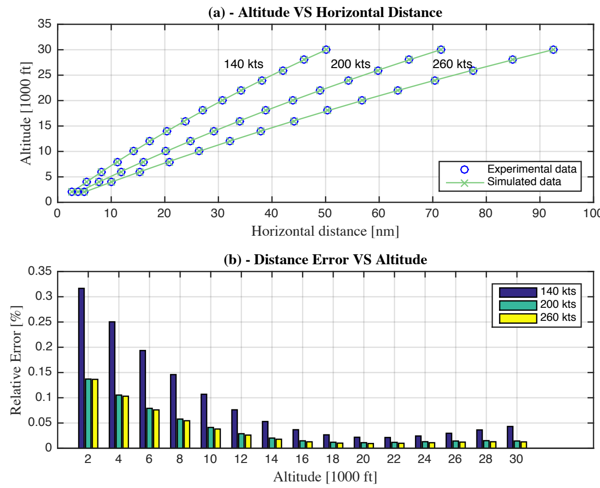

Fig. 8. Altitude and Horizontal Distance Estimations

Figure 8-(a) shows three comparisons between the aircraft vertical trajectory measured with the flight simulator and the aircraft trajectory estimated with the model. Fig, 8-(b) exposes the relative error for each trajectory. A positive error means that the model was climbing slower than the flight simulator. It is clear that the aero-propulsive model was able to find a solution that fits the experimental data. Indeed, as it can be seen, the error is at least equal to 0.35%. Moreover, it should be noticed that the error decrease considerably with the altitude. This can be explained by the fact that the more the aircraft climbs, the longer the travelled distance is. Therefore, the model error becomes neglected and the relative error decreases. Thus, as longer the aircrafts travels, the more accurate the model is.

In a general way, as shown in Fig. 9-(a), same observations can be made for the fuel burn estimation. As shown in Fig. 9-(b), the relative error between the experimental data and the predicted fuel burn is always less than 5%.

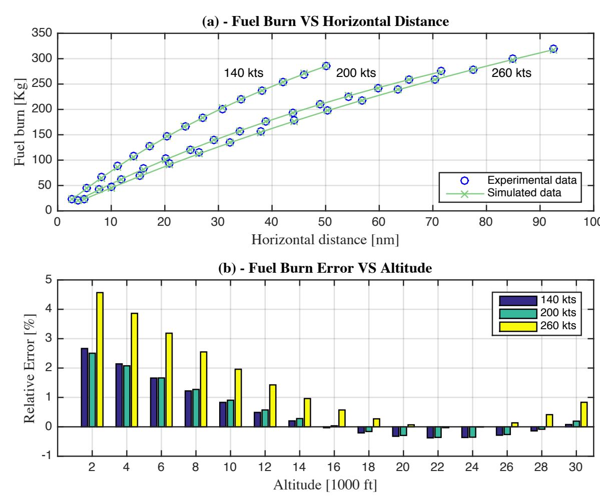

Fig. 9. Fuel Burn Estimation

TABLE III. SUCCESS RATIO AND NUMBER OF VALID FLIGHT TESTS

Flight Test Category	***Number of flight test***	***Performance***	***Success ratio***
Identification	9 (13%)	Horizontal Distance (*HD*)	100%
		Fuel Burn (*FB*)	100%
Validation	61 (87%)	Horizontal Distance (*HD*)	100%
		Fuel Burn (*FB*)	100%

The same analysis was repeated for all the 70 flight tests in order to validate the accuracy of the aero-propulsive model within the entire aircraft flight envelope. Table 3 shows the success ratio obtained and the number of flight test realized for both identification and validation processes. As it can be seen, the methodology gives an excellent estimation of the aircraft performance. Indeed, all the criteria imposed in this paper are satisfied with a success rate of 100% for each flight test category (identification and validation).

V. CONCLUSIONS AND FUTURES WORKS

In this paper, an aero-propulsive model for the Cessna Citation X in climbing flight was created using identification techniques from flight tests. A total of 70 flight tests were performed with a professional level D flight simulator designed and manufactured by CAE Inc., where the level D is the highest certification level for the flight dynamics modeling.

A complete mathematical model of the aircraft in climbing flight was presented, and an estimation algorithm was developed to identify the different parameters of the model. The identified parameters that compose the aero-propulsive model were next formatted into 3-D lookup tables in order to allow their interpolation within the whole Cessna Citation X flight envelope.

Results showed that the proposed methodology gave an excellent estimation of the aircraft performance with a success rate of 100% for both identification and validation process. Thus, it has been concluded that the aero-propulsive model created in this paper were experimentally validated.

ACKNOWLEDGMENT

This work was performed at the Laboratory of Applied Research in Active Controls, Avionics and AeroServo-Elasticity research (LARCASE). The Aircraft Research Flight Simulator was obtained by Dr Ruxandra Botez, Full Professor, thanks to the research grants that were approved by the Canadian Foundation of Innovation (CFI) and Ministère du Développement Économique, de l'Innovation et de l'Exportation (MDEIE) and the contribution of CAE Inc. Thanks are dues to CAE Inc. team and its leader Mr Ken Dustin, and to Mr. Oscar Carranza Moyao for their support in the development of the Aircraft Research Flight Simulator at the LARCASE laboratory. Special thanks are also dues to Mrs Odette Lacasse at ETS for her support in the research proposal. Thanks are dues also to the CMC Electronics-Esterline team, more specifically to Mr Reza Neshat and Mr Oussama Abdul-baki for their interest in this subject.

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Education and Training Needs for Aviation Engineers and Researchers in Europe

Karol GŐTZ
The Air Transport Department
University of Zilina
Žilina, Slovakia
gotz@fpedas.uniza.sk

Antonín KAZDA
The Air Transport Department
University of Zilina
Žilina, Slovakia
kazda@fpedas.uniza.sk

Benedikt BADÁNIK
The Air Transport Department
University of Zilina
Žilina, Slovakia
badanik@fpedas.uniza.sk

***Abstract*— Last years it is the air transport industry which took over aerospace and has the leading role. This is demonstrated by number of employees and created GDP. However, from a global perspective aviation in Europe is losing its position especially with respect to the Middle East and Asian companies. We should ask whether the existing support of air transport education and research is adequate and what should be done to change the situation.**

Keywords—education; training; needs; air transport; Europe

I. Background

How does the current air transport employee base around the Europe looks like? What is the average employee age? What are the skills needed at the present? Which skills and knowledge would be needed in seven to ten years? Answering these questions by industry can give academia outlines for their next decade development.

Within a frame of FP 7 European Project AirTN NextGen and the task 3.2 the University of Zilina aims to identify Air Transport Industry needs in the field of specialised aviation education. To bring academia and industry experts together the "Workshop on Education and Training Needs for Aviation" had been organized on 23 September 2015 in Brussels' Covent Garden. More than 40 experts from 24 European countries and from different areas of aviation industry and academia have registered and attended the workshop. Within them universities, airport operators, airline companies and last but not least maintenance organisations. The cooperation between universities and industry have been found crucial for past couple years in terms of identifying the educational needs for air transport. As the field of air transport is wide; indeed it is understandable that we should evaluate training and educational requirements by each group of stakeholders.

II. European Aviation Industry Situation

Accordingly to the Air Transport Action Group the European aerospace industry created 378 thousand jobs in 2012. On the other side airports, airlines, air traffic management there were circa 800 thousand employees in Europe in total.[1] If we include also 1.43 million jobs in group "other on airports" (e.g. catering companies, shops, aviation fuel suppliers, construction companies, travel agencies) the number of jobs in the European air transport industry exclude aerospace increases to circa 2.23 million jobs.

Table below shows breakdown of European aviation related job positions in thousands for year 2012.[1]

TABLE I. European Aviation Related Positions (in Thousands)

Airports	Other on-airport	Airlines	Aerospace	Air Traffic Management
156	1 430	576	378	64
6%	55%	22%	14.5%	2.5%

The following chart represents the trend in employment between years 2004 and 2012. It is clearly visible that employment rates are increasing and decreasing in areas of Airports, Aerospace and Airlines. On the other hand the area "Other on-airport" employment is increasing rapidly. Even though these jobs include also lower educated staff such as shopping assistants, these positions induce managerial positions and put increased load on for example security etc.

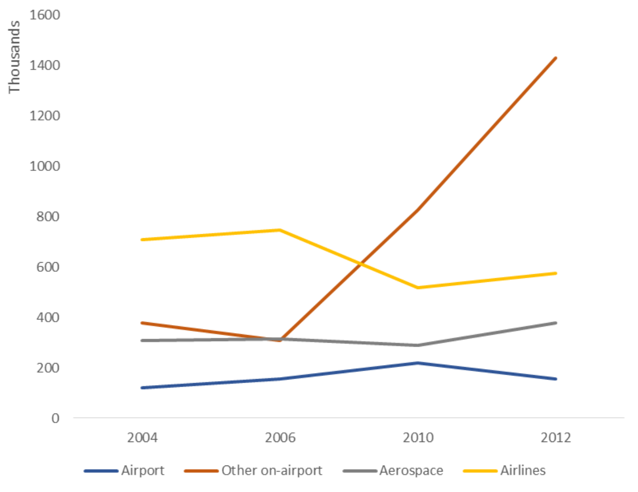

Fig. 1. European aviation employement trend [2]

The total GDP of the world aviation sector with direct economic impact in Europe reached $210 billion in 2012. In total air transport supports 11.7 million jobs and $860 billion in GDP in Europe- However, the latest study from 2012 does not include the breakdown of GDP for each sector.

The aerospace sector contributed almost one third of the total GDP in 2006 with almost the same number of employees as the other on-airport sector, which only contributed around 13% GDP. The GDP increased significantly in 2010 and 2014. This significant change is likely due to a new approach of what was included in the industry with direct economy impact; however, no detailed information is available.[3] The airlines made the greatest contribution to the economy, and if airports are also included, it is clear that the air transport sector is much bigger than the aerospace industry.

The following figure shows breakdown of GDP produced in Europe by each aviation sector in 2006.[4]

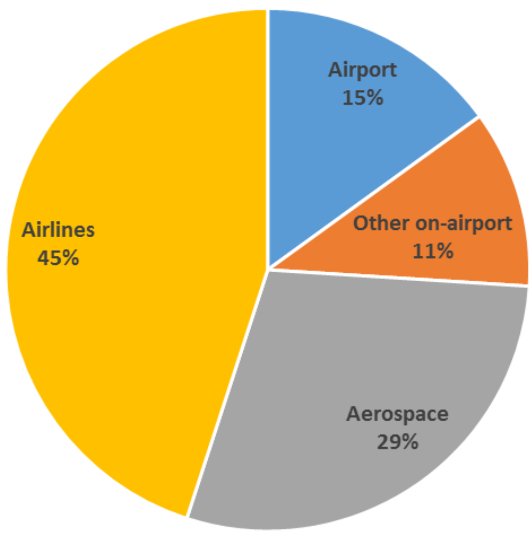

Fig. 2. European aviation GDP breakdown 2006

Compared to the aerospace the air transport in Europe is in terms of jobs growing annually three times faster. This approximation is based on data from a period between 2004 and 2012.[1][2][4] Air transport industry is therefore seeking for a new workforce; workforce composed of young, skilled and well educated people of both genders. In the present Europe is struggling with the lack of educated and trained professionals in different fields of air transportation.

Academia always reacted on the industry needs. Therefore the oldest aerospace courses could be traced back to 1910 but most of the air transport courses were opened after the WWII only as they responded to the fast growth of air transportation which boomed after 1950.

Thanks to the longer history and significant industry lobbing the European aviation research and education is today dominated by the aerospace. However, it doesn´t match the external conditions and air transport industry needs.

III. Industry Needs

A. *Aircraft Operators / Airlines*

According to the presentations of Workshop participants each sector of air transportation has different needs. To start with the aircraft operators, their requirements are different and dependent on the size and the business model. Airlines have different needs compared to business aviation. Each of these companies need both pilots and operational staff. But the educational requirements could be different. For example some of operators doubt if pilots need a university degree and prefer engage professionals without higher education to keep labour costs low.

According to MRO organisations it is also the case of technicians involved in heavy maintenance. However, business aviation companies are struggling with different needs. The world of business aviation is not the same as the world of large traditional airlines. Pilots working for business aviation have to be highly reliable professionals but on the other hand also educated and good managers and to have good communication skills.

The same requirements of higher education apply also for another aircraft operator employees involved in the administrative, planning or management processes. The current need is to have a flexible staff with knowledge of air transport and language. Accordingly to Workshop participants, a good knowledge of project management, general knowledge of air transport and standard working level of foreign language provide robust background for a candidate. Therefore main task for academia is to provide such a package.

To address these requirements a complex education and training model known as iPOP™ could be used. The model includes education, motivation and training from “a cradle to a grave” in line with the industry needs.[5] There must exist a continual support of the employee life-long development to ensure following: retain existing employees; promote existing employees; establish future employee pipeline; “to build” the future employee; recruit and retain future employee; to get new skills and certifications. Communication and cooperation between academia and industry is therefore critical for success in all these areas.

B. *Heavy Maintenance / MRO*

Compared to the aircraft operators, Maintenance and Repair Organisations (MRO) have slightly different employees structure therefore requirements and needs. Current practice is that some of MRO companies are moving from the "old" European states to the Central or Eastern Europe to cut down labour costs. Needless to say such changes cannot jeopardise the air transport safety levels.

Advantage of the Central and Eastern Europe lies in skilled workforce and good craftsmanship. Technicians do not need to have a university degree, but the leading staff do. The leading personnel should have mechanical engineering background to understand the technology which backdates in decades; followed by learning the leadership skills in combination with project management to effectively control scarce resources of the MRO company. The common training and educational need for MRO and aircraft operators/airlines are the management skills of a candidate and a good level of aviation knowledge in combination with language.

C. *Airport*

Large airports are often perceived as small cities. Each organisation or company based around or at the airport have different requirements on employees. Staff majority working at the airport do not need higher education to deliver their work right. But airport operations cover also high number of staff which needs university degree. The reason is not certainly a requirement to have a title; but be educated, trained and skilled in certain area of the air transport.

Accordingly to industry experience, the graduates do not have all skills needed by the industry, in particular communication and negotiation competences and leadership skills

There is also an emerging need to unify training courses for specific positions of handling staff to increase mobility of skilled personnel. These airport employees do not need university degree, but their knowledge and skills need to be gained and trained. To date there are no certification courses in Europe for such positions as air-bridge operator, tug vehicle driver, de-icing trucks operators, fire-fighters etc. These positions require staff with appropriate knowledge, but each airport or handling agency must to train their workers accordingly. Courses providing certification for highly specialized positions could support employees in their career when changing positions and also decrease handling agencies training costs. These advantages are emerging especially in today's deregulated market environment.

D. *Air Traffic Management*

The area of Air Traffic Management covers a wide range of organisations and companies; starts with ANSPs, going thru State Regulators and finishes by consulting companies. Accordingly to the Eurocontrol experience the way forward lies in close cooperation between academia and the industry. This cooperation can feed industry by motivated students. These students are often relieved of the corporate uniformity and therefore more likely bringing new ideas into the fusty corporate environment.

Basic knowledge and skills needed are fluent English so all employees can communicate together and analytical and critical thinking, which supports robust decisions and conclusions; and last but not least the computer literacy though employees are able to work with IT technologies on a required level and reasonable speed. Important skills to be taught and trained are also presentation and communication skills. Communication skills are often supported by analytical and critical thinking.

IV. MISSING SKILLS ORIGINS AND PREDICTED SHORTAGE OF STAFF

A. *Absence of leadership skills*

"If companies think their junior staff lack leadership skills, maybe the real problem is a lack of visible role models within the company." For 30 years Roy Franklin ran what became San Juan (community) airlines, without a single fatality or serious injury, despite appalling island winter weather and hazardous fire-fighting mountain flights. The passengers who were often his neighbours were entrusting their lives to the sound-judgement of the pilot. Roy earned this respect by placing passenger safety first when deciding when to fly and on occasion, by knowingly placing his own life in danger to fly a seriously ill patient to the regional hospital during appalling weather.[7] Roy's background was as a Naval Pilot, where rapid decision-making required extensive pre-flight scenario-thinking. Roy's mental fly-the-flight BEFORE physically making the flight, along with a post flight debrief approach passed on valuable expertise to other less experienced pilots. Roy didn't talk about leadership, he lived it and provided a visible example to enable younger pilots to model themselves on.

B. *Are so individualist that they are unable to work in teams*

If the airline industry is stating that they would prefer staff candidates who have a more holistic view of their position within the company and society in general, the future may involve making staff selection decisions using a decision-weighting based more on staff attitude and being less fixated on best-in-class technical aptitude. Professor Geert Hofstede viewed individualism as one component in the dimensions of national culture. Hofstede defined individualism as having a preference for "a loosely-knit social framework in which individuals are expected to take care of only themselves and their immediate families. Its opposite, collectivism, represents a preference for a tightly-knit framework in society in which individuals can expect their relatives or members of a particular in-group to look after them in exchange for unquestioning loyalty".[8]

C. *Absence of theory-based feedback loop after practical experience (absence of introspection)*

By focusing on the commercial pilot market and only taking on students who are willing to simultaneously pursue an aviation management degree on-site, Airline Training solutions are delivering a more rounded graduate, one who better comprehends the chain of factors involved in safe decision-making. Hayden Malone of Airline Training solutions (Jacksonville, Florida) has shown that even small-scale training schools can enhance the theory-practice feedback loop in pilot education by linking up with globally-accredited third level education organizations such as Embry-Riddle Aeronautical University.[9]

D. *Predicted future staff shortages*

Is there really an emerging shortage of pilots ?...or is there growing evidence of a flawed training system failing to deliver the quantities of graduating pilots which the industry requires ? An 83% dropout rate for student pilots is evidence that something is seriously wrong.[10] Perhaps the weakness is in the absence of a marketing budget which would enable the flight school to charge more profitable fee rates, which in turn would enable them to hire and retain only those instructors whose students don't drop out at alarming rates. Flight training schools should market themselves based on their graduation rates and subsequent graduate employment rates instead of merely matching the cheapest flight rate per hour in the region.

V. Conclusions

Further discussion between academia and industry could be recommended to understand better each other and to fit student´s profile to industry needs.

The Air Transport Department (ATD) of the University of Zilina has already started a research aimed at better understanding of the air transport industry needs. The research is based on The Survey on Quality of Aviation University Courses in Europe and The Survey on Aviation Students' Internships and its Status in Europe.

The Survey on Quality of Aviation University Courses in Europe evaluates the aviation university courses against the needs of the aviation industry. Outcomes of the survey will be used to redesign the academic courses so that more students are attracted to aviation; so that graduates are more easily dovetailed into aviation related careers and so that the academic institutions can strengthen their role in meeting the global aviation challenges.

The Survey on Aviation Students' Internships and its Status in Europe evaluates internship placements and compares requirements on students, aviation companies and legislative statuses within different member states' participants. Outcomes of the survey will be used to redesign the internship requirements so that more students are supported in their aviation courses and future careers; so that graduates are more easily dovetailed into aviation related careers and so that the academic institutions can strengthen their role in meeting the global aviation challenges.

Accordingly to the majority of experts the cooperation between the air transport industry and academia is of the highest importance. Industry-academia alliance can give an answer to the question from the beginning: "Which skills and knowledge would be needed in seven to ten years?" However, not all needs could be fulfilled by accredited courses because of the "big moment of inertia" and long time needed for changes.

The following figure represents the ideal flow of education, theory and industry needs within all sides involved.

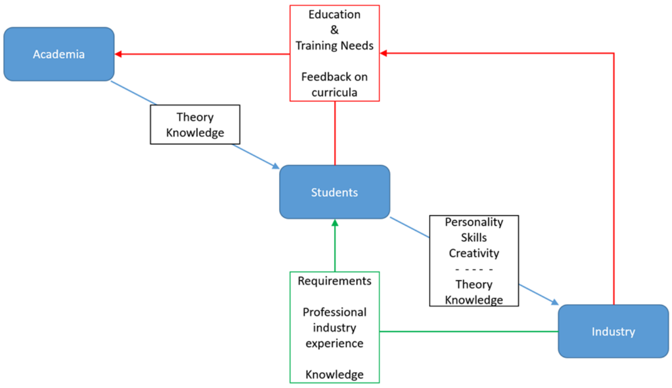

Fig. 3. Optimal knowledge flow within aviation network

It is doubtful if the High-Level Target Concepts defined in ACARE SRA2 could be reached by improvements in technologies. For example jet engines are at the top of the technology cycle and in energy efficiency, and environmental impact technology allows only small improvements. On the other hand we can cut down fuel consumption, flight times and emissions in tens of percent by operational and flight procedures. However, from a global perspective aviation in Europe is losing its position and we should ask whether the existing support of air transport education and research is adequate and if it should get more attention and resources.

Many times the graduates do not have all skills needed by the industry, in particular communication and negotiation competences and leadership. Followed by theoretical knowledge, computer literacy or project management skills etc.

At present the way forward therefore could lie in gradual increase of cooperation between academia and industry. Students - interns who cooperate on different basis with the industry can bring valuable information to academia; while on the other hand also appreciated new concepts and knowledge to the industry.

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IS ECONOMY OF SCALE IN AIR NAVIGATION SERVICES PROVISION REALLY ALWAYS THE BEST CHOICE?

Andrej Grebenšek, Ph.D.
University of Ljubljana
Faculty of Mechanical Engineering
Ljubljana, Slovenia
grebensek.andrej@gmail.com

Tadej Kosel, Ph.D.
University of Ljubljana
Faculty of Mechanical Engineering
Ljubljana, Slovenia
tadej.kosel@fs.uni-lj.si

***Abstract** – Professional and general public believes that the effective provision of air navigation services is most easily achieved by the economy of scale. Similar consideration is also supported by various air transport associations. In order to test the feasibility of the economy of scale in real life a simulation and analysis of the response to the forecasted change in air traffic volumes and consequently the income of the selection of air navigation services providers in Europe has been done. Results show that in these particular cases, potential integration of providers into one larger "virtual" service provider, in order to achieve economies of scale, did not automatically result in the business optimization.*

Driven by the results of the simulation obtained, second part of the paper focuses on potential areas of optimization and provides an overview of suggestions on what can be done outside of the scope of the economy of scale and can potentially indeed lead to short-term or even long-term optimization of the business.

***Key words** – Air Traffic Management, Air Navigation Services provision, economy of scale, efficiency.*

I. INTRODUCTION

Professional and general public usually believes that the effective provision of air navigation services can easily be achieved by the economy of scale. Similar consideration is also supported by various air transport associations, IATA (International Air Transport Association), AEA (Association of European Airlines) and ERA (Association of European Regional Airlines), which in their proposal titled "A Blueprint for the Single European Sky " [1] carried out a comparison of European air navigation service providers to an American air navigation services provider, the FAA. Key figures for comparison are collected in Table 1.

***Table 1** - Key figures for comparison EU to USA* [1]

	EU	USA
Surface	11,5 million km^2	10,4 million km^2
Airports	450	509
ANSPs	38	1
En-route centres	63	20
Traffic	9,5 million	15,9 million
Non-ATCO staff	40.300	20.600
Air Traffic Controllers	16.700	14.600
Controlled flight hours	13,8 million	23,4 million

Key figures show that the US air traffic management (ATM) system is capable of processing about 67% more operations with approximately 38% fewer staff. This is to be, according to the authors of the above mentioned comparison, attributed to the fragmentation of European services, as in Europe, currently 63 area control centres operate, whereas in the United States only 20. They also estimate that a reduction in the number of regional air traffic control centres from 63 to 20 would provide huge additional investment in technical solutions and mobility of the workforce, which probably would not make sense, therefore they propose that the European air traffic management system is organized in a way that it would be able to process twice the amount of flight operations (20 million) with only 40 regional air traffic control centres and the same amount of air traffic controllers (16,700) and considerably smaller number of additional staff (26,720). In this way, the following objectives could be achieved:

- 20 million operations per year;
- The accuracy of landings within one minute;
- A reduction in average duration of flight of 10 minutes;
- An annual reduction in costs due to the inefficiencies of the system by €3 billion;
- Savings of €6 billion due to better flight efficiency;
- Annual saving of 18 million tons of CO_2 emissions;
- Additional €419 billion in gross domestic product between 2013 and 2030.

All the above is the perfect story for political pressure on European air navigation services providers, but no one so far provided any valid suggestion on how all this could be implemented in practical terms or whether it is at all feasible.

United States have many advantages over Europe in particular in the following:

- They are one, homogeneous nation, with one language, one law and with minimal influence of cultural heterogeneity;
- Air navigation services are provided by a monopolistic organization in the public sector, more specifically as a part of the state administration;
- Provision of air navigation services is not excluded from the state, as is the case in the European Union;
- Air traffic management is uniform, with uniform standards since its beginning;
- Air navigation services provision is not separated from the oversight function of these services (both functions are carried out by the same government institutions);
- The content and the methodology of air traffic controllers, pilots and other aviation personnel training throughout the territory is uniform, so they consequently all think and react in the same way;
- Financing is still carried out according to the principle of full cost recovery and not according to the principle of risk-sharing, as in the case of the European Union, where air navigation services providers bear a share of burden of financial loss in the event of decrease in air traffic;
- Safety standards are more loose, and consequently significantly more responsibility for the safe conduct of operations is delegated to the pilots;
- Tolerance to the different business solutions is significantly higher - e.g. equal treatment of small private aircraft and aircraft of the biggest airlines at major international airports;
- They have one army, military flying on the entire territory is unified, also rules of the game related to mutual sharing of the airspace are unified;
- Technical and technological solutions are uniformly determined and supported through one government, on the other hand evaluation of these solutions and approvals are done by only one supervisory authority.

Europe is in all the above-mentioned significantly more chaotic and will probably need several generations to be able to set the same starting point as the United States.

In order to test the feasibility of the economy of scale in real life, a simulation and analysis of the response to the forecasted change in air traffic volumes and consequently the income of the selection of air navigation services providers in Europe has been done. Although the air navigation services providers in this study are de-identified, the data for calculation are taken from their respective real-time Performance plans [2]. For the purpose of this study data form Reference Period 1 (RP-1) has been taken as the period has just been concluded and the facts and figures can be scrutinized. Data for the current Reference Period 2 (RP-2) [3] are still at the level of estimates only. On the other hand, for the purpose of this study the only significant difference in the two mentioned reference periods is in the cost recovery principle, which in RP-2 will have even more negative effect on the air navigation services providers in case of negative business result.

II. JOINT OPERATIONS BUSINESS RESULTS

Analysis of potential in the economy of scale was done based on the assumption that Functional Airspace Blocks (FABs) are by default more efficient since they provide a potential for joint service provision over a larger territory with a greater amount of traffic. For that purpose, based on the data provided, simulation of integration (joint service provision) with the following scenarios has been done:

- One big and one small air navigation services provider;
- Two small air navigation services providers and;
- Five air navigation providers of the mixed size.

As a starting point the data on forecasted traffic and determined unit rates were collected from the respective Performance Plans of the Member States of the European Union, which were in 2012 submitted to the European Commission [4]. As a second step forecasted corrections in traffic volumes were taken from European Organization for the safety of air navigation (EUROCONTROL) available data [5]. Virtual unit rate used in calculations represents the statistical average value depending on the proportion of the costs of the individual service provider in the amount of total determined costs of the virtual service provider. This unit rate which in practical terms represents the common unit rate for a virtual service provider, providing joint air navigation services provision was calculated with the help of the following formula:

$$\overline{UR} = \frac{\sum_1^n UR*SU}{\sum_1^n SU} \quad (1)$$

Where:

- $\overline{UR}$ is common unit rate;
- UR is respective unit rate of a single air navigation services provider;
- SU is amount of forecasted service units (traffic);
- n is number of air navigation services providers.

As a first example one big (Provider A) and one small (Provider B) neighbouring air navigation services provider were grouped into the Virtual operator 1, which in practice would make quite logical and expected connection in particular due to the fact that they operate with similar unit rates. Results are presented in Table 2.

Results show that such merger does not make much sense, especially in case if the bigger air navigation services provider ends up in loos. In this case a smaller service provider subsidizes the bigger one, in addition, it appears that the final business outcome of joint operations of the service providers is even slightly worse than the sum of the results of both individual providers.

In the same way a simulation for the Virtual provider 2 was carried out, where two smaller providers were joined (Provider B and Provider C). Such combination would be logical and easily anticipated by the experts and general public. Results are presented in Table 3.

Table 2 *- Comparison of business result of Virtual provider 1*

Year	2012	2013	2014
Virtual provider 1			
Planned SU	3.146.792	3.255.730	3.420.976
Determined cost (income)	204.094.863,00 €	207.426.312,00 €	205.687.132,00 €
$\overline{UR}$	64,86 €	63,71 €	60,13 €
SU correction, sept.2012	2.923.000	2.974.000	3.076.000
Difference in SU	-223.792	-281.730	-344.976
Actual income	189.580.145,29 €	189.476.968,88 €	184.945.354,20 €
Profit/loss	**-14.514.717,71 €**	**-17.949.343,12 €**	**-20.741.777,80 €**
Provider A			
Planned SU	2.720.000	2.814.000	2.947.000
Determined cost (income)	175.389.738,00 €	178.548.762,00 €	177.105.559,00 €
UR	64,48 €	63,45 €	60,10 €
SU correction, sept.2012	2.486.000	2.518.000	2.604.000
Difference in SU	-234.000	-296.000	-343.000
Actual income	160.297.280,00 €	159.767.100,00 €	156.500.400,00 €
Profit/loss	-15.088.320,00 €	-18.781.200,00 €	-20.614.300,00 €
Provider B			
Planned SU	426.792	441.730	473.976
Determined cost (income)	28.705.125,00 €	28.877.550,00 €	28.581.573,00 €
UR	67,26 €	65,37 €	60,30 €
SU correction, sept.2012	437.000	456.000	472.000
Difference in SU	10.208	14.270	-1.976
Actual income	29.392.620,00 €	29.808.720,00 €	28.461.600,00 €
Profit/loss	686.590,08 €	932.829,90 €	-119.152,80 €
Cumulative profit/loss	**-14.401.729,92 €**	**-17.848.370,10 €**	**-20.733.452,80 €**

***Table 3** - Comparison of business result of Virtual provider 2*

Year	2012	2013	2014
	Virtual provider 2		
Planned SU	1.367.592	1.419.230	1.491.676
Determined cost (income)	81.870.072,00 €	83.083.097,00 €	82.639.385,00 €
$\overline{UR}$	59,86 €	58,54 €	55,40 €
SU correction, sept.2012	1.378.000	1.432.000	1.496.000
Difference in SU	10.408	12.770	4.324
Actual income	82.493.140,66 €	83.830.665,15 €	82.878.936,15 €
Profit/loss	**623.068,66 €**	**747.568,15 €**	**239.551,15 €**
	Provider C		
Planned SU	940.800	977.500	1.017.700
Determined cost (income)	53.164.947,00 €	54.205.547,00 €	54.057.812,00 €
UR	56,51 €	55,45 €	53,12 €
SU correction, sept.2012	941.000	976.000	1.024.000
Difference in SU	200	-1.500	6.300
Actual income	53.175.910,00 €	54.119.200,00 €	54.394.880,00 €
Profit/loss	11.302,00 €	-83.175,00 €	334.656,00 €
	Provider B		
Planned SU	426.792	441.730	473.976
Determined cost (income)	28.705.125,00 €	28.877.550,00 €	28.581.573,00 €
UR	67,26 €	65,37 €	60,30 €
SU correction, sept.2012	437.000	456.000	472.000
Difference in SU	10.208	14.270	-1.976
Actual income	29.392.620,00 €	29.808.720,00 €	28.461.600,00 €
Profit/loss	686.590,08 €	932.829,90 €	-119.152,80 €
Cumulative profit/loss	**697.892,08 €**	**849.654,90 €**	**215.503,20 €**

Also in this case results show that joint operations through the economy of scale do not bring any special improvement in profit or loss, and that obviously the main room for the improvement of business outcome lies elsewhere.

Joining the service provision does not lead to remarkable reduction of operating costs by default. Both service providers should almost certainly retain all air traffic controllers and other operational personnel. They must also retain all the technical resources with all the associated on going operating costs, maintenance and depreciation. Quick savings could only be achieved by the reduction of administration personnel (duplicate management functions), which would in most cases be less than ten persons or much less than 1% of total estimated costs. This would only be a single (one time) measure which would only have the effect in the first year of operations.

As the last simulation a combination of five service providers (for two of them data was not available since they are/were not members of the European Union and they were not obliged to deliver the Performance plan) was carried out. Results are presented in Table 4.

Results show that despite of the fact that in theory such collaboration or integration, promises a number of advantages, for the majority of air navigation services providers it is not supportive and they will therefore probably resist it in every possible way.

In this case, the clear winner is the biggest Provider A, which at the expense of the other air navigation services providers almost halved its planned loss. Biggest losers of such integration are the two smallest air navigation services providers, Provider B and Provider C, which instead of having profit, ended up in loss. Such philosophy of integration is therefore by default not logical and implies further pressure and potential unfair burden on small air navigation services providers.

Table 4 - Comparison of business result of FAB Virtual provider

	Year	2012	2013	2014
Provider A	**Autonomous**			
	Planned SU	2720000	2814000	2947000
	Determined cost (income)	175.389.738,00 €	178.548.762,00 €	177.105.559,00 €
	UR	64,48 €	63,45 €	60,10 €
	SU correction, sept.2012	2486000	2518000	2604000
	Difference in SU	-234000	-296000	-343000
	Actual income	160.297.280,00 €	159.767.100,00 €	156.500.400,00 €
	Profit/loss	**-15.088.320,00 €**	**-18.781.200,00 €**	**-20.614.300,00 €**
	As part of FAB			
	$\overline{UR}$	51,11 €	50,70 €	48,84 €
	Share of costs in FAB	40,08%	39,98%	39,74%
	Actual income	168.444.569,49 €	169.087.446,66 €	168.112.896,99 €
	Profit/loss	**-6.945.168,51 €**	**-9.461.315,34 €**	**-8.992.662,01 €**
Provider B	**Autonomous**			
	Planned SU	426792	441730	473976
	Determined cost (income)	28.705.125,00 €	28.877.550,00 €	28.581.573,00 €
	UR	67,26 €	65,37 €	60,30 €
	SU correction, sept.2012	437000	456000	472000
	Difference in SU	10208	14270	-1976
	Actual income	29.392.620,00 €	29.808.720,00 €	28.461.600,00 €
	Profit/loss	**686.590,08 €**	**932.829,90 €**	**-119.152,80 €**
	As part of FAB			
	$\overline{UR}$	51,11 €	50,70 €	48,84 €
	Share of costs in FAB	6,56%	6,47%	6,41%
	Actual income	27.568.445,44 €	27.347.325,97 €	27.130.323,09 €
	Profit/loss	**-1.136.679,56 €**	**-1.530.224,03 €**	**-1.451.249,91 €**
Provider C	Autonomous			
	Planned SU	940800	977500	1017700
	Determined cost (income)	53.164.947,00 €	54.205.547,00 €	54.057.812,00 €
	UR	56,51 €	55,45 €	53,12 €
	SU correction, sept.2012	941000	976000	1024000
	Difference in SU	200	-1500	6300
	Actual income	53.175.910,00 €	54.119.200,00 €	54.394.880,00 €
	Profit/loss	**11.302,00 €**	**-83.175,00 €**	**334.656,00 €**
	As part of FAB			
	$\overline{UR}$	51,11 €	50,70 €	48,84 €
	Share of costs in FAB	12,15%	12,14%	12,13%
	Actual income	51.059.695,46 €	51.333.190,07 €	51.312.987,75 €
	Profit/loss	**-2.105.251,54 €**	**-2.872.356,93 €**	**-2.744.824,25 €**
Provider D	**Autonomous**			
	Planned SU	2351760	2419960	2499820
	Determined cost (income)	98.119.353,00 €	99.960.020,00 €	101.993.998,00 €
	UR	41,72 €	41,31 €	40,80 €
	SU correction, sept.2012	2317000	2333000	2413000
	Difference in SU	-34760	-86960	-86820
	Actual income	96.665.240,00 €	96.376.230,00 €	98.450.400,00 €
	Profit/loss	**-1.450.187,20 €**	**-3.592.317,60 €**	**-3.542.256,00 €**
	As part of FAB			
	$\overline{UR}$	51,11 €	50,70 €	48,84 €
	Share of costs in FAB	22,42%	22,38%	22,88%
	Actual income	94.233.974,94 €	94.663.129,33 €	96.815.179,47 €
	Profit/loss	**-3.885.378,06 €**	**-5.296.890,67 €**	**-5.178.818,53 €**
Provider E	**Autonomous**			
	Planned SU	2122692	2154532	2186850
	Determined cost (income)	82.224.708,00 €	84.997.223,00 €	83.968.263,00 €
	UR	38,74 €	39,44 €	38,40 €
	SU correction, sept.2012	2042000	2058000	2149000
	Difference in SU	-80692	-96532	-37850
	Actual income	79.107.080,00 €	81.167.520,00 €	82.521.600,00 €
	Profit/loss	**-3.126.008,08 €**	**-3.807.222,08 €**	**-1.453.440,00 €**
	As part of FAB			
	$\overline{UR}$	51,11 €	50,70 €	48,84 €
	Share of costs in FAB	18,79%	19,03%	18,84%
	Actual income	78.968.733,85 €	80.493.212,32 €	79.704.714,11 €
	Profit/loss	**-3.255.974,15 €**	**-4.504.010,68 €**	**-4.263.548,89 €**

III. ALTERNATIVES TO THE ECONOMY OF SCALE

Simulation and analysis of the response of European air navigation services providers to changes in announced air traffic volumes and the resulting differences in the estimates of revenue, show that the potential integration of service providers into one larger "virtual" service provider, in order to achieve the economy of scale, does not necessarily lead to business optimization. In the three cases presented the final outcome of operations, assuming unchanged entry conditions, of the combined (virtual) air navigation services provider, is no better than the sum of the results of individual air navigation services providers.

As an alternative, real synergy of integration could potentially be achieved through joint procurement, joint staff training, staff mobility and joint use of at least part of the technical resources. In order to bring this to life to a greater extent, at least in Europe, a lot of time will be needed (as already written, probably several generations).

The immediate problem is caused already by potential joint ownership of the assets, as the country, in order to be able to declare flight information region (FIR) in accordance with International Civil Aviation Organization (ICAO) standards, is obliged to provide at least Flight information service (FIS) and Alerting service (AS). In order to do that it needs at least basic communication, navigation and surveillance resources and, of course, means for (automatic) data processing. These resources should be at any time unconditionally available, which in principle can be ensured only through the individual ownership.

The biggest obstacle related to joint procurement lies in the local legislation and political unwillingness at the national level, since the potential liberalization of this domain may jeopardize the interests of the lobbies, or even influential individuals.

The joint staff training is usually not well accepted by the bigger nations with long tradition in this domain, since they are convinced that their way of training is the only proper and adequate one, leading to a high-quality end result. Sometimes they do not see that their learning processes are unnecessarily lengthy and costly, their teaching content, and teaching materials somehow archaic, since they always find an excuse in the tradition.

In the case of staff mobility at a given moment the greatest barrier is the language proficiency. Air traffic controllers, at least in the lower part of the airspace and airports are expected to be in particular for safety reasons in addition to English, fluent as well in the local language. Non-professional pilots can be in Europe in this respect quite unpredictable and dangerous.

As far as the common use of at least part of technical resources is concerned, air navigation services providers are often faced with the fact that the technical staff needed for the immediate intervention on safety critical technical resources should be located close to these resources, therefore decentralized. The latter reduces the effect of the joint, that is, centralized management of technical resources. Although operating in a "cloud" probably also in the field of air traffic management is a close reality, the one that will provide the infrastructure for such operations, will have absolute domination over those that will only utilize the services of the "cloud". As appealing as it may look like at the first instance it could become a nightmare from which there may be no escape over the time.

Even when the above-mentioned potential for the synergy comes to life, the question arises whether it will be large enough, to enable the air navigation services providers to follow the guidelines of the European Commission on the final results of the business impact.

As already indicated, the real synergy effects can be largely attributed to the non-operational part of business of air navigation services providers (administration, training, cost of purchase and maintenance of technical equipment, etc.). According to publicly available information found in the various publications of EUROCONTROL, Civil Air Navigation Service Organization (CANSO) and air navigation services providers (ACE reports, performance plans, etc.) [6], the cost of non-operational part of the business in the proportion to the total cost amounts to about 35-40%, which also includes the depreciation of fixed assets. If air navigation services providers want to follow the requirements of the European Commission, the Member States of the European Union are required to reduce their costs by at least 3,5% per annum (Single European Sky Performance Scheme for the first reference 2012-2014 [7]). This means that they should achieve average savings of about 10% in each of the above mentioned domains by achieving synergistic effects. This certainly represents a fairly high requirement, especially bearing in mind that these savings should provide long-term effects, throughout many years and not just one single year.

In training, saving of roughly 10% can be achieved for a short term period, a year or two, through the integration of training institutions by joint development of teaching materials, literature and courses. The number of staff needed in such a way can almost immediately be halved. Savings in their earnings or their more economical utilisation can immediately be achieved. However, this effect is present only until all the courses are designed and training documentation produced. Thereafter large savings are gone, especially in the training of the operational staff, which is to a considerable extent practical, including simulations, and on-the-job training, where immediately a greater number of candidates (which would consequently get into the training process through the economies of scale) requires a larger number of lecturers and instructors (or at least the same number as would be necessary for the training of the same amount of candidates divided into smaller groups).

The same applies to the joint acquisition and maintenance of equipment. Operational equipment is renewed on average at least every seven years. With proper maintenance records provided to the regulatory authority, lifespan of each piece of operational equipment can also be extended (but not forever). Therefore savings in purchase of the relevant equipment can only be achieved every seventh year or so. Indeed, it is potentially possible that more favourable offer is obtained provided that the volume of orders is higher. The minimum discount that should be obtained should not be lower than 10%.

Another story is in the maintenance of the equipment. Potential for savings is in the combination of the services provided through specialization of the individual technical departments within the individual air navigation services providers to only one technical field of expertize. By specializing one service provider only in communications, next one in navigation, the third one in surveillance and the fourth one in automated systems, each technical area in a wider range of participating air navigation services providers, can be covered by a group of »flying experts«, thus achieving certain savings in the number of highly qualified personnel. On the other hand quantity of experts responsible for the daily maintenance of technical resources remains more or less the same. Such group of »flying experts« provides maximum savings only in case of purchase and installation of new technical systems, or in case of major routine maintenance while sufficient number of properly qualified experts who are able to instantly respond to unplanned malfunction of technical resources is still required by the respective air navigation services provider. The response time in these cases is required in minutes, not more than few hours, but not in days.

IV. CONCLUSION

From the above it can be concluded that the economy of scale by itself does not, by default ensure more cost-efficient operations. Most of the effort would generally provide only short-term savings, for a period of about one year, but not systemic, long-term savings. In order to be more efficient, fair business environment is mandatory, which in Europe is obstructed by a whole lot of political and international particularities. To support the economy of scale, European Union has designed functional airspace blocks, which are already the reality. Unfortunately in creation of particular functional airspace blocks a whole series of factors that could make the business environment more efficient (e.g. the creation of functional airspace blocks in a way to compensate for the variability of air traffic or air traffic complexity, etc.) has been ignored. As proved in this simulation also a creation of common unit rate, so favoured by the European Commission, can have a significant draw back effect.

Possibly more appropriate way of development will be evident in the introduction of new technical and technological solutions that are being developed through the Single European Sky programme, by the Single European Sky ATM Research (SESAR).

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Innovative Baggage Delivery for Sustainable Air Transport

Pavel Loskot
Swansea University, Swansea, SA2 8PP, UK
E-mail: p.loskot@swan.ac.uk

Peter Ball
Zafire Ltd., Manor Park, Banbury OX16 3TB, UK
E-mail: pball@zafire.com

***Abstract*—The passenger travel processes in Air Transport (AT) have not changed for the past 40 years. Here we contribute to the IATA visions of Simplifying the Business (StB) and improving the passenger experience by proposing to dissociate passenger travel and baggage delivery. This innovative aspect has profound positive consequences on the AT logistics and economies. Even though it requires a significant change in the current AT regulations, the proposed improvement is likely to be phased-in and eventually adopted by the airlines as well as the aircraft manufacturers. Our analysis shows that dissociating passenger and baggage flows can be vital for maintaining sustainability of AT. Moreover, the enabling technologies supporting this change either already exist, or are being developed.**

***Index Terms*—Air Transport, Baggage delivery, Passenger experience, Simplifying the Business, Sustainability.**

1. Air Transport and IATA Visions

The infrastructure, processes and systems in AT have not changed for over 40 years, so they are dated, inefficient and complex. Some of the main challenges are passenger queuing at various check and service points at the airport, mishandled bags, and unexpected service disruptions, for example, due to a bad weather or aircraft maintenance. These problems are causing excessive delays and costs, and they are exacerbated as the passenger numbers and the cargo volumes grow faster than the system capacity [1], [2]. For instance, the number of passengers worldwide has increased from 1.89 billions in 2003 to 3.3 in 2014 (i.e., a 75% increase).

The airlines and the airports have been well aware of these problems. The IATA (International Air Transport Association) established several programs to accommodate the growing demand for the AT services [3]. These programs are structured around three main objectives: 1. Airline products with new distribution capabilities and e-services, 2. Real-time interactions, and 3. Seamless and hassle-free services. The latter objective concerns the relevant themes such as Smart Security, Baggage Services, Security Access and Egress, Automated Border Control and Fast Travel. In simple terms, the overall aim is to simplify the processes and improve the passenger experience while enhancing the security, safety, and the utilization efficiency of space, staff and other assets. The passenger experience is improved by providing them with more autonomy which have focused so far on baggage self-tagging, baggage self-drop-off, and self-checking services.

2. Air Transport of PAX, Baggage and Cargo

The AT network realizes the delivery of passengers, their baggage and cargo. This delivery is a very complex process consisting of many integrated services and supporting sub-processes. The aircraft serving as the AT carriers have finite volumetric and weight load capacities which are usually optimized to maximize the delivery efficiency [4], [5], [6]. Such efficiency can be measured as a revenue for the operator (e.g., an airline, or an airport), and increasingly also in terms of the generated CO_2 emissions [7], [8]. For the long-term average seat occupancy of about 80%, the long-haul flights generate a modest \$6 profit per passenger, however, a substantial profit of \$2.40 per kilogram of cargo [1], [3]; it is clear that cargo delivery is critical for the airline financial viability [9].

A typical commercial airliner trades-off the payload with its operational range as shown in Fig. 1. The payload-range trade-off curve also depends on the particular aircraft configuration (e.g., whether using the winglets) and the engine parameters. The payload only represents passengers, their baggage and cargo; the dry operating weight (DOW) includes everything else except the fuel [7], [8]. The maximum take-off weight (MTOW) is limiting for longer flights whereas the maximum landing weight (MLW) is a concern for shorter flights. The maximum zero-fuel weight (MZFW) becomes limiting when the payload and fuel are optimized for a given range. In Fig. 1, R_1 is the maximum range with the maximum payload. The ranges between R_1 and R_2 require to trade-off the payload for fuel. The maximum range R_2 achievable with full fuel tanks can be exceeded if the payload is further reduced to make the aircraft more fuel efficient. The payload-range trade-off of the new aircraft designs corresponds to R_3 (see Section 4).

The average passenger weight (combined male and female) is 73-75kg and the child 34-36kg [10], [7]. The hand (carry-on) luggage and checked-in luggage allowances differ per airline and the travel class: an economy class passenger on a long-haul flight is usually allowed to carry up to 7kg single luggage on board, and to check-in one piece of luggage up to 23kg for free. The maximum seating capacity of an aircraft decreases with the number of travel classes offered. A long-haul airliner typically carries: 240-520 passengers (80% occupancy) with 7kg average hand luggage per passenger, average checked-in luggage of 23kg (80% of travelers) and 2×23kg (remaining 20% of passengers) which amount to:

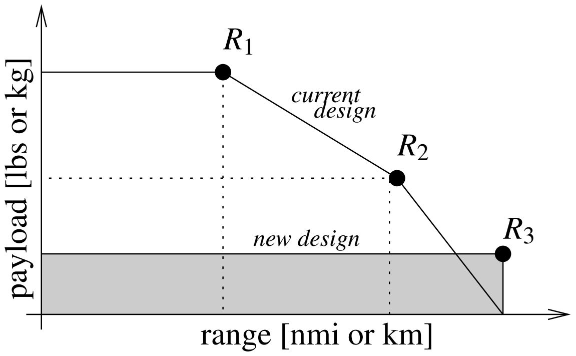

Figure 1. A typical payload-range characteristic of the current and future aircraft.

20-33	tons of passengers with hand luggage;
7-15	tons of checked-in luggage;
23-28	tons of cargo;
50-76	tons of the total payload.

The variants of the new Airbus A350 aircraft report the volumetric and structural cargo payloads of up to 52 tons [7], in addition to passengers and baggage. The purposely modified airliners known as the freighters can increase the maximum total payload of cargo to as much as 140 tons [7], [8].

The cargo is consolidated by the 3rd party forwarders (e.g., UPC, TNT, DHL) from the shippers and suppliers, usually into unit load devices (UDLs). The cargo delivery is optimized for efficient routing, loading and unloading and priority handling [5], [6]. The air cargo tariffs and premiums are determined to manage the demand against the available transportation capacity [3]. The average revenue per one kilogram of cargo delivery is calculated as [4]:

$$\mathrm{TRF}\ [\$/kg] = \frac{\sum_i \mathrm{CW}_i \times \mathrm{TRF}_i}{\sum_i \mathrm{CW}_i}$$

where $\mathrm{CW}_1 < \mathrm{CW}_2 < \ldots$ are cargo weights, and $\mathrm{TRF}_1 > \mathrm{TRF}_2 > \ldots$ are the corresponding tariffs. The tariffs can be determined through bids for the available carrier capacity.

A. Dissociating Passenger Travel and Baggage Delivery

Passenger travel as well as baggage handling and delivery is regulated by the IATA regulations. The IATA's General Conditions of Carriage [3] recommends that:

> "*...checked baggage will be carried on the same aircraft as the passenger unless Carrier decides that this is impractical, in which case Carrier will carry the checked baggage on Carrier's next flight on which space is available.*"

Moreover, most airlines operate the policy that luggage of checked-in passengers who fail to board the flight must be off-loaded for the security reasons. Thus, currently only a small number of bags are delivered on the next flight, and the affected passengers will not be notified until they attempt to collect their luggage at the destination airport. Provided that most or all of the bags are allowed to be delivered on flights other than the passengers' flight, many significant improvements to the AT delivery services can be devised as we will discuss in the rest of the paper. Specifically, the implementation aspects of dissociating passenger travel and baggage delivery are considered in Section 3, and the benefits and future trends are summarized in Section 4.

Consider a single passenger travel from the point of origin (usually the passenger's home, work place, or a hotel in the return journey) to the destination (a hotel, or home in the return journey). The passenger leaves the origin at time T_0 for the departure at time T_1. After the flight of duration $(T_2 - T_1)$, the passenger arrives to the destination at time T_3. Associated to these events at times T_0, T_1, T_2 and T_3 are additional events E_0, E_1, E_2 and E_3 occurring at times $T_0 + \Delta T_0$, $T_1 + \Delta T_1$, $T_2 + \Delta T_2$ and $T_3 + \Delta T_3$, respectively, as depicted in Fig. 2. The events E_i represent:

- E_0: baggage sent from the origin to departure airport;
- E_1: baggage is delivered to the departure airport;
- E_2: baggage is delivered to the arrival airport;
- E_3: baggage is collected by the passenger.

In the conventional (current) system, passenger travel and baggage delivery are coupled (synchronized), so that $\Delta T_i = 0$, for all $i = 0, 1, 2, 3$. However, once these two processes become separated, the events E_i, $i = 0, 1, 2, 3$ generally occur before or after the corresponding times T_i (i.e., $\Delta T_i \neq 0$) which allows to consider entirely new AT services with the significantly improved passenger experience.

B. Baggage Delivery Strategies

Even though dissociation of passenger travel and baggage delivery is conceptually simple, its implementation is rather non-trivial, since it is constrained by the strict AT regulations, especially those involving the AT safety and security. Importantly, at all times, baggage ownership has to be defined. In particular, the passengers hand over their baggage to the airline or the airport baggage service before the departure, and then take over their baggage back upon the arrival. Other baggage ownership handovers frequently occur during baggage handling and delivery (e.g., loading and unloading).

Passenger travel involves three segments: journey to and from the airport (ground segments), and the air travel between the departure and destination airports. The passenger and baggage dissociation for the ground segments is specific as it does not involve the air travel. Hence, the 3rd parties may provide a new travel service to deliver passenger baggage to and from the airport. Prior to the departure, the passengers can either drop their luggage off at a dedicated collection point (established, e.g., at a post office, central bus or railway station, by large supermarkets and similar such sites), or their luggage is conveniently collected from their premises. This enables hassle-free passenger travel to the departure airport, encouraging the use of more efficient and ecological public transport. At the destination airport, instead of collecting baggage from the belt in the arrival hall, the 3rd party can again provide a new delivery service for baggage to the selected destination (typically, a hotel) which simplifies passenger

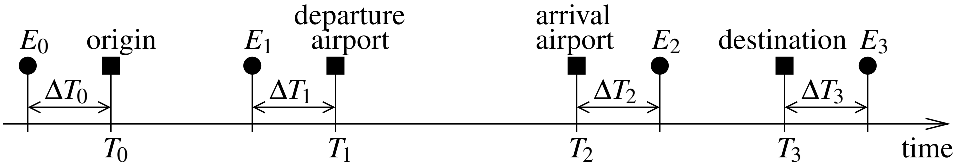

Figure 2. The time axis of passenger travel and baggage delivery between an origin and a destination.

travel from the airport. For instance, the Manchester airport in the UK is experiencing over 40,000 vehicle movements daily, so any consolidation of the travel to and from this airport by means of public buses and trains can greatly contribute to its sustainability.

Dissociating passenger travel and baggage delivery within the air segment is the most complex as it requires changes to the current airline and airport procedures and regulations. On the other hand, unlike baggage dissociation over the ground segment, the required technology and infrastructure is already available at the airports, so the changes are mainly related to baggage handling and logistics. In particular, let $\Delta T_0 = \Delta T_1 = 0$, i.e., the passenger delivers his/her luggage to the departure airport, and check it in with the airline. The airline schedules luggage delivery to the arrival airport. The passenger is notified about the most likely collection time, for example, during the check-in, or even during the air-ticket booking prior to his/her travel to the departure airport. Since luggage is likely to be delivered after the passenger arrival, the airline agrees with the passenger the collection method at the destination. The airline can exploit the delayed luggage delivery to better optimize the profit-paying cargo delivery, especially if sufficient number of passengers sign up for the delayed luggage service, and there is a premium for the expedited cargo delivery. The incentives (e.g., extra travel miles) can be used to manage the demand for this new baggage service. For instance, the passengers can be encouraged to send their luggage to the airport early prior to their travel; according to the airline operational procedures, luggage is usually loaded to the aircraft at least 0.5 hours prior to the departure.

C. Aircraft Load Optimization

In order to assess the feasibility of the proposed dissociated baggage delivery, we consider an AT network segment consisting of an origin airport, a destination airport and a single stopover airport. Similar analysis can be performed for more complex AT network topology having multiple (e.g., stopover) airports by iteratively expanding the model in Fig. 3.

Let there be p passengers traveling from the origin to a destination airport with p_1 passengers on the direct flight, and $p_2 = p - p_1$ stopover passengers. The corresponding baggage volume (e.g., expressed as weight in kilograms) is denoted as $b = b_1 + b_2$, and the cargo volume as $c = c_1 + c_2$. We assume that the passenger numbers p_1 and p_2 on the respective flights are fixed. Provided that the passengers and their baggage can be dissociated, our goal is to optimize loading of each flight.

Denote as L_1 the maximum available load (capacity) for $c_1 + b_1$ on the direct flight, and as L_{21} and L_{22} the maximum

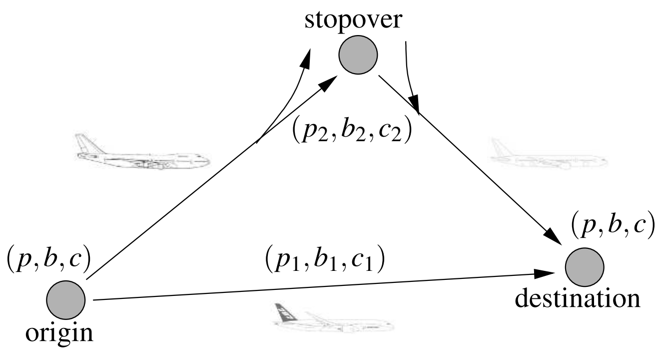

Figure 3. A single origin and destination segment of the AT network with the indicated quantities of passengers (PAX), baggage and cargo.

available loads for $c_2 + b_2$ on the two indirect flights. Note that there is likely to be more passengers and more load transported on the flights from the origin to the stopover, and from the stopover to the destination than (p_2, b_2, c_2), however, these additional passengers and loads are not included in L_{21} and L_{22}. Thus, we have the constrained loads,

$$\begin{aligned} b_1 + c_1 &\leq L_1 \\ b_2 + c_2 &\leq \min(L_{21}, L_{22}). \end{aligned}$$

If α_1, α_2, β_1 and β_2 denote the unit transport costs (tariffs per kilogram of weight) of b_1, b_2, c_1 and c_2, respectively, on the corresponding flight segments, we want to minimize the total transport cost:

$$\begin{aligned} & \min\left(\alpha_1 b_1 + \alpha_2 b_2 + \beta_1 c_1 + \beta_2 c_2\right) \\ = \; & \min\left(\underbrace{\alpha_2 b + \beta_2 c}_{\text{const}} + b_1 \underbrace{(\alpha_1 - \alpha_2)}_{\Delta\alpha_{12}} + c_1 \underbrace{(\beta_1 - \beta_2)}_{\Delta\beta_{12}}\right) \\ = \; & \min\left(b_1 \Delta\alpha_{12} + c_1 \Delta\beta_{12}\right) = \min M(b_1, c_1) \qquad (1) \\ & \text{s.t. } L_2 \leq (b_1 + c_1) \leq L_1 \end{aligned}$$

where we denoted $L_2 = c + b - \min(L_{21}, L_{22})$. We further assume that the load capacity $L_1 > L_2$, and that the transport costs $\Delta\alpha_{12} < 0$ and $\Delta\beta_{12} < 0$ to meet the transport demands as indicated above.

The problem (1) is a simple linear program with two decision variables b_1 and c_1 given the transport capacities L_1 and L_2, the loads c and b, and the set of costs $\{\alpha_1, \alpha_2, \beta_1, \beta_2\}$. This problem can be readily solved graphically. In particular, the feasible region of decisions (b_1, c_1) satisfying the load constraints is shown as a shaded area in Fig. 4. Provided that $|\Delta\alpha_{12}| < |\Delta\beta_{12}|$, i.e., the tariff differential for baggage

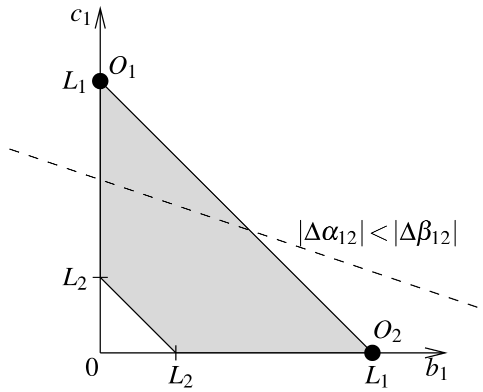

Figure 4. The payload optimization for the direct and stopover delivery in Fig. 3.

delivery between the direct and indirect flights is smaller than the tariff differential for cargo delivery, the optimum solution minimizing the transport cost corresponds to the point O_1 in Fig. 4. The dashed line in Fig. 4 is defined by the expression:

$$c_1 = -\frac{\Delta\alpha_{12}}{\Delta\beta_{12}} b_1 + \frac{M}{\Delta\beta_{12}}$$

and the minimum cost is given by the minimum value of M. On the other hand, if the tariff differentials are such that $|\Delta\alpha_{12}| > |\Delta\beta_{12}|$, the dashed line in Fig. 4 would have the gradient smaller than -1, and the optimum is given by the point O_2. Finally, if $|\Delta\alpha_{12}| = |\Delta\beta_{12}|$, i.e., both types of the loads have the same differential cost, the dashed line in Fig. 4 would have the gradient equal to -1, and any decision contained on the line between the end-points O_1 and O_2 is optimum. However, in practice, the tariffs for baggage and cargo delivery are likely to differ significantly [3]. If the transport capacity $L_1 > c_1$ and the optimum load is given by O_1, the remaining capacity $(L_1 - c_1)$ on the direct flight is used for transporting baggage b or cargo c_2, depending whether the costs $\alpha_1 < \beta_2$ or $\alpha_1 > \beta_2$, respectively. Similar conclusions applies for the optimum O_2 and the non-zero transport capacity $(L_1 - b_1)$.

We can readily generalize the load optimization problem in (1) to more types of cargo. The cargo types are defined by their different transportation tariffs. As shown in the solution of (1), the loads with larger tariff differential are more important and should be considered before the other loads. While still assuming only a single origin and a single destination, we can further generalize the load optimization problem to the case of multiple stopovers. We then minimize the total cost $\sum_{ij} \alpha_{ij} c_{ij}$ over all origin-destination routes i with the cargo loading c_{ij}, for a given set of costs $\{\alpha_{ij}\}$.

Consequently, by dissociating passenger travel from baggage delivery, we can consider baggage to be another type of cargo. This brings a great flexibility to optimize the aircraft loading, since baggage delivery is currently provided on most flights of the commercial airlines.

Table I
SOME FLIGHT STATISTICS BETWEEN SELECTED AIRPORTS

Orig.	Dest.	dur.	direct	1 stop	2 stops	total
EDI	PEK	< 24h	0	42	94	136
DUB	PEK	< 24h	0	49	62	111
LHR	PEK	< 24h	3	103	21	127
EDI	FCO	< 12h	1	27	15	43
DUB	FCO	< 12h	2	43	10	55
LHR	FCO	< 12h	3	80	2	85
EDI	DXB	< 12h	0	52	6	58
DUB	DXB	< 12h	4	63	7	74
LHR	DXB	< 12h	20	102	5	127
EDI	JFK	< 18h	0	89	23	112
DUB	JFK	< 18h	8	66	9	83
LHR	JFK	< 18h	69	141	11	221
EDI	PIT	< 18h	0	4	51	55
DUB	PIT	< 18h	0	30	61	91
LHR	PIT	< 18h	0	156	51	207
EDI	GIG	< 24h	0	9	35	44
DUB	GIG	< 24h	0	7	52	59
LHR	GIG	< 24h	1	42	33	76
EDI	SYD	< 32h	0	6	104	110
DUB	SYD	< 32h	0	17	44	61
LHR	SYD	< 32h	0	93	65	158

D. Initial Implementation Strategy

We consider dissociation of baggage delivery for the air travel segment only in order to outline an initial implementation strategy. We propose to deliver baggage on the flights with the minimum number of hops (stopover airports). Specifically, all baggage should be delivered on the direct flights between the airport hubs, and baggage delivery on the flights with one stopover is preferred to the flights with two stopovers and so on. Tab. I contains the typical numbers of daily flights with up to 2 stopovers, given the maximum overall journey duration (in hours) between the given origin and destination airports denoted by their 3-letter IATA codes[1]. For the three selected origin airports in the UK and Ireland (EDI, LHR and DUB), the destination airports are chosen in the different continents.

As indicated above, we assume a typical airline load of 7-15 tons of checked-in baggage which represents about $1/3$ to $1/2$ of the overall cargo load of 23-28 tons. Consequently, in order to estimate the average number of flights N_{B} required to aggregate baggage delivery (i.e., the baggage load on these flights has priority over the cargo load) over one day, we denote as B the average baggage load per (origin-to-destination) flight, and as C the same quantity, but for the cargo load. Then, $B = \alpha \cdot C$ where typically, the fraction $\frac{1}{3} \le \alpha \le \frac{1}{2}$ (i.e., the higher the average passenger flight occupancy, the larger α), and the flight average load excluding the passengers is, $B + C = (1+\alpha)C$. For the total number of daily flights N_{tot} considered, we have that, $N_{\mathrm{tot}} \cdot B \approx N_{\mathrm{B}}(B + C)$, and thus,

$$N_{\mathrm{B}} \approx N_{\mathrm{tot}} \cdot \frac{\alpha}{1+\alpha}$$

where the function $f(\alpha) = \alpha/(1+\alpha)$ is strictly increasing. For example, $f(1/2) = 1/3$, so about $1/3$ of the daily flights

[1]Data collected manually from skyscanner.net for a typical week day in November.

between the given origin and destination airports can be used to carry all the daily baggage volume on the remaining $2/3$ of the flights reserved for the cargo (no baggage) delivery. More importantly, these $1/3$ daily flights for the aggregated baggage delivery should be allocated over the routes with the minimum number of hops (stopovers). Moreover, since the flights between the origin and destination airports are usually scheduled over the whole day (except a period after the midnight, say, 12am till 5am), the maximum baggage delivery delay (after the passenger's arrival to the destination airport) is approximately $(24-5)/3 \doteq 6.3$ hours which is acceptable. In practice, this maximum delay is likely to be smaller, for example, when baggage is delivered on the direct flight while the passenger travel includes one stopover. Note also that we assume that the airlines fully collaborate (beyond the current flight share schemes) to better utilize the aggregated baggage transport capacity between the origin and destination airports.

In summary, delivering baggage over the flights with smaller number of stopovers (ideally, via the direct flights only), relieves the baggage load congestion, and thus, increases the load throughput at the stopover airports. We recommend to route baggage over the direct flights only whenever possible (i.e., when the aggregated load on the direct flights is sufficient), and especially when the destination airport is a large air travel hub.

3. Implementation Aspects

In general, the implementation strategy is critical to overcome many challenges. The main challenge to enable dissociation of passenger travel and baggage delivery is the security, especially when the 3rd parties become involved by offering new baggage delivery services. The modern X-ray scans can reliably detect any suspicious or prohibited luggage content, so they are nowadays used immediately after the baggage check-in at the airports. However, to resolve the luggage content issue requires on-site presence of the passenger. This may constrain baggage delivery to the departure airport either together with the passenger arrival or earlier, but not later. The X-ray scans at the departure airport are also expected to be used for the remote customs clearances under the import regulations of the destination country [3]. The 3rd party baggage delivery to/from the airport requires additional measures to prevent unauthorized tampering with luggage such as the use of secure lockable transport containers.

The provisioning of the passenger services in AT is often shared by the airport authorities, the airlines and the other 3rd parties. Thus, their coordination using well-defined communication and data sharing protocols and models is important. The added flexibility of the proposed baggage delivery creates opportunities to utilize assets, resources and the infrastructure more efficiently. However, the changes in baggage handling procedures also necessitate new service level definitions (e.g., on-time delivery guarantees and penalty for late delivery), new business models (e.g., new incentives, costs and infrastructure sharing strategies) as well as new supporting services (e.g., real-time anywhere baggage tracking, insurance of the luggage contents and of the agreed on-time delivery).

Dissociation of passenger travel and baggage delivery is likely to be implemented in several phases following the current IATA's phased approaches and roadmaps to significant upgrades of the AT infrastructures and procedures. For instance, Checkpoint of the Future program [3] defines the risk assessment and the required technology and operations for the three implementation phases to be completed by 2014, 2017 and 2020, respectively. The Fast Travel and Bags Ready-to-Go programs of the IATA [11] aim to improve the airport passenger throughput and capacity, especially by focusing to speed-up the baggage check-in processes. Hence, the proposed dissociated baggage delivery is highly relevant to these two programs. In particular, the home check-in is now widely adopted by the airlines and passengers, however, the innovations in the baggage check-in processes have not been considered until recently. Many airlines already have self-check-in kiosks allowing the passengers to print their own bag-tag in order to speed-up the baggage drop-off. Some airlines (e.g., KLM and Qantas) are subsidizing the programmable electronic bag-tags [12], [13], [14]. The electronic bag-tags are reusable, allow smartphone programming, and to some extent a real-time localization of the baggage. Other airlines (e.g., British Airways and Air France) are trialing the cost-effective home-printed bag-tags. These solutions lower operational costs, and provides new revenue incomes to the AT service providers.

The ICCT (Information, Communication and Computing Technologies) are the key enabler of these improvements by providing accurate and trusted information in real-time to wherever it is needed for the timely operational decision making. It is recognized that as much as 97% of the passengers are now traveling with their smartphones [2]. Particularly over the ground segments (to/from the airports), dissociation of passenger travel from baggage delivery is fundamentally dependent on real-time tracking of baggage location. This increases security, enables efficient management of the baggage flows (especially during the unplanned service disruptions), and creates the piece of mind for the passengers. The baggage tracking is likely to be realized as a multi-tier network of tracking devices:

- The low-cost RFID-type chips containing a newly introduced UUID (Universally Unique Identifier) [2] attached to luggage seek as well as can be queried by the nearby access points.
- The access points are aware of their location; they exploit GPS-type tracking when they are mobile (e.g., mounted on the baggage delivery vehicles). The portable (handheld) access points can be used in case the manual baggage handling becomes necessary.
- The access points periodically report all baggage they have authenticated to the tracking center.

Furthermore, the IATA requires that the airlines track and record all baggage process steps (e.g., delivery, acquisition, transfer, handover, aircraft loading and unloading) since 2018.

4. Benefits and Future Trends

The proposed dissociation of passenger travel and baggage delivery contributes directly to the IATA InBag program which is concerned with the baggage processes across the industry [3]. The main objectives are to increase the airport throughput (especially at large busy airport hubs) and improve the passenger experience, and ultimately, baggage dissociation should be over the whole journey (door-to-door). The airport throughput is increased by simplifying and automating the processes and reducing their response times. In fact, the trend of automating the processes in AT is a strong driver supporting the proposed idea of baggage dissociation. The passenger experience is improved by making the services more reliable, more intuitive and more user-friendly while providing the passengers with more autonomy and control. Baggage dissociated from the passengers can be routed more directly to the destination which streamlines its delivery over the AT network. The airlines may collaborate to deliver all luggage several times a day on the dedicated cargo flights, for example, at least among the major airport hubs.

The airlines (the IATA) as well as the airports are likely to support delivery of baggage to and from the airports by the 3rd party forwarders. Such service could be integrated with the existing cargo and parcel AT delivery to exploit the existing infrastructure. This greatly simplifies the check-in process and fully avoids the baggage drop-off at the departure airport. The baggage-free passengers are then much more likely to use public transport to and from the airports, thus relieving the airport traffic congestion. The new baggage delivery is likely to differentiate among several service levels and fee options, for example, to manage delivery priorities. Furthermore, once the dissociated baggage delivery is fully implemented, one has to wonder whether the regulation would require that the passenger travel and their baggage is delivered from the same departure airport to the same destination airport, even though possibly at different times. If such requirement is not adopted, the baggage delivery service will be completely independent of passenger travel (who may well decide not to travel at all), and it will then resemble a courier or parcel delivery service.

The large busy airports now operate close to their capacity while the demand for AT is continuously increasing [2]. Hence, there is a need to completely reconsider the airport designs to reflect the growing demands, and to better accommodate the new regulations and processes as they are being introduced by the IATA [3]. For instance, the new airport design may have passenger-only and baggage-only terminals with the supporting infrastructure optimized accordingly.

Baggage dissociation is also likely to encourage new aircraft designs. The passenger-only aircraft are faster to load and unload, they can either accommodate more passengers, or provide more room for the passengers (i.e., contribute to the passenger experience), and at the same time, they are lighter, and thus faster and more fuel efficient. Such new aircraft designs represent multi-billion opportunities for the aircraft manufacturers such as Airbus and Boeing. Recently, Airbus filed several relevant patents on the new aircraft designs supporting these ideas [15], [16].

Independent baggage delivery can be aligned with the recent proposal on the Physical Internet [17]. The Physical Internet mimics the delivery of data packets by proposing to physically deliver things in the standardized containers. Hence, it is likely that future luggage will be standardized including the shape, size, materials, and accessories (e.g., the wheels and handles for easy moving, loading and storage). Such standardized luggage will have integrated sensors (location, temperature, acceleration) and the recording of the sensor outputs.

Moreover, many sensors will be deployed in the realization of the current IATA programs and visions. Such sensor networks can be considered to support the roll-out of the emerging Internet of Things (IoT).

We conclude that our study outlined in this paper indicates that dissociating passenger travel and baggage delivery is a promising step towards more sustainable future Air Transport.

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Aircraft Lateral Flight Optimization Using Artificial Bees Colony

Alejandro Murrieta-Mendoza, Audric Bunel, Ruxandra M. Botez
Université du Québec – École de Technologie Supérieure
The Research Laboratory in Active Controls, Avionics and Aerosevoelasticity (LARCASE)
Montreal, Canada
ruxandra.botez@etsmtl.ca alejandro.murrieta-mendoza.1@ens.etsmtl.ca

***Abstract*— Fuel powered flights release polluting emissions to the atmosphere. The aeronautical industry has set itself the goal of reducing their global emissions share. Flight trajectory optimization is a way to reduce fuel consumption, thus reducing fuel emissions. Wind has a strong influence in fuel consumption. Tailwinds are desirable since they "push" the aircraft to its destination incrementing the ground speed for a given true air speed. This paper presents an algorithm that implements the artificial bee colony metaheuristic optimization algorithm to find the combination of waypoints that reduce the flight time between the departure and the destination points. The trajectory analyzed is at fixed Mach number and a fixed altitude. Fuel burn is computed using a performance database developed using experimental test data. The algorithm has the peculiarity that it does not require a fixed grid to generate the generated trajectories. Results have shown that for all tests the algorithm is able to identify trajectories with favorable wind, reducing the flight time, thus the fuel consumption and the flight cost.**

Keywords—Trajectory; Optimization; ABC; Bee; Lateral, Navigation, Aircraft

I. Introduction

The aeronautical industry is responsible of 2% of the total dioxide carbon (CO_2) released to the atmosphere. For this reason the industry has set the goal of reducing the polluting emissions generated primarily by fossil fuel such as reducing by the year 2050 the CO_2 emissions to 50% of those recorded in the year 2005. [1, 2]

To reach the reductions emission goal, aircraft operations have been seen as an interesting way to reduce fuel consumption, thus fuel emissions. Airlines have implemented different methods to reduce flight consumption such as engine washing, reduction of Auxiliary Power Unit (APU), weight reduction among others [3]. The descent phase has been explored principally because during the approach and landing phase, the aircraft and its pollution (emissions and noise) are released near populated areas. The most important improvement during descent is the Continuous Descent Approach (CDA) [4, 5]. This approach, contrary to the typical descent, consists in setting the engines in IDLE consuming low quantities of fuel and descending at a constant angle (typical 3°). It is important to correctly execute the descent approach and landing since executing the missed approach procedure significantly augments the total flight costs [6, 7].

According to [8, 9], not all aircraft fly at their optimal speeds and altitudes. For this reasons, different algorithms have been implemented to reduce flight costs by providing the optimal flight conditions. Optimal Control has been used to solve the equations of motion as in [10-15]. Genetic Algorithms have been used to optimize the lateral navigation (LNAV) and/or the vertical Navigation (VNAV) reference trajectory [16-20]. Branch and Cut has been implemented to optimize the vertical reference profile [21, 22]. Dynamic programming has been used to optimize the VNAV [23] and the LNAV [24]. Dijkstra's algorithm was explored for commercial and general purpose aircraft [25, 26]. Techniques to reduce the search space to reduce the computation time were developed in [27, 28]. Most of these algorithms required a grid where the aircraft was imposed to flight from/to the available waypoints.

The objective of this paper is to develop an algorithm to find the set of waypoints (longitude, latitude) from the departure waypoint, generally the Top of Climb (ToC), to the destination waypoint, the Top of Descent (ToD) that minimizes the flight cost.

The desirable LNAV reference route is the one that minimizes the flight cost. This reference trajectory has certain weather conditions that decrease the required energy (and flight time) for the plane to link the arrival to the destination point. The desirable weather conditions consist mostly in a tailwind and low temperatures. To find these weather conditions, the Artificial Bee Colony (ABC) algorithm was implemented in this paper. The ABC algorithm identified the best weather parameters to reduce the flight cost instead of focusing only in fuel consumption. When a complete trajectory taking into account the weather only was identified (all waypoints from ToC to ToD), the flight cost taking into account fuel consumptions was evaluated

As the ABC algorithm presents a well balance between the search space exploration and the exploitation ability, it is a good choice for the aircraft LNAV optimization. The ABC nature of researching multiple trajectories at the "same time" (or iteration) allows avoiding the trajectory to stagnate at a local optimal. The constant optimization provided by the ABC provides a very fine flight plan, able to maximize the wind influence to decrease the fuel consumption. The flight considered was at fixed altitude and Mach number.

The paper is arranged as follows, the methodology used to compute the flight cost is described, followed by the search space definition, and then the ABC theory and its implementations are described followed by results, conclusion, and future work.

II. METHODOLOGY

A. *Flight Cost – The Performance Database*

The aircraft model used in this paper to compute the flight cost is given in the form of a database. This database was created using in-flight experimental performance data. This database was constructed and developed by our industrial partner and it is called a Performance Database (PDB). The PDB contains different flight phases such as climb, acceleration, cruise, deceleration, and descent. However, because this paper focuses in cruise at a fixed flight level, only the PDB cruise phase was used. A methodology to create a PDB was described in[29].

The PDB can be considered as a black box which receives inputs to provide the pre-defined outputs. For the cruise phase, the required inputs are: the aircraft weight (kg), the speed (Mach number), the altitude (ft.), and the international standard atmosphere temperature deviation (°C). As an output the PDB provides the fuel flow (kg/hr). All inputs must be provided in order to obtain the desired output.

The PDB being a database contain discrete input data. Some inputs in the PDB, especially the aircraft weight and temperature, do not contain all exact possible values required to compute the fuel burned. When the exact variable input provided to the PDB is not available, interpolations among the PDB input limits are executed to obtain the desired output for the required input parameters. These interpolations are performed normally for aircraft weight as fuel is being burned and standard temperature deviation as the aircraft moves through the atmosphere. A complete methodology to compute a flight cost using a PDB was presented in [30, 31].The function used to compute the flight cost is shown in (1).

$$FlightCost = FlightTime\left(Fuel\,Flow + Cost\,Index\right) \quad (1)$$

The Cost Index is a variable that translates the time cost in terms of fuel; it is defined by the airline and remains constant through the flight. It is the goal of the ABC algorithm to minimize (1).

B. *The Optimization Algorithm*

1) *The search Space*

The aircraft moves in environment, which will be referred as from now on as the "search space". The search space is located within the atmosphere and evolves constantly, changing wind conditions, temperature, and pressure.

The algorithm developed in this paper did not require a fixed waypoints grid such as many of the algorithms in the literature. The imposed waypoints grids in the literature were fixed equidistant waypoint located at a given perpendicular distance from the geodesic (shortest path between two points in a sphere) reference waypoints. The search space proposed in this paper was composed of geodesic reference waypoints as well where the position of the grid waypoints can be located at any distance from the reference geodesic waypoint. The distances, perpendicular to the reference trajectory, are determined by the ABC algorithm in a dynamic way. The grid difference is shown in Fig. 1.

Some trajectories created with the dynamic grid are shown in Fig. 2, notice again that the created waypoints are parallel to the geodesic reference route created. The black centerline represents the waypoints that form the original flight plan, which for this study is the geodesic line. The red lines represent the search space limits. No waypoint will be outside of these borders. Waypoints that form alternate trajectories are placed perpendicularly from the original flight-plan waypoints. Notice how the distance between the created waypoints are at different distances from the geodesic are not imposed, not at equidistant multiple distances as in Fig. 1. The created waypoints are shown in blue. In other words, the grid waypoints are dynamic, and it is the algorithm that decides where to place them as long as they are perpendicular to the reference waypoint.

2) *The Artificial Bee Colony Background*

Artificial Bee Colony (ABC) is one of the most metaheuristic algorithms. This algorithm mimics the honey bees' intelligent behavior their search for food sources. A set of honey bees make a swarm able to successfully accomplish tasks through social cooperation, the ABC was first defined in [32].

There are three types of bees in the ABC algorithm: the "employed bees", the "onlooker bees", and the "scout bees". The employed bees search different food sources around the current food source in their memories. They share the known found food sources information to the onlooker bees. The onlooker bees tend to select the highest quality food sources from the ones found by the employed bees. A scout bee is an employed bee searching for a new food source.

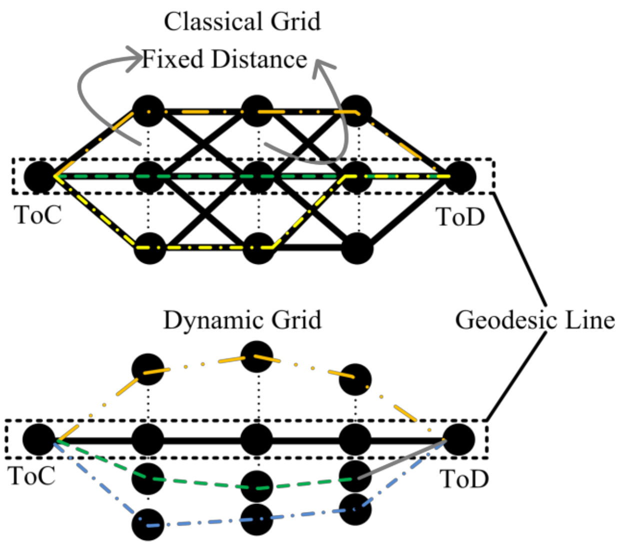

Fig. 1. Typical vs Dynamic Grid

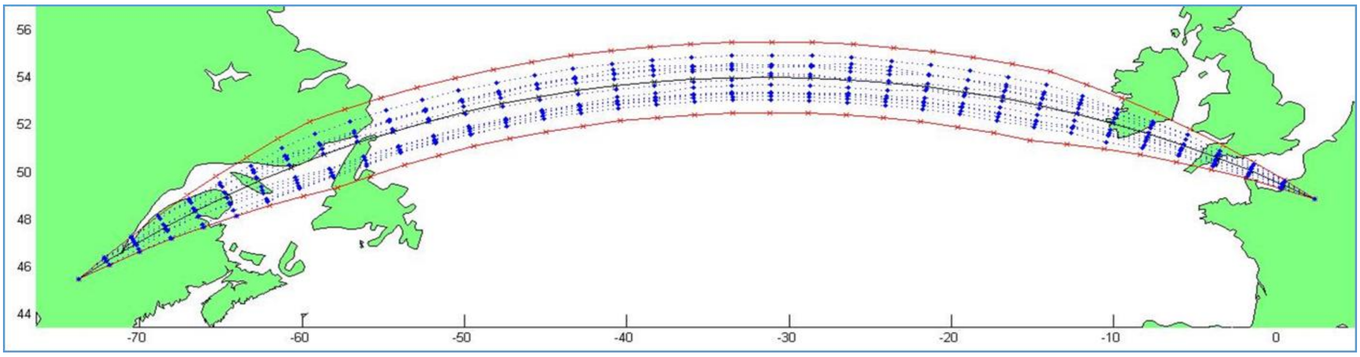

Fig. 2. Trajectories created using the dynamic grid.

3) The ABC in the trajectory optimization

The solution for the shortest LNAV reference trajectory problem can be defined as the set of waypoints from the ToC to ToD that minimizes the flight cost. For the ABC implementation, a given complete trajectory from ToC to ToD is assigned to a "bee" (it can be either employed, onlooker, or scout). The ABC algorithm methodology used in this paper is as follows.

Inputs: Departure and arrival Waypoint (Normally the ToC and the ToD). Weather information. Cost Index. Number of employed bees (*Ne*). Number of onlooker bees (*No*). Number of iterations, maximal counter number.

Phase I - Initialization: A predefined number of trajectories are created. The more trajectories there are; the more search space will be initially covered, but the computation time would increase. A fully-random trajectory creation would be time consuming. In order to reduce the algorithm execution time, there are pre-defined patterns in trajectory randomized creation. Every semi-random trajectory generated is assigned to an "employed bee". Thus, there are an equal number of generated trajectories as there are employed bees. Trajectories are evaluated, by using its positions and the weather at the estimated passage time of the plane.

Phase II - Employed bee: In this step, every employed bee will create a random mutation on their assigned trajectory. The mutation is created by taking into account the behavior of the other trajectories. The more different trajectories there are the more variations in the mutations there will be. The mutated trajectory cost is evaluated and compared to the original trajectory. If the mutated trajectory is more economical than the original trajectory, it becomes the new trajectory for that employed bee; if the mutated trajectory is less economical than the current trajectory assigned the bee, it is discarded.

Phase III - Onlooker bee phase: Depending on their fitness, every trajectory explored by the employed bees is rated. The onlooker bees can follow any trajectory; however, they will be influenced by the trajectories rating. The higher a given trajectory rating, the more likely it is to be selected by several onlooker bees. As there are as many onlooker bees as employed bees, the trajectories with the lowest ratings may not be selected.

Every onlooker bee phase will mutate its selected trajectory, in the same way as during the employed bee phase. The mutated trajectory fitness is computed. When all the onlooker bees have been used, the most economical trajectory is memorized and allocated in memory. As the algorithm is able to give a solution from here, it could be stopped now, or it can be allowed to continue its calculation to refine the solution. This allows a full control of the execution time as it is not mandatory to wait for the end of the calculation to have a solution.

Phase IV - Scout bee phase: Regardless of the phase, every time a mutation fails to create a more economical solution, a counter associated to the studied trajectory is incremented. If a trajectory mutation succeeds, its counter is reseated. However, when the counter reaches a pre-defined number, the associated trajectory is discarded. This allows avoiding spending too much time on a trajectory that is not promising after many mutations, since it might be already the global optimal, or it is stuck in a local optimal. It is not important if the trajectory to be discarded the most economical so far, since it has already been memorized. The discarded trajectory is replaced by a new generic trajectory; based on the initialization process. This is what it is called a "scout bee".If the maximal number of iterations is reached, the algorithm stops here. Otherwise, the algorithm returns to the Employed bee phase, and repeat all this process.

III. Results

The trajectories shown below represent a flight from Montreal – Paris. The geodesic distance for this trajectory is of around 2970 nm. 36 waypoints were considered taking into account weather information. Mach number and flight level were kept constant along the flight. Two flight cases were examined.

Firstly, two schema of the calculated optimal trajectory are presented below. The interest is to show how the form of the trajectories influences the final result.

Fig 3 represents the first flight. The black lines represent the original flight plan (in the center) and the boundaries. The optimum flight plan found is schematized in red. All the trajectories owned by "employed bees" can be observed in green**.**

It is important to observe as well the comportment of the non-optimal trajectories. If it is supposed that all the research space has been covered by the created generic trajectories, then

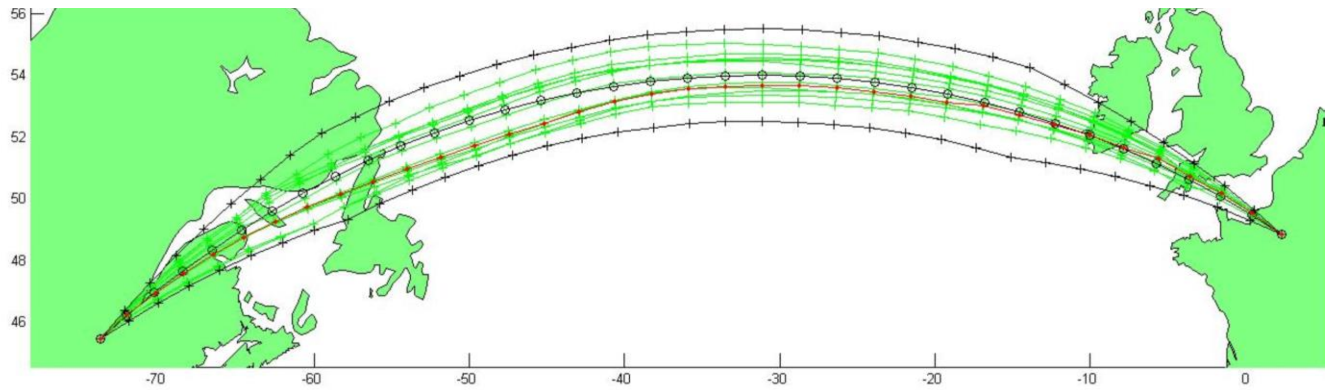

Fig 3. Flight Test 1: Optimized trajectory (red), and explored trajectories (green)

the empty space is the inefficient space. And so if many of them converge to the optimum trajectory, it suggests a strong solution near the optimal found.

In the example of Fig. 3, six trajectories out of twelve are close to the optimal. The other trajectories are searching the rest of the search space, and are most probably either trapped in a local maximum, or not enough developed. This is especially true when the employed bee has abandoned its old solution for a new generic one. However this comportment assures a better coverage of the area, and allows avoiding the local maximum efficiently.

The algorithm was executed again for the same trajectory using the same parameters. As the algorithm depends on the initial semi-random trajectories, and mutations are influenced by these trajectories, the same result is not expected as it can be seen in Fig 4. Although the most economical trajectory seems smoother than the one in Fig 3. the fuel consumption is higher for about 40kg. Looking at the green trajectories, it can be seen that the algorithm is not yet converging to the optimal solution.

The algorithm was executed 1200 times for a flight from Montreal to Paris, the 23th of June 2013. The speed of the plane was 0.8 Mach and its altitude was 33 000 feet. The shortest path in distance for this trajectory was around 2970 NM. The flight began at 12h00m00s 36 waypoints were considered, taking into account weather information.

Following the route of reference (geodesic) the plane requires 26,804 kg of fuel. For 1200 runs, the amount of fuel that the optimized trajectories were able to save was from 102kg to 164kg. The average amount of saved fuel is 140kg, and the median is 139kg. Fig.5 presents the fuel consumption for this test. The horizontal axis is the number of test result, from the lowest to the best, in term of saved fuel

Another variable that influences flight cost is flight time. The algorithm developed in this paper is as well able to save flight time. Following the geodesic reference trajectory, the aircraft required 22,288 s to complete its flight. The results provided by the optimized trajectories saved flight time in a range from 86 seconds to 142 seconds. The average saved time was 119 seconds, and the median was 119 seconds too. Results for the simulated flights can be seen in Fig 6 where the horizontal axis is the test number (sorted by fuel saved).

The algorithm computation required around 260 seconds to find the optimal trajectory. This is considered to be a good computation time result taking into account that 36 waypoints were considered. Computation time can be reduced even further at the stake of diminishing the quality of the solution found.

For every special case, the algorithm can be modified to find better result, as it was the case of a variant explored. In this variant the number of employed bees was two times higher, the iterations were reduced by half, and the mutation counter limit was changed. For the same flight, 240 test were executed, and it as observed that an increment of 10 kg of fuel was found. However, tailoring the algorithm per flight case is not practical as it is time consuming, and the search space can change on a daily basis.

During different algorithm tests, as expected, it was observed that weather has a strongly influence. By decreasing the aircraft Mach number to 0.62, the algorithm saved 186 kg of fuel, for a total consumption of 25,8 tons.

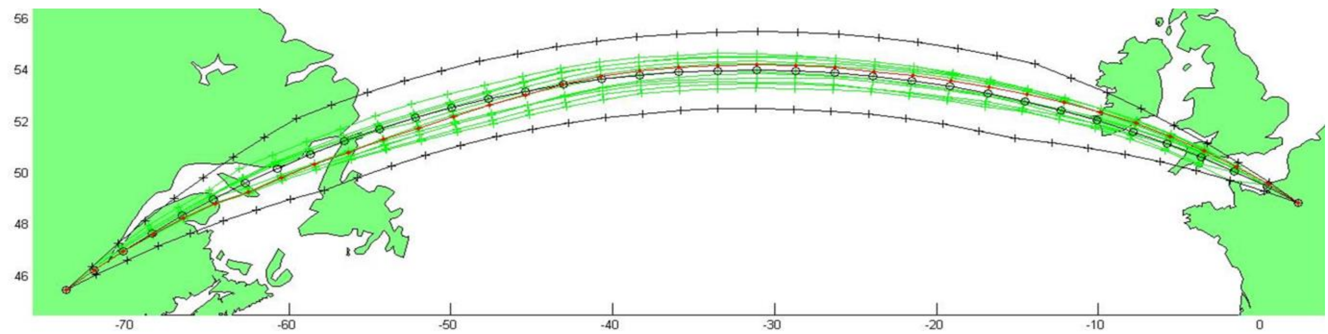

Fig 3. Flight Test 2: Optimized trajectory (red), and explored trajectories (green)

IV. Conclusion And Future Work

An algorithm that optimized the direct trajectory for the lateral navigation trajectory was developed using weather data and an aircraft performance database. The developed ABC algorithm was relatively robust with a low computation time. The preliminary results showed that the optimized trajectories evaluated reduced the flight time, fuel burn, and thus flight cost.

More appropriate results can be found by changing the algorithm parameters such as the number of employed bee, the formula of rating during the onlooker bee phase, the maximum mutation fail allowed, and etc. A deeper study would be required to set the best combination of parameters.

If more time calculation was to be allowed, the ABC could create a smoother and more interesting optimal trajectory. The algorithm's ability to provide the optimal trajectory with a dynamic grid makes it theoretically able to be closer to the true optimal trajectory than an algorithm using a grid.

The low computation time required by the algorithm allows improving this algorithm. Future work consists in using the ABC to optimize the vertical navigation profile, and the speed schedule to fulfill the required time of arrival constraint.

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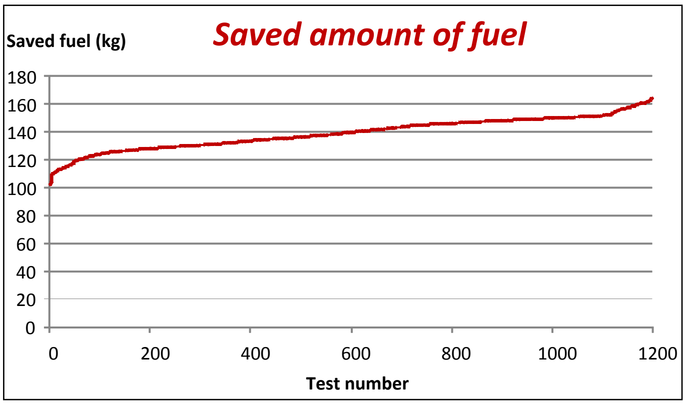

Fig. 5. Saved Fuel for 1200 trajectories

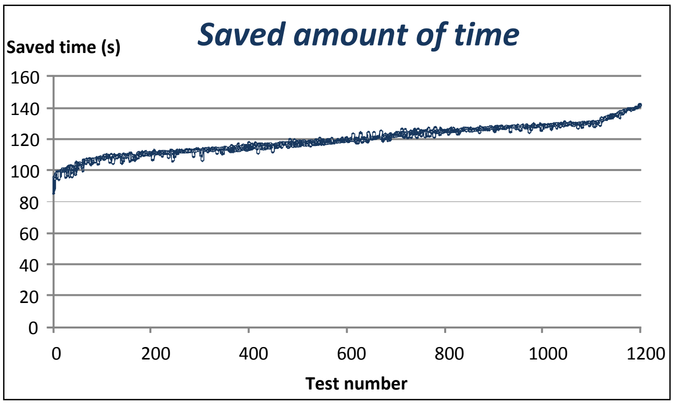

Fig 6 : Saved amount of time

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Development and Validation of an ATC Research Simulator

Tomislav Radišić, PhD
Doris Novak, PhD
Biljana Juričić, PhD
Department of Aeronautics
Faculty of Transport and Traffic Sciences, University of Zagreb
Zagreb, Croatia
tradisic@fpz.hr

Abstract—**ATM research and development relies heavily on simulation methods. For studies involving human factors, real-time human-in-the-loop simulations provide the most reliable results. From the perspective of a researcher, these types of studies are often also the most complex to perform. One of the issues researchers face is the lack of suitable research simulators that can be freely modified to perform in the desired manner. Commercial simulators are mostly produced for training and each upgrade, especially development of custom modules, is quite costly, sometimes even prohibitively so. For this reason, in this paper the process of research simulator development will be presented, from the definition of simulator requirements to simulator validation and operation. Some of the key technologies will also be presented along the way. The simulator presented here was built and used to examine the effect of trajectory-based operations on air traffic complexity in en-route sectors. Authors believe that although this design is not generic enough to be used for all purposes, there is still a large number of research topics that can be examined with such simulator. Furthermore, methods and solutions presented in this paper can also be applied to other simulator designs.**

Keywords - ATC; simulation; real-time; human-in-the-loop; air traffic complexity

I. INTRODUCTION

Simulation is a core method for ATM research and training, with different purposes requiring different levels of fidelity and simulation scope. Fidelity refers to the level of similarity between the simulated environment and the actual operations. Simulation scope can be broadly divided into strategic and tactical simulations. Strategic simulation tools (e.g. EUROCONTROL's NEST) are used to analyze current and forecast future ATM situation on a global level. On the other hand, tactical simulation tools are used to accurately simulate ATC operations on a sector level (e.g. ATCoach by UFA or Micronav's BEST Radar Simulator). Whatever the purpose, research teams have several ways to acquire the required simulation research tools. Large organizations such as NASA or EUROCONTROL are able to develop and maintain their own ATC research simulator centers. Smaller research groups have to use commercial ATC simulators which are very high fidelity but not easily customizable or develop their own purpose-built simulators with limited features and fidelity. Another option is to use a third-party open-source ATC simulator such as the one developed at the University of Queensland [1] with all its limitations.

This paper presents a set of methods and tools that can be used to develop a custom research ATC simulator. Advantages of a purpose-built simulator are: complete control of the features developed for the specific research task, ability to develop the simulator to the desired standard of fidelity and scope, better understanding of the simulator operations, lower cost, and possibility of future upgrade. Disadvantages, of course, should also be considered and they include: need for expert programming knowledge, need for deep understanding of ATC operations and tools, and spending time that could otherwise be used to do actual research.

The ATC research simulator presented in this paper was developed to study air traffic complexity on a tactical (sector) level. Research objective was to determine the effect trajectory-based operations (TBO) have on air traffic complexity. The scope of the study was limited to nominal en-route operations with no extreme weather conditions. It is presented here as an example of how the simulator requirements were shaped by research objective and how those requirements were implemented in a way which enables future development and growth.

II. SIMULATOR REQUIREMENTS

Simulator requirements can be divided into two groups – general and specific. General simulator requirements are those that are independent of simulator purpose. They are commonly accepted as best practice for most forms of application development. In this project, following general requirements for the simulator development were set: reliability (decreased likelihood of simulation failure, robust exception handling), maintainability (simple code structures, standard naming conventions, modular design, documented code, testability), efficiency (network, disk, and memory management, code optimization), extensibility (loosely coupled modules), and portability (external configuration) [2].

To define specific simulator requirements, the researcher will have to provide answers to questions regarding the purpose and the aim of the research that will be conducted. These are: Is fast-time or real-time simulation needed? How accurate should the aircraft model be? Should generic or actual aircraft types be used? How representative of the real working environment should the simulator be? What hardware is needed? Will there be a pseudo-pilot or will the ATCOs do everything by themselves? What type of communication will there be: voice, datalink, or both? Is it necessary to be able to simulate failures? How detailed should the weather and surveillance models be?

With these questions and general requirements in mind, the following specific requirements for the development of the ATC simulator have been set according to the aims of the study:

Real-time human-in-the-loop simulation. For high-fidelity ATC simulation it is necessary to include the actual ATCOs in the simulation. This means that the simulation will have to be performed in real-time and that the working environment will have to be as similar as possible to the real working environment.

Accurate and versatile aircraft model. It was determined that the aircraft model used in this research had to satisfy following criteria: ability to model more than 95% of aircraft types flying in Europe, have accurate aircraft climb and descent profiles, have realistic turn performance, realistically model aircraft performance and limitations, have reasonably accurate 3D/4D FMS algorithms. This enables usage of the actual traffic data without the need to exclude or substitute aircraft types. Also, accurately modelled turns and vertical profiles enable simulating terminal operations.

Realistic working environment. It had to be similar to the actual working environment to which the ATCOs are used to. This includes the layout of the radar screen, auxiliary screens, keyboard, mouse, and communication switches. User interface had to be similar to the existing ATC simulators and workstations to give the ATCOs a smooth transfer to the simulator (without extensive training). In this project, working environment was adjusted to resemble actual working environment that the participants were used to. For some other purposes, a generic simulator layout could be useful.

Representative ATC tool operation. For this research a limited set of ATC tools had to be developed. It was not necessary to develop a complete set of professional ATC tools because this study consisted of a limited set of simulation scenarios and traffic situations. Those ATC tools that were developed though, needed to function in a manner that is representative of the actual tools. Also, new tools could easily be added due to modular design of the simulator. Required tools were: map tools, display tools, range and bearing lines, level filter, SSR code filter, separation tool, area proximity warning, short-term conflict alert, separation infringement alert, route/trajectory display, flight profile display, strip-less flight progress monitoring tools, datalink interface, velocity vectors, and flight trails.

Ability to record all necessary data. Since the primary purpose of this simulator was research, it was important to implement the function to record as much data as possible. Data that had to be saved were: complete aircraft states (trajectory, heading, TAS, mass, thrust, pitch, bank, fuel flow etc.), human-machine interactions (mouse and keyboard events), voice communications, and radar screen images.

Easy data editing. Medium and high fidelity ATC simulations are based on actual airspace configurations or sufficiently complex generic instances thereof. Simulator had to enable easy configuration of all airspace-defining data and quick switching between different airspace configurations. Additionally, simulation scenarios had to be created and edited, therefore, the data editor had to allow quick and easy scenario creation and updating. In this project, a data pipeline was established for feeding actual historic flight plan data into the simulator, thus automatically generating traffic for scenarios.

Voice and data link communication. Some ATC simulators allow the air traffic controller to directly change the aircraft state variables such as heading, level or speed. However, ATC simulators aiming at high(er) fidelity have to adopt the approach that more closely mimics the actual ATC operations. This means that ATCO has to issue instructions to the pilot either via voice communication or data link and it is pilot's job to follow those instructions (or, in the case of simulation, it is pseudo-pilot's job to do so). This type of operations is very important in studies examining capacity, workload or complexity, because the communication tasks make a substantial fraction of controller taskload and in some cases they even limit the sector capacity. In this study a commercial VoIP solution was used for voice communication and data link was implemented in the simulator itself.

Local Area Network operations. Since the controller's and pseudo-pilot's stations need to exchange data in real-time, some form of communication was needed between the two stations. In this study the communication was limited to local area network which somewhat simplified the development due to high bandwidth and insignificant lag. For remote operations (over Internet) special care must be taken to reduce the bandwidth requirements and lag.

Simple meteorological model. While weather phenomena are very complex and diverse and have a profound impact on flight operations, for ATC simulation a simplified model is adequate for most purposes. Arguably the most important weather phenomena, in nominal operations, from the perspective of an air traffic controller are wind, thunderstorms, icing, and turbulence [3]. For studies dealing with the weather more specifically, a more advanced model should probably be used.

Support for TBO. The simulator used in this research had to be able to support trajectory-based operations (TBO). TBO support consisted of generating 4D trajectories, simulating aircraft flying 4D trajectories, and displaying those aircraft with all additional information (trajectories and flight profiles).

Simple surveillance system model. ATC simulator can be built to accurately represent various surveillance systems, such as radars, ADS-B, and multilateration, and their properties.

This type of surveillance system models are useful when controller's response to partial radar failures or system degradation are studied. In this study nominal operations were studied, therefore only a simple radar system model was needed. Radar targets were updated every 5 seconds with actual aircraft positions with no options for reduced accuracy or precision. Pseudo-pilot had the option of setting the assigned SSR code and squawking IDENT, while the controllers had the option of filtering the traffic according to SSR codes. It is possible to upgrade this model with more features if the need arises.

These specific simulator requirements were used during the development of the ATC research simulator for this study (air traffic complexity assessment). For other types of studies, different specific requirements would have to be defined and met.

III. Simulator Framework overview

In accordance with the previously discussed simulator requirements, a prototype was developed and it will be presented in this section. Authors believe that although this design is not generic enough to be used for all purposes, there is still a large number of research topics that can be examined with such simulator. Furthermore, methods and solutions presented in this section can also be applied to other simulator designs.

Proposed simulator framework can be broadly separated into two parts: data and application. Each of these two parts has a series of components. Since the first rule of application portability is not having any hard-coded data, all data and configuration was separated from the application (Figure 1, left side). This includes all user interface (UI) labels, tool tips, names, and database headers, which are all stored in the *Settings* file. Database components also include: geographic data (country borders, coastline, elevation model), Base of Aircraft Data – BADA (EUROCONTROL's database of aircraft performance data), weather (3D grid with wind direction and speed, thunderstorm locations and times, icing and turbulence areas), scenarios (determines which sets of geographic, weather, airspace, and flight plan data will be used), flight plans (database of all flight plans, some or all of which are used in a scenario), and airspace (data defining airspace(s), one airspace is used in any scenario).

Next, short description of simulator modules will be presented (Figure 1, middle). Simulator administrator (researcher) uses *Data Editor* module to input or modify the

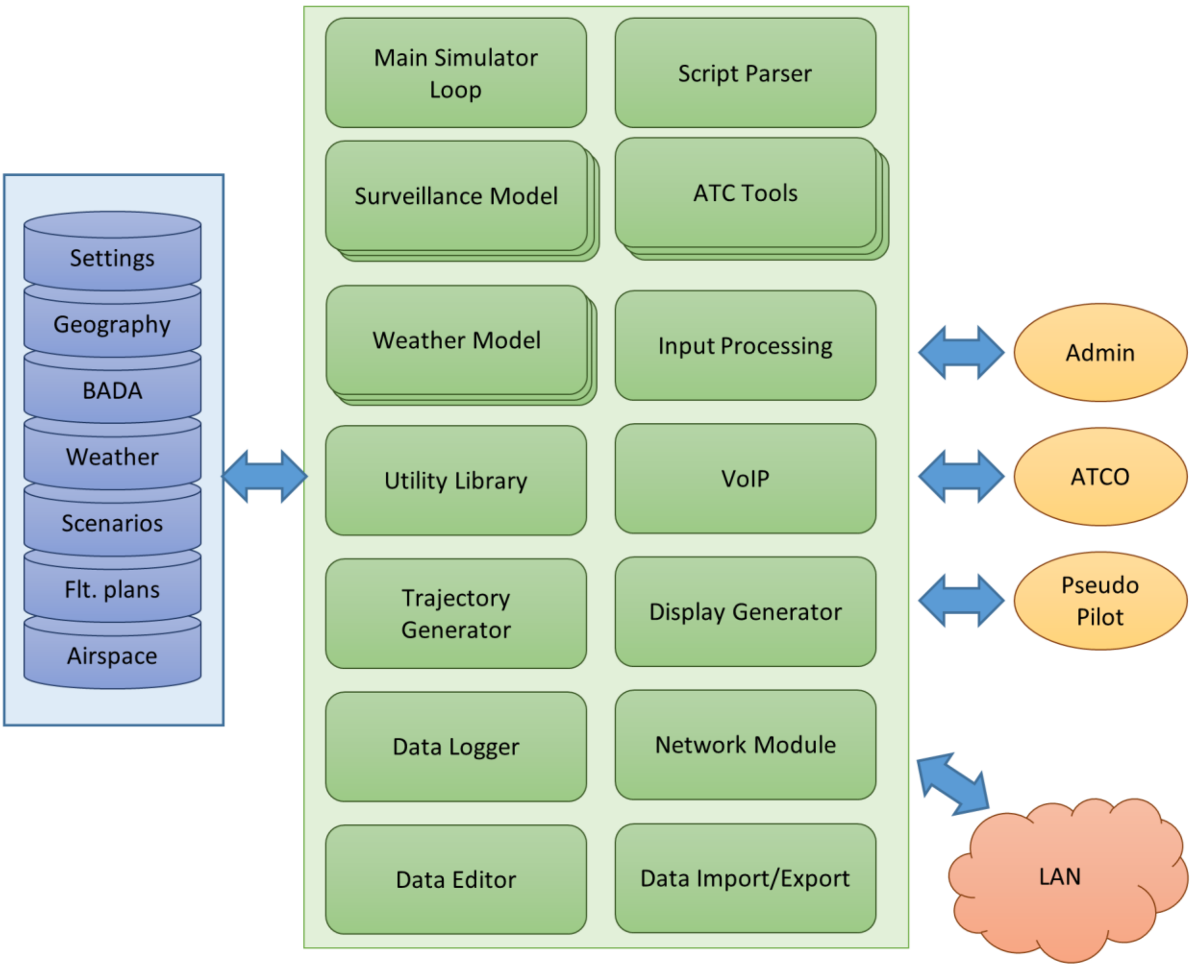


Fig. 1. Simulator Framework

data stored in the databases. For example, in this study Aeronautical Information Publications (AIPs) were used to obtain airspace data, EUROCONTROL's Demand Data Repository 2 (DDR2) was used for historic air traffic, local meteorological service providers or *meteocentre.com* were used to obtain weather information, and the database of Global Administrative Areas (*www.gadm.org*) was used for country borders and coastlines. Researcher then prepares simulation scenarios which use subsets of this data for the actual simulation runs with addition of scenario script which initiates scenario events (e.g. climb/descent requests, failures etc.).

Main Simulator Loop is responsible for activation of specific modules based on settings and scenario objectives. Multiple versions of some modules (e.g. weather model) can be available for use and depending on the purpose of the simulation, appropriate model will be loaded by the *Main Simulator Loop*. Most modules are started in separate asynchronous threads to prevent one module from pausing others while some longer operation is completed. This module also adjusts the UI and simulator operations for the requested station (ATCO or pseudo-pilot), establishes network connection with the other station (via *Network Module*), and controls the simulator operation (via *Input Processing* module).

Once the simulator is active and the scenario selected, *Data Import/Export* module loads all required data into memory for faster retrieval (in line with efficiency requirement). This data is then used by *Trajectory Generator*, along with data generated by the *Weather Model*, to generate current aircraft positions and their future trajectories. *Display Generator* then renders the radar screen by overlaying radar targets and labels onto the background map created from geographic and airspace data.

IV. CORE SIMULATOR TECHNOLOGY

In this section some of the technology needed for simulator development will be presented. General coding techniques, such as data input/output, parsing, event handling, or multi-threading, will not be covered here in order to save space. The focus will be on three simulator components: aircraft model, workstation hardware layout, and ATC tools.

A. Aircraft Model

Aircraft model is the integral part of the *Trajectory Generator* module and is in fact a hybrid model made of three separate models: aircraft performance model, aircraft dynamics model and flight management system model.

Having considered all requirements mentioned in previous sections, EUROCONTROL's Base of Aircraft Data (BADA) Aircraft Performance Model (APM) was chosen as a starting point for aircraft model. Its main advantages are support for many different aircraft types, easy implementation, and excellent documentation.

BADA, however, provides only for modelling aircraft performance so the models of aircraft dynamics and Flight Management system (FMS) had to be developed from the start. BADA is a database of aircraft data developed and updated by EUROCONTROL Experimental Centre (EEC). As mentioned by [4] the aircraft performance information provided in BADA '*is designed for use in trajectory simulation and prediction in ATM research as well as for modeling and strategic planning in ground ATM operations*'. It provides ASCII files containing operation performance parameters for 405 aircraft types – of these 150 are original and 255 are equivalent aircraft types. Equivalent aircraft types, also known as synonym types, are not covered by one of the BADA files directly, they are linked to one of the 150 original types [5]. For each original aircraft type three files are provided. *Operations performance* file with specific parameters needed to model the performance of that aircraft type. *Airline procedures* file which contains speed schedules for airlines (one default speed schedule is provided for each aircraft type – user can define others). *Performance table* file which provides tabulated TAS, rate of climb/descent, and fuel consumption for each aircraft type at different flight levels. In addition, synonym file (links original and equivalent aircraft types) and global aircraft parameters file are provided.

The kinetic approach to aircraft performance modelling, as used in BADA, seeks to accurately model forces acting on aircraft represented as a single point. Total Energy Model (TEM) is then used to determine the distribution of the work done by these forces towards increase or decrease of aircraft's potential and/or kinetic energy.

As shown in the HYBRIDGE project [6], for ATM simulation purposes, aircraft dynamics can be adequately modelled using a Point Mass Model (PMM). It is the aircraft dynamics system which, based on six state variables (x, y, and z coordinates, TAS, heading, and mass), four inputs (thrust, pitch, bank, and drag), and three disturbances (three wind components), determines the change of aircraft state variables (1). Since three of the six state variables represent aircraft coordinates, output of this system effectively provides aircraft trajectory.

$$\dot{x} = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \\ \dot{x}_6 \end{bmatrix} = \begin{bmatrix} x_4 \cos(x_5)\cos(u_3) + w_1 \\ x_4 \sin(x_5)\cos(u_3) + w_2 \\ x_4 \sin(u_3) + w_3 \\ -\left[\left(\frac{u_4 S\rho}{2}\right)\cdot\left(\frac{x_4^2}{x_6}\right)\right] - [g\sin(u_3)] + \left(\frac{u_1}{x_6}\right) \\ \left[\left(\frac{C_L S\rho}{2}\right)\cdot\left(\frac{x_4}{x_6}\right)\right]\cdot\sin(u_2) \\ -\eta\cdot u_1 \end{bmatrix} = f(x,u,w) \quad (1)$$

This system uses state variables (x), inputs (u) and disturbances (w), along with additional terms such as aircraft total wing surface area, S, air density at altitude, ρ, acceleration due to gravity, g, aerodynamic lift, C_L, and fuel consumption factor, η, to calculate the change in state variables.

The purpose of the FMS model is to determine how to change inputs in order for aircraft to follow the desired path from the flight plan. The inputs that FMS uses are similar to the inputs that pilots use to control an aircraft.

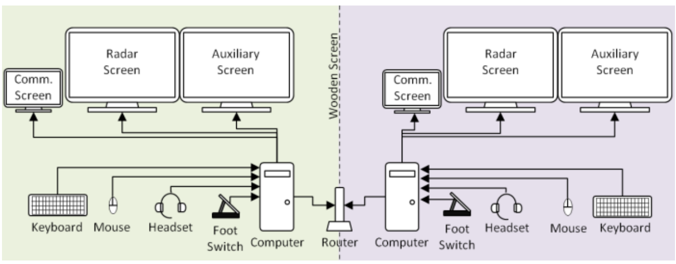
The first thing an FMS must do is to determine the current aircraft position and speed relative to the desired path and speed. Next, it must determine the inputs needed to correct differences between the two. There are however, some differences in control strategies between different phases of flight. For example, the aircraft is controlled differently in climb than in descent, aircraft configuration is different during the approach phase than in cruise flight, different limits on control inputs are enforced during different phases, etc. Due to this, aircraft state is additionally described by a set of discrete variables (e.g. variable *ClimbMode* can have values: *Climb*, *Level*, and *Descent*). For each of the discrete variables (states) a simple finite state machine (FSM), governing conditions under which aircraft changed states, was developed. The values of the variables that are set by finite state machines are used to determine the values of inputs (u) used in (1).

Of the four inputs, pitch angle and thrust are used together to achieve the required TAS and rate of climb/descent. Bank angle is used to move the aircraft towards the desired flight track, and the drag coefficient is set in accordance with the aircraft configuration that is required for the current phase of flight (e.g. gear and flaps are extended during approach phase). A series of limitations is set on the maximum values and maximum rate of change of pitch angle, bank angle, and thrust in order to prevent unusual or overly dynamic maneuvers.

B. Workstations

Humans receive most of the information about their surroundings visually. Radar screen is the main source of the visual information for the air traffic controller. Therefore, the simulator used for this research had to be as representative of the real radar screen as possible.

It must be noted that the term 'radar screen' is slightly misleading in the context of modern air traffic control. Though radars are still the primary source of aircraft position information, modern ATC workstations do not have an actual radar screen. The information provided by the radar is instead heavily filtered and correlated with other information related to that particular aircraft. Because of this, modern 'radar' screens are more akin common computer screens with fairly simple vector graphics than the old analogue radar screens. The main difference between the common commercial electronics computer screen and professional ATC work station screen is the aspect ratio. While computer screens are usually produced in a number of widescreen formats, ATC screens usually have 1:1 aspect ratio (i.e. they are square). Therefore, the case can be made for using commercial off-the-shelf screens to simulate ATC work stations. This approach was used in this research. Hardware layout can be seen in Figure 2.



ATCO Station — Pseudo-pilot Station

Fig. 2. Hardware Layout

Other devices used for human-machine interaction in the context of ATC are keyboard, mouse, and radio communication switch (hand and/or foot operated).

Headphones and microphone are used for radio communication.

For this research, following work station configuration was used:

- One computer screen for radar display.
- One computer screen for additional information (flight plans, meteorological information).
- One touchscreen for central switchboard (telephone and frequency switches).
- Keyboard and mouse for data entry and manipulation
- Headset (headphones + microphone) with hand and foot operated comm. switches.

C. User Interface and ATC Tools

Radar screen interface elements used for this research can be divided into three sections:

- Map with correlated radar targets (aircraft and data labels)
- Tool strip (ATC tools and basic information)
- Control panels (displayed according to controllers actions).

The layout of radar screen display of the simulator developed for this research can be seen in Figure 3. Map is built of individual layers, which represent country borders, Flight Information Region (FIR) borders, coast, restricted airspace zones, navigation points, navigation aids etc. Map can be dragged with mouse and zoomed in/out with mouse scroll button.

Aircraft are displayed as circles with trail of dots representing aircraft's trajectory in the past 30 seconds, and with a line showing its current track vector. The color of the aircraft target changes depending on the state of that aircraft.

Aircraft labels are connected with the appropriate aircraft by solid lines. Labels initially show limited set of flight data; however, they expand on mouse hover to show expanded set of data. Labels are also the main interface between controller and strip-less flight progress monitoring system. By clicking on the aircraft label, the controller can accept the aircraft from the transferring ATC unit, and assign flight level, speed, heading or route according to instructions given to the aircraft (Figure 4). This allows the controller to keep track of the given instructions and to monitor flight's progress. It also makes possible for clearance adherence algorithms to work.

Tool strip is located at the top of the radar screen and houses the following tools (seen at the top of the Figure 3):

- Map re-center – Centers the map on the center of the airspace sector. It is used to quickly return to the main

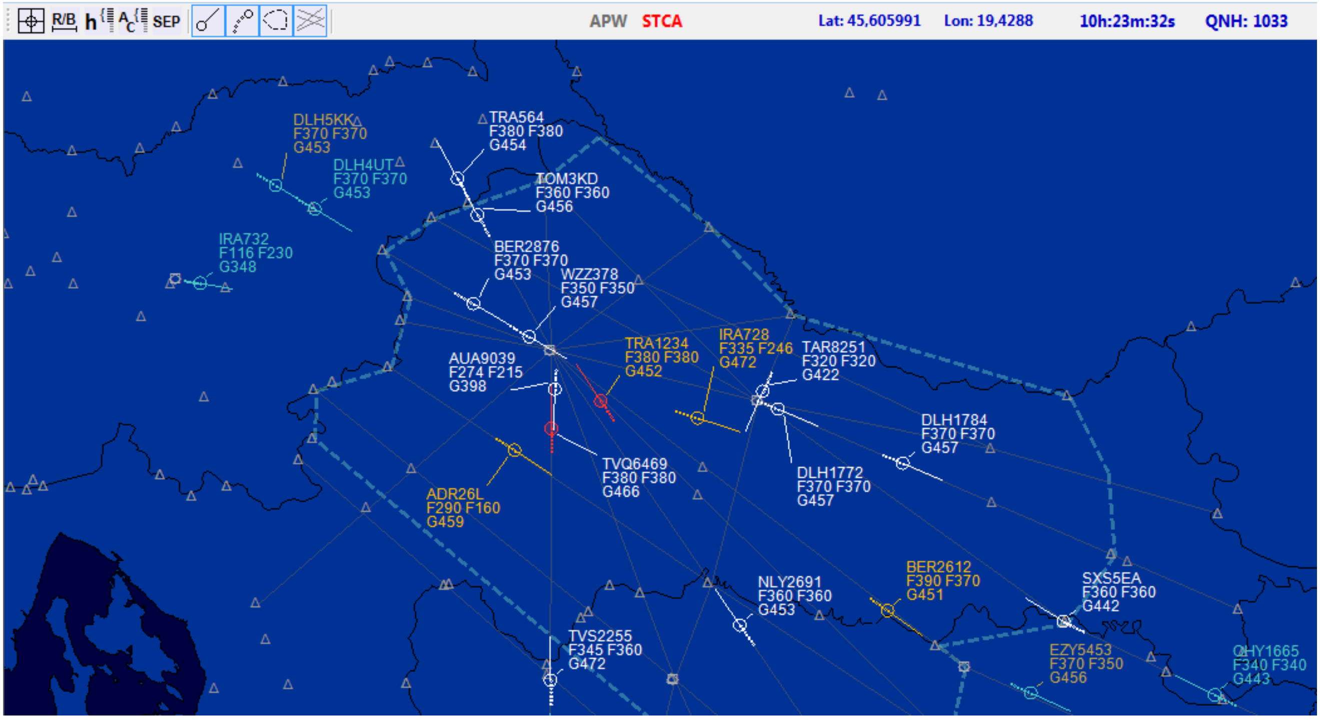


Fig. 3. Main Radar Display

mode of display after zooming in or scrolling to the side.

- Range and bearing line – Measures the distance and range between two points on the map.
- Height filter – Filters the aircraft according to altitude. Filtered out aircraft are displayed as grey aircraft targets without labels.
- SSR code filter – Filters the aircraft according to Secondary Surveillance Radar (SSR) codes.
- Separation tool – Extends the track vectors of two selected aircraft to the point of their closest approach and displays separation distance (in nautical miles) and time until the point of closest approach is reached (in minutes and seconds).
- Display tools – used to adjust four display layers directly from the simulator. These layers are: aircraft track vectors, aircraft trails, sector boundaries, and standard routes. All other display layers are editable through text files.
- Area Proximity Warning (APW) – Activates when an aircraft is about to enter the sector without being accepted or, when an aircraft is about to exit the sector without being transferred to another ATC unit. The 'APW' sign starts to flash purple and is accompanied by a single sound alert.
- Short Term Conflict Alert (STCA) – Activates when two aircraft are less than two minutes away from separation minimum infringement. The 'STCA' sign starts to flash red and is accompanied by a single sound alert.
- Separation infringement alert – Activates when two aircraft have infringed on the separation minima. The whole tool strip flashes red and aural warning is sounded repeatedly.
- Other data – Latitude/longitude display, simulation time, QNH.

For aircraft flying TBO, an air traffic controller can also see the trajectory profile. This information is displayed in a separate window on the secondary monitor. Flight profile information is used by controllers to separate aircraft flying conventional operations from TBO aircraft.

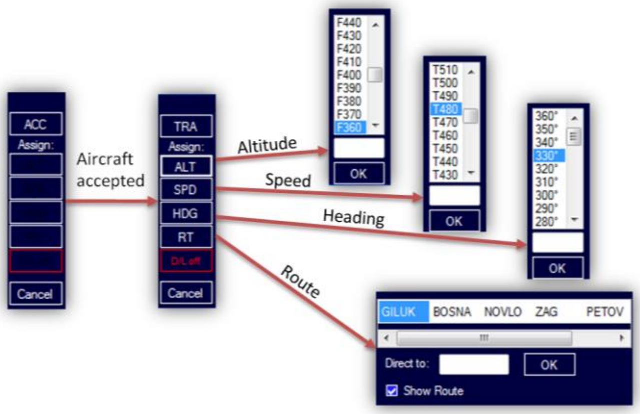


Fig. 4. Stripless Flight Progress Monitoring

Both air traffic controller and pseudo-pilot also have a separate list of flights which contains aircraft call-sign, type, departure aerodrome, route, destination aerodrome, and requested flight level (RFL). The user can sort this list by any column desired. Pseudo-pilot can open the main command panel by double-clicking the desired aircraft's call-sign.

V. Simulator Validation

The purpose of validation is to determine whether the simulator satisfies specified requirements. A full-scale, commercial ATC simulator solution is a complex system with multiple sub-systems using different models and technologies. On the other hand, this ATC simulator is a simplified, single-purpose system with significantly lower complexity and breadth of functions. The simulator was never to be used as a training device in its current form, nor has it had to be certified for safety-of-life functions. These conditions made the validation of the simulator much less demanding.

Though code testability requirement was met by implementing unit tests at class level, during the integration additional validation of the more complex modules had to be performed. Validation of the aircraft model was very important because accurate aircraft model enabled study participants (ATCOs) to make use of their experience and expert knowledge of aircraft performance to accurately assess the traffic situation (e.g. for conflict detection). It was also quite complex because the aircraft model is a hybrid system made of three distinct models (BADA APM, aircraft dynamics model, and FMS model). The approach taken in this research was to validate the aircraft model holistically by comparing the output of the aircraft model with the actual flight data obtained via Quick Access Recorder (Figure 5). The Quick Access Recorder (QAR) data was obtained for five flights by the Airbus A320 and five by the Bombardier Q400. Though it would have been more representative of the real aircraft distribution to include at least one heavy aircraft into this comparison, such data was unavailable. Nevertheless, the medium range jets and turboprops constitute largest relative fraction of the actual aircraft types in airspace of interest, so the authors believed that the compared aircraft were representative enough. The comparison of actual and modelled flights was however, made difficult by several factors.

First, variation of the weather conditions that occurred during the course of the actual flights introduced many errors. For instance, in one flight the wind varied from 5 knots at ground level to more than 80 knots at FL 240. The simple 3D grid wind model therefore, could not be used. Instead, the aircraft model was temporarily upgraded to include weather information from the look-up table produced from the QAR data. This ensured that the modelled aircraft ‘flew’ in almost exactly the same weather conditions as the actual aircraft. Each row in the look-up table corresponded to the weather conditions in a 100 meter thick layer of the atmosphere. The upgrade was later dismantled because it had no utility in further simulations.

The second problem was the speed schedule used by the airlines. BADA’s default speed schedule was found to be biased towards higher speeds overall, so the speeds had to be decreased in order to match the speed schedule of the actual flight. For example, in BADA the Airbus A320 is scheduled to climb with 250 knots CAS at low altitudes and 300 knots at high, while the actual flight was flown with around 240 and 280 knots, respectively. Also, the BADA airline procedures

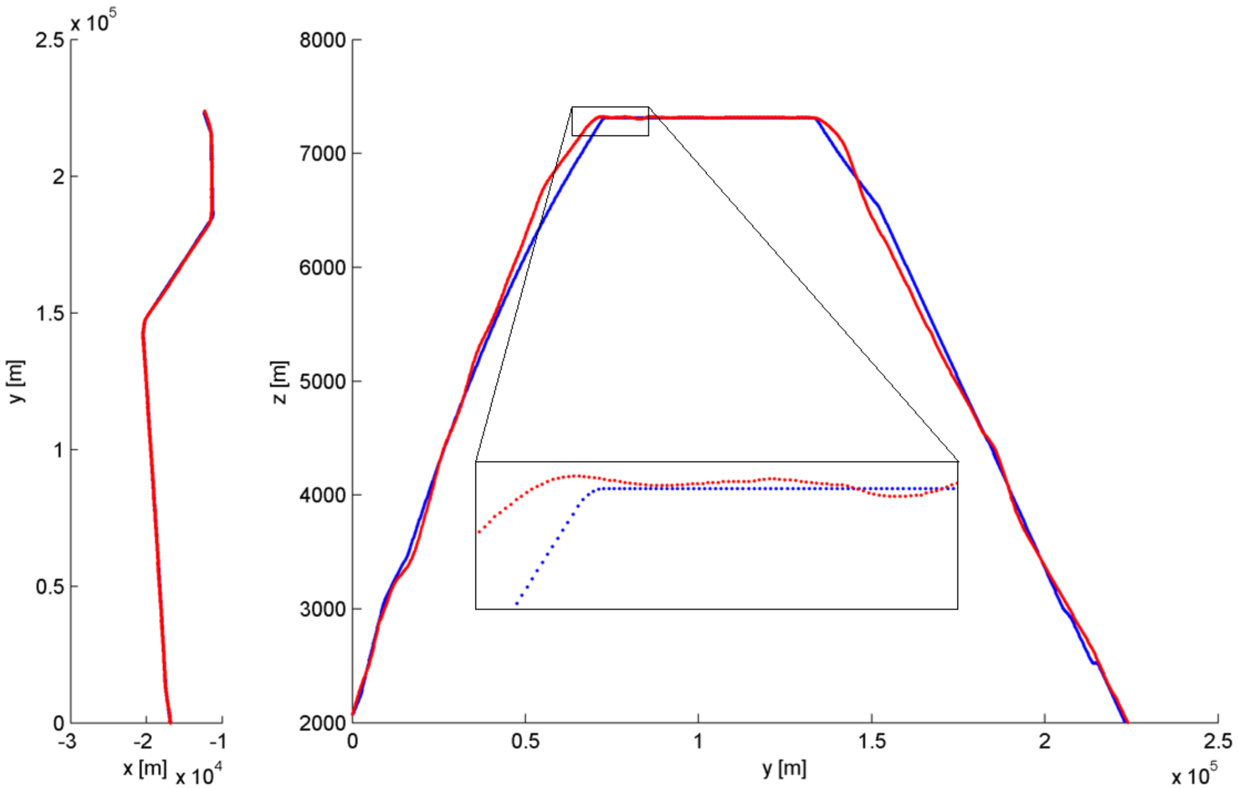


Fig. 5. Comparison of the Actual (Red) and the Simulated (Blue) Aircraft Trajectory (Top And Profile View)

model has only three different values for speed per flight phase (climb, cruise, descent) compared with many speed settings available to the actual FMS.

The third factor affecting the aircraft performance was the initial aircraft mass. Unfortunately (and surprisingly), the QAR data did not have the actual mass information so the masses of the modelled aircraft had to be tuned until the model performed as good as it could.

An example of the comparison between actual and modelled aircraft trajectory can be seen in Figure 5. Pictured is the trajectory of the Airbus A320 on a short local flight. Red lines represent the actual flight and blue lines the simulated flight. On the left of the figure is the top view and on the right is profile view.

One feature that is immediately noticeable is the relative smoothness of the simulated trajectory compared to the actual trajectory. Obviously, the FMS of the actual aircraft has to account for more disturbances than the simulated one (e.g. turbulence), however, the differences in trajectories at such a small level are not noticeable on the radar screen.

Finally, for the same example flight the 3-D error is shown in Figure 6. The error is calculated as a 3-D distance from the actual aircraft to the simulated aircraft for each second of the flight; therefore, apart from vertical and lateral, it also includes the along-track error. Maximum error is 4.7 km which is negligible for the purpose of this research.

All in all, the aircraft model can be considered valid and representative of the actual aircraft in the context of ATC operations. Several adjustments (wind, speed schedule, mass) are needed to bring the simulation results closer to the actual flight data since the default settings for an aircraft type are different than the settings used in practice.

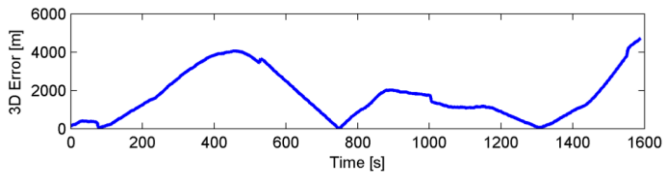


Fig. 6. 3-D Error of the Simulated Trajectory

Next in the validation process was the validation of the user interface and functionality testing. User interface was designed in accordance with the best practices observed from two professional ATC systems. However, as stated previously, not all of the tools have been, or needed to be, developed because not all of them were useful for this research. Validation of the user interface and functionality testing was performed during the trial runs with the assistance of two air traffic controllers who were not involved in this research in any other way. Feedback was received via unstructured interviews during which the controllers explained which user interface elements and simulator functions needed to be modified and why. These trial runs resulted in minor changes to functionality of the separation tool, color schemes, and interface layout. Additionally, some of the simulation scenarios were adjusted during these runs.

VI. SIMULATOR-SUPPORTED STUDY

The ATC research simulator was developed in order to examine the effect of TBO on air traffic complexity. In this section a brief overview of that study, with emphasis on simulator operations, will be presented. Full explanation of methodology and detailed analysis of the results will be presented in another paper.

This research was motivated by a combination of factors. The SESAR documents clearly emphasize the expected reduction in air traffic complexity after the introduction of TBO [7] but on the closer inspection the authors have concluded that there was virtually no scientific evidence of such an effect. Although the positive effect of TBO on complexity could be expected (based on the aggregated body of evidence explaining interactions among complexity, workload, and capacity [8], [9], [10], and [11]), only a dedicated study could prove or disprove its existence. Filling the gap between current evidence and expected results was the main motivation for the authors to begin the research.

Other reasons for this research stem from the previous research by the authors. Previous research, which was mostly focused on 4D navigation and conflict detection and resolution, was conducted using the fast-time simulations which proved (to the authors) the feasibility of 3D and 4D trajectory generation using hybrid aircraft models. A logical step forward was to test the concept using the real-time human-in-the-loop simulations.

Therefore, the main objective of this research was to measure the effect of TBO on air traffic complexity in en-route operations. This was to be achieved by performing an experiment on an ATC HITL simulator with air traffic controllers giving subjective complexity scores for conventional and trajectory-based operations.

Participants in the experiment were all trained and licensed ATCOs who had experience controlling the traffic in the Croatia Upper North airspace sector.

Nine different simulation runs were conducted involving three operations environments (conventional traffic, 30% aircraft flying TBO, or 70% aircraft flying TBO) and three air traffic levels (*low*, *high*, or *future*). Traffic data were sampled during off-peak periods to build scenarios with low traffic levels, and from peak periods to build scenarios with high traffic levels. In scenarios featuring a future traffic level, additional flights were added to routine traffic to give rise to an unrealistically high aircraft count; in addition, the proportion of aircraft climbing or descending was higher than in scenarios with low or high traffic levels. The aim of the future simulations was to expose controllers to complexity beyond what can be expected nowadays and beyond what the controllers had previously encountered in their careers.

Before the simulations, each controller received brief training in order to become accustomed with the simulator interface and operational procedures. The training consisted of an introductory lecture, pre-simulator briefing, trial simulator runs, and a post-simulator briefing. The introductory lecture covered basic topics in air traffic complexity, the subjective complexity rating scale used in our study, TBO, simulator tools and features, airspace, simulator scenarios, and operational procedures. The trial simulator runs lasted at least 90 min and involved two scenarios, one with conventional operations and one with TBO. All participants declined to participate in additional training simulations that were offered, indicating that they felt sufficiently comfortable with the simulator operations.

Controllers were asked to subjectively rate air traffic complexity throughout the simulation, using a modified Air Traffic Workload Input Technique (ATWIT) [12] scale that we term the Air Traffic Complexity Input Technique (ATCIT). The ATCIT scale features seven levels of complexity.

TABLE I. ATCIT SCALE

Complexity Level	Description
1	No complexity – no traffic
2	Very low complexity – very little traffic, no interactions
3	Low complexity – situation and interactions obvious at a glance
4	Somewhat low complexity – firm grasp of the situation, interactions are anticipated and prepared for
5	Somewhat high complexity – aware of the situation, interactions are handled in time
6	High complexity – having trouble staying aware of all interactions, occasionally surprised by unnoticed interactions and conflict alerts
7	Very high complexity – losing situational awareness, unable to track all interactions, responding reactively

The levels of subjective complexity on this scale reflect primarily the controller's self-assessment of situational awareness, while also taking into account aircraft-aircraft and aircraft-airspace interactions. Before using this scale, controllers were briefed about the objectives of the ATCIT scale and the meaning of 'complexity', 'interaction', and 'situational awareness'.

During each simulation run, a Subjective Complexity Measurement (SCM) tool opened every 2 minutes, accompanied by non-intrusive aural notification. The tool presented 7 buttons labeled 1-7, and the controller had to click on the button most closely matching the perceived level of air traffic complexity. Each assessment was time-stamped and stored. This is an example of simulator customization that might be very difficult or impossible to perform on an off-the-shelf simulator.

Our hypothesis in these experiments was that TBO would lead to lower air traffic complexity than conventional operations in en-route airspace sectors. The hypothesis was tested in three stages: first, means were compared between conventional and TBO scenarios in simulations with *low* traffic level; next, this process was repeated for simulations with *high* and *future* traffic levels. The hypothesis was tested using one-way repeated-measures ANOVA independently for each of the three traffic levels.

For scenarios with *low* traffic levels, after correcting for lack of sphericity, the results showed no significant effect of TBO on subjective complexity. For scenarios with *high* traffic levels, the results showed that TBO was associated with significantly lower subjective air traffic complexity scores. Post-hoc analysis showed that the mean difference was significant only between 0% TBO and 70% TBO, and between 30% TBO and 70% TBO. Since subjective complexity was assessed on an ordinal scale, we confirmed our results using the non-parametric Friedman test which yielded same results.

For scenarios with *future*-traffic analysis showed that TBO significantly reduced subjective air traffic complexity scores. Post-hoc analysis using the less stringent least significant difference to adjust for multiple comparisons showed significant differences between 0% TBO and 70% TBO and between 0% TBO and 30% TBO, but not between 30% TBO and 70% TBO. Results were confirmed with non-parametric Friedman testing.

These results suggest that TBO can significantly reduce subjective air traffic complexity, but only when the traffic level and proportion of TBO aircraft are high.

VII. CONCLUSION

ATC simulators are commonly used tools for ATM research, however, they are usually not available to smaller research teams due to cost. This paper showed the methods and technology needed to build an ATC simulator for real-time human-in-the-loop use. While developing such a simulator is not always cost-effective, adhering to the general simulator requirements mentioned in this paper ensures that the simulator is easy to upgrade and reuse thus increasing its utility.

Specific simulator requirements should be defined based on the simulator purpose. Here, an example of specific requirements for ATC simulator used in HITL en-route simulations was presented. These requirements are specific to this project; however, authors believe that there are many other research problems that could be tackled with it (e.g. capacity, complexity, or workload assessment, ATC tool validation, procedure design and validation etc.).

The example of simulator framework presented in this paper shows one possible approach to achieving the maintainability requirement through modularity. It also shows which modules are required for implementation of which functionality in this type of ATC simulator. A brief overview of key technologies was presented to help guide other researchers wishing to develop a simulator of their own. The simulator was validated in two ways: by comparing the generated trajectories with actual aircraft trajectories and by comparing the user interface and ATC tools functionality with commercial ATC simulation devices. Both comparisons showed that the simulator performed adequately.

Finally, the study for which this simulator has been developed was presented. During this study the simulator performed well. Licensed ATCOs had no trouble adapting to it during the first 90 minutes of training. Besides testing the simulator in actual working environment, study also provided meaningful results in terms of air traffic complexity assessment. It showed that the air traffic complexity in en-route operations will decrease once the trajectory-based operations were implemented. This decrease in complexity will only be noticeable in traffic situations with larger fraction of aircraft flying TBO and in situations with larger traffic volume.

ACKNOWLEDGMENT

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Cessna Citation X Pitch Rate Control Design using Guardian Maps

Georges Ghazi, Kevin G. Rezk and Ruxandra M. Botez
École de Technologie Supérieure – University of Quebec
Laboratory of Applied Research in Active Controls, Avionics and AeroServoElasticity
Montreal, Quebec, Canada
http://www.larcase.etsmtl.ca / ruxandra.botez@etsmtl.ca

***Abstract*— Satisfying handling qualities remains one of the major concerns of flight control engineers. In addition to satisfy many stringent performances, Flight Control Systems (FCS) have to be robust to various uncertainties. Although modern control techniques can handle many types of constraints, fulfilling these requirements remains a challenge for engineers. It is therefore of interest to find a method that keeps the simplicity of classical architecture while taking advantage of modern techniques. In this paper, a new algorithm to design a pitch rate controller is presented. Based upon the guardian maps theory, the algorithm tries to find a controller that satisfies several performances expressed in terms of handling qualities. To validate the proposed methodology, simulations for 10 flight conditions have been performed using a full nonlinear level D aircraft model of the Cessna Citation X business aircraft. The results obtained showed that the proposed algorithm works very well.**

Keywords — Cessna Citation X; flight control; robustness; guardian maps; handling qualities.

I. Introduction

The beginning of the Fly-By-Wire technology early in the 1960s [1, 2] has led the aerospace industry to develop more evolved and efficient flight control systems in order to build safer and reliable airplanes. With the constant augmentation of aircraft in the sky, the need of designing flight control systems that are efficient and robust became one of the main goals of the aerospace industry. However, the development and the integration of flight control systems are costly and time-consuming. This is why in recent years, several researchers and engineers have focused their works to provide effective and robust controller design techniques .

The improvement of numerical optimization algorithms has greatly contributed to the development of modern control techniques such as H_∞ or *μ-synthesis* [3, 4]. These two methods aim to find a controller that minimizes disturbances effects while stabilizing the system in closed-loop [4]. They are therefore helpful for the aerospace industry because they can fulfill many stringent constraints while remaining robust to parametric uncertainties.

Boughari *et al.* in [5] presented a procedure to design a robust controller for the Cessna Citation X aircraft business jet using the H_∞ theory. In this study, the H_∞ synthesis was combined with two meta-heuristic algorithms (the genetic algorithm and the differential evolution algorithm) in order to find the optimal H_∞ weighting functions that describe the closed-loop performances. The methodology was applied to obtain a robust lateral controller for different flight conditions within the Cessna Citation X aircraft flight envelope. The controller was finally exported into Simulink and simulations using a full nonlinear aircraft model have proved the efficiency of the controller.

Similarly, Mystkowski in [6] presented a procedure based on the *μ-synthesis* technique to design a robust longitudinal and lateral controller for a family of micro Unmanned Aerial Vehicles (UAV). The controller was first computed in Matlab using the robust control toolbox, and then optimized via fixed-point arithmetics. Finally, the controller was implemented in a single-board microcomputer in order to be tested on the real system. However, according to the author, the high order of the controller did not allow its implementation on any microcomputer.

To solve the implementation problem, Saussié *et al.* proposed in [7] to reduce the high order of the controller by using robust modal control techniques. In this study, the authors performed first a H_∞ synthesis in order to find aircraft pitch rate controller for the Bombardier Challenger 604 aircraft that satisfied several handling qualities while being robust to mass and center of gravity variations. The obtained controller was next reduced to make it similar to a classical structure usually used by the aerospace industry. Simulations for 8 aircraft flight conditions in terms of mass and center of gravity location were performed and promising results were obtained.

All these examples showed the improvement made with modern control techniques such as H_∞ or *μ-synthesis.* However, even if the controllers designed with these techniques can handle many stringent constraints while being robust to uncertainties, their counterpart is their high order (at least the same order as the system). Aeronautical engineers still use the classical flight control approach mainly because the high order controller high order prevents its integration on the real system [8]. In addition to providing relatively simple controller architecture, classical methods allow a better understanding of the controller behavior.

Classical flight control systems are based on successive feedbacks and require a really good knowledge of the system [8, 9]. However, because of their simplicity, they cannot take into account uncertainties or stringent constraints as the modern techniques do. It is therefore of interest to find a method that keeps the simplicity of a classical architecture while using modern techniques advantages.

Ghazi and Botez in [10, 11], proposed a simple fixed architecture controller for the Cessna Citation X business jet aircraft. As usually used in classical flight controls [12, 13], the controller architecture consisted of a Stability Augmentation System (SAS) and a Command Augmentation System (CAS). The gains for each loop (SAS and CAS) were computed with an automatic procedure based on a combination between the LQR theory [13-15], a genetic algorithm and the guardian maps approach [16]. The specific combination allowed the authors to obtain a controller for the whole aircraft flight envelope that was efficient and robust to various uncertainties. The controller was successfully applied on a Cessna Citation X full nonlinear model and very good results were obtained.

The procedure proposed by Ghazi and Botez assumed that all the aircraft states are available for the flight control system. However, in some cases, sensors used to measure specific flight parameters are really expensive. Consequently, only a few flight parameters are measurable, and the LQR method cannot be applied.

Saussié *et al.* in [17] presented a robustness augmentation algorithm for a fixed aircraft pitch rate architecture controller. The proposed algorithm relied upon the guardian maps theory and was used to improve the robustness of an initial controller that satisfied pole confinement constraints. The procedure was applied to design the pitch rate controller of a Challenger 604 aircraft and obtained results were promising. However, according to the authors, although the general principle of the algorithm remained relatively simple, the update of the gains inside the algorithm remained the most difficult part.

In this paper, a methodology to design a longitudinal pitch rate control system for the business aircraft Cessna Citation X is presented. The proposed procedure is based upon a classical fixed architecture controller mixed with an optimization algorithm that allow to find the best gains of the longitudinal flight control system in order to achieve given performance. The methodology has been validated using a nonlinear aircraft model of the Cessna Citation X built in Matlab/Simulink using data from a level D aircraft research flight simulator designed and manufactured by CAE Inc. According to the Federal Aviation Administration (FAA, AC 120-40B), the level D is the highest certification level that can be delivered by certification authorities for the flight dynamic.

Fig. 1. Level D Cessna Citation X Flight Simulator

This paper is arranged as follows. In Section 2, the Cessna Citation X aircraft model is introduced, a brief description of the controller architecture is provided, and the handling qualities of interest are exposed. Section 3 briefly presents the guardian maps theory. Section 4 shows the procedure used to tune the controller gain in order to achieve all the desired performance. Section 5 deals with the results and the validation of the algorithm. Finally, conclusions and future work is provided.

II. Flight Controller Problem

This section aims to describe the Cessna Citation X aircraft longitudinal control problem. First, a brief description of the aircraft open-loop model is given, followed by a presentation of the controller architecture. Then, a list of requirements (handling qualities) is enumerated.

A. Cessna Citation X Open Loop Model

In this paper, the Cessna Citation X aircraft is modelled using a six degrees of freedom nonlinear model developed by Ghazi and Botez in [18, 19]. However, for design purpose, this paper considers only the aircraft longitudinal motion. Using trim and linearization routines, the aircraft equations of motion have been linearized for different flight conditions in terms of altitude, speed, gross weight and center gravity position. Then, as usually done in flight control systems [20, 21], the phugoid mode was truncated and only the short period mode was considered. The short period approximation models obtained by linearization were next compared and validated using linear models obtained with system identification techniques from flight tests [22, 23].

The actuators and sensors dynamics are modelled using two fourth order transfer functions with delay due to data processing. After reduction using modal truncation, the high order open-loop transfer function was reduced to an 8th state space model denoted as:

$$\begin{aligned} \Delta \dot{\boldsymbol{x}} &= \boldsymbol{A}\, \Delta \boldsymbol{x} + \boldsymbol{B}\, \Delta \delta_c \\ \Delta q &= \boldsymbol{C}_q \Delta \boldsymbol{x} \\ \Delta n_z &= \boldsymbol{C}_{nz} \Delta \boldsymbol{x} \end{aligned} \qquad (1)$$

where $\Delta\boldsymbol{x}$ represents the aircraft, actuators and sensors vector state, $\Delta\delta_c$ is the elevator command position, Δq is the aircraft pitch rate and Δn_z is the aircraft normal acceleration.

B. Controller Architecture

To track the pitch rate commands Δq_{ref}, the classical controller architecture shown in Fig. 2 is used.

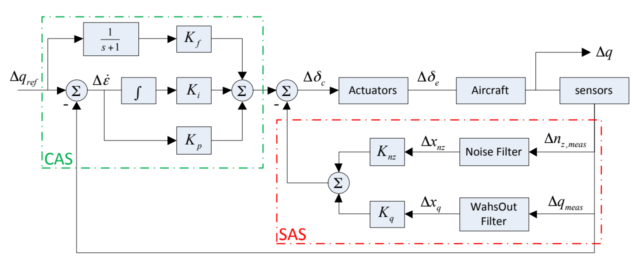

Fig. 2. Pitch Rate Controller Architecture

As usually done in classical flight controls [20, 21], the controller consists of a Stability Augmentation System (SAS) and a Command Augmentation System (CAS).

The SAS is composed of two feedback loops with fixed first order filters: a washout filter and a noise filter. The gains K_{nz} and K_q are adjustable gains and must be tuned in order to improve the aircraft stability. The CAS loop is formed of a proportional-integral controller and a feedforward loop. The first order transfer function of the feedforward loop has been added in order to make the command smoothest. The three gains K_p, K_i and K_f, are also adjustable and must be designed in order to improve the aircraft handling qualities.

Finally, the performances of the closed-loop are governed by the set of gains $\boldsymbol{K} = \{K_q, K_{nz}, K_p, K_i, K_f\}$.

C. Longitudinal Flight Requirements

The longitudinal flight requirements are the minimum acceptable standards to which the stability, control and handling of the aircraft must be designed. They are used to make sure that the aircraft has good flying and handling qualities. The flying qualities (FQs) concern how well a long-term task can be fulfilled, while handling qualities (HQs) represent how the aircraft behaves at short-term to specific inputs [21]. The considered boundaries of the flying and handling qualities according to military standards [24] are given in Table 1. They are expressed in terms of short period damping ratio ζ_{sp}, settling time ST, steady state error SSE, Gibson dropback Db, gain margin M_G and phase margin M_ϕ.

The Gibson dropback is a short-term measure of the pitch attitude. It is usually relevant when the pilot is trying to change the pitch rate (q) of the aircraft. The dropback can be calculated based on the reduced-order attitude θ response to a stick step. Examples of positive, zero and negative dropback are illustrated in Fig. 3.

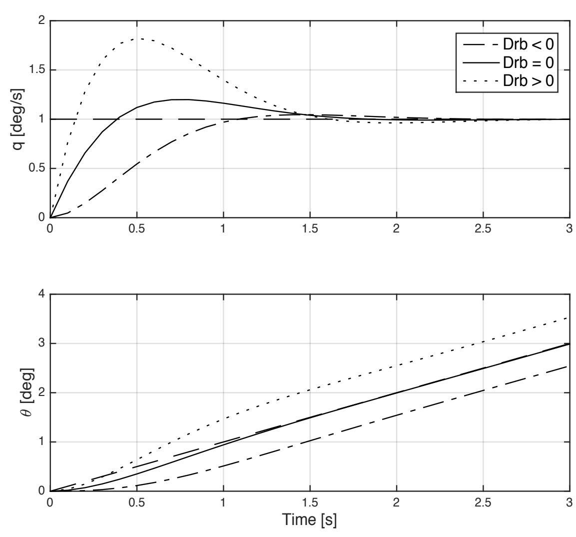

Fig. 3. Dropback illustration

TABLE I. FLYING AND HANDLING QUALITIES BOUNDARIES

HQs / FQs	Level 1	Good Level 1
ζ_{sp}	$0.35 \leq \zeta_{sp} \leq 1.35$	$0.7 \leq \zeta_{sp} \leq 1.35$
SSE	$SSE \leq 0.1$ (deg/s)	$SSE \leq 0.1$(deg/s)
ST	$ST(2\%) \leq 3(s)$	$ST(1\%) \leq 3(s)$
Db	$-0.2 \leq Db \leq 0.5$	$0.0 \leq Db \leq 0.3$
M_G	$M_G \geq 6$ dB	
M_ϕ	$M_\phi \geq 45°$	

III. AN INTRODUCTION TO THE GUARDIAN MAPS

The guardian map approach was introduced by Saydy *et al.* [16] as a tool for the study of "generalized stability" of parameterized families of matrices (or polynomials). The "generalized stability" refers to the confinement of matrix eigenvalues to general open subsets of the complex plan.

A. Definition

Basically, guardian maps are scalar functions defined for a specific system that vanish whenever the system is at the limit of stability. The system of interest can be represented either by a set of $n \times n$ real matrices or by an n^{th}-order polynomials. To simplify the study, the definitions that follow are directly applied to families of matrices. However, it can be easily adapted to polynomials.

Definition 1: *Let* Ω *be an open subset of the complex plan of interest. The system defined by the Eq. (1) is stable relative to* Ω *if the matrix* $\boldsymbol{A}$ *have all its eigenvalue in* Ω*, i.e. if* $\boldsymbol{\sigma}(\boldsymbol{A}) \subset \Omega$.

Here $\boldsymbol{\sigma}(\boldsymbol{A})$ denotes the set consisting of all the eigenvalue of $\boldsymbol{A}$. Thus, the set of all matrices, which are stable relative to Ω, can be therefore defined such as:

$$S(\Omega) = \{\boldsymbol{A} \in \mathbb{R}^{n \times n} : \boldsymbol{\sigma}(\boldsymbol{A}) \subset \Omega\} \quad (2)$$

Based on this last definition, the mathematical formulation of the guardian maps can be defined as follow [16]:

Definition 2: *Let* ν *map* $\mathbb{R}^{n \times n}$ *into* $\mathbb{C}$*. We say that* ν *guards* $S(\Omega)$ *if for all* $\boldsymbol{A} \in \overline{S}(\Omega)$*, the following equivalence holds:*

$$\nu(\boldsymbol{A}) = 0 \Leftrightarrow \boldsymbol{A} \in \partial S(\Omega) \quad (3)$$

Here $\overline{S}$ *denotes the closure of the set* S *and* ∂S *its boundary. We say that* ν *is a guardian map for* S.

B. Guardian Maps Examples

To illustrate the concept of guardian maps, let's consider the three most classical stability regions of the complex plan illustrated in Fig. 4.

Negativity Margin: the open α-shifted left half-plane region defined by $\{\lambda \in \mathbb{C} : \text{Re}(\lambda) < \alpha\}$ is guarded by:

$$\nu_\alpha(\boldsymbol{A}) = \det(\boldsymbol{A} \odot \boldsymbol{I} - \alpha \boldsymbol{I} \odot \boldsymbol{I}) \det(\boldsymbol{A} - \alpha \boldsymbol{I}) \quad (4)$$

where $\odot$ denotes the bialternate product of two matrices.

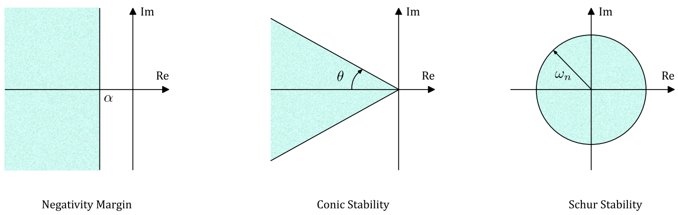

Fig. 4. Classical stability regions of the complex plan

Damping Stability: the region delimited by the damping cone with the half-angle $\theta = \mathrm{acos}(\zeta)$ is guarded by:

$$\nu_\zeta(\boldsymbol{A}) = \det(\boldsymbol{A}^2 \odot \boldsymbol{I} + (1 - 2\zeta^2)\boldsymbol{A} \odot \boldsymbol{A}) \det(\boldsymbol{A}) \qquad (5)$$

where ζ is the limiting damping ratio.

Schur stability: the region defined by the open disk with a radius ω_n is guarded by:

$$\nu_{\omega_n}(\boldsymbol{A}) = \det(\boldsymbol{A} \odot \boldsymbol{A} - {\omega_n}^2 \boldsymbol{I} \odot \boldsymbol{I}) \det(\boldsymbol{A} - \omega_n \boldsymbol{I}) \det(\boldsymbol{A} + \omega_n \boldsymbol{I}) \qquad (6)$$

It can be noticed from Eq. (4) that the Hurwitz stability (i.e. the open left half-plan) is a simple case of the negativity margin with $\alpha = 0$. However, a systematic method of constructing guardian maps for other regions that those considered is this paper can be found in [16].

C. Two-parameters family matrices stability test

Let (S_r) be a two-parameters family of linear systems described by the following general form:

$$(S_r) \equiv \begin{cases} \Delta \dot{\boldsymbol{x}} = \boldsymbol{A}(\boldsymbol{r})\Delta \boldsymbol{x} + \boldsymbol{B}(\boldsymbol{r}) \Delta \boldsymbol{\eta} \\ \Delta \boldsymbol{y} = \boldsymbol{C}(\boldsymbol{r})\Delta \boldsymbol{x} + \boldsymbol{D}(\boldsymbol{r}) \Delta \boldsymbol{\eta} \end{cases} \qquad (7)$$

where $\boldsymbol{r} \in \mathbb{R}^2$ is a parameter vector where each parameter r_i, $i = \{1,2\}$ lies in a given range for which only the bounds are known, say $\boldsymbol{r} \in U \subset \mathbb{R}^2$ (i.e. $r_i \in \left[\underline{r_i}, \overline{r}_i\right], \forall i \in [\![1,2]\!]$).

To test if the two-parameters family (S_r) is stable relative to an open subset of the complex plan Ω for all $\boldsymbol{r} \in U$, the following theorem and corollary can be used.

***Theorem 1*:** (Saydy *et al.* [16]) *Let $S(\Omega)$ be guarded by the map ν_Ω. The family $\{\boldsymbol{A}(\boldsymbol{r}) : \boldsymbol{r} \in U\}$ is stable relative to Ω if and only if:*

(i). It is nominally stable, i.e. $\boldsymbol{A}(\boldsymbol{r}_0) \in S(\Omega)$ for some $\boldsymbol{r}_0 \in U$; and,

(ii). $\nu_\Omega(\boldsymbol{A}(\boldsymbol{r})) \neq 0$, for all $\boldsymbol{r} \in U$.

Corollary 1: *Let $S(\Omega)$ be guarded by the map ν_Ω and consider the family $\{\boldsymbol{A}(\boldsymbol{r}) : \boldsymbol{r} \in U\}$. Then the set C defined by:*

$$C = \left\{ r \in \mathbb{R}^k : \nu_\Omega(\boldsymbol{A}(\boldsymbol{r})) = 0 \right\} \qquad (8)$$

divides the space parameters $\mathbb{R}^k$ into components C_i that are either stable or unstable relative to Ω. Then, to see which situation prevails for a given component C_i, one simply has to test $\boldsymbol{A}(\boldsymbol{r})$ for any one vector in C_i.

IV. Controller design method

This section introduces the algorithm based upon the guardian maps. First, the procedure is applied to a specific case in order to better illustrate the mains steps of the algorithm. Subsequently, a procedure for solving the flight controller problem described in section **Flight Controller Problem** is presented.

A. Two Degrees of Freedom Controller Design Example

To illustrate the proposed algorithm, we consider here the synthesis of a PI controller for the unstable system illustrated in Fig. 5,

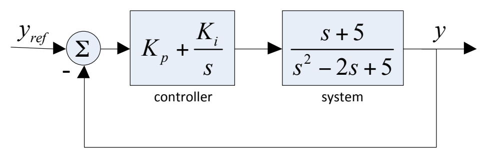

Fig. 5. PI Feedback Configuration

where the equivalent state-space representation of the closed-loop is given by the following equation:

$$\boldsymbol{A}(K_p, K_i) = \begin{bmatrix} 2 - K_p & -5K_p - 5 & K_i \\ 1 & 0 & 0 \\ -1 & -5 & 0 \end{bmatrix}, \ \boldsymbol{B} = \begin{bmatrix} K_p \\ 0 \\ 1 \end{bmatrix} \qquad (9)$$

In addition to stabilise the initial system, the PI controller must place the pole of the closed-loop inside a sub-region of the complex plan defined by $\Omega_t(-1.5, 0.7, 12) = \{\lambda \in \mathbb{C} : Re(\lambda) < -1.5, \zeta(\lambda) > 0.7, |\lambda| < 12\}$.

As shown in Fig. 6, the algorithm and the synthesis procedure consist essentially of four steps:

- ***Step 1:*** using Eqs. (4)-(6), the algorithm computes the guardian maps of $\boldsymbol{A}(K_p, K_i)$ for Ω_t, and finds the contours of the map that reveal for which combination of (K_p, K_i) the guardian maps vanish (see Fig. 6 – step 1). According to ***Definition 2***, these contours reveal the values of (K_p, K_i) that bring the closed-loop at the limit of the sub-region Ω_t.

- ***Step 2:*** the algorithm researches a region in which the closed-loop is stable relative to Ω_t. To do that, the algorithm selects randomly five points along each contour and verifies if the neighbourhood of each point ensure that all the eigenvalues of $\boldsymbol{A}(K_p, K_i)$ are inside Ω_t (see Fig. 6 – step 2). If such a point exists, it is then selected as starting point.

- ***Step 3:*** the algorithm builds a simplex by selecting randomly three points in the neighbourhood of the starting point (see Fig. 6 – step 3).

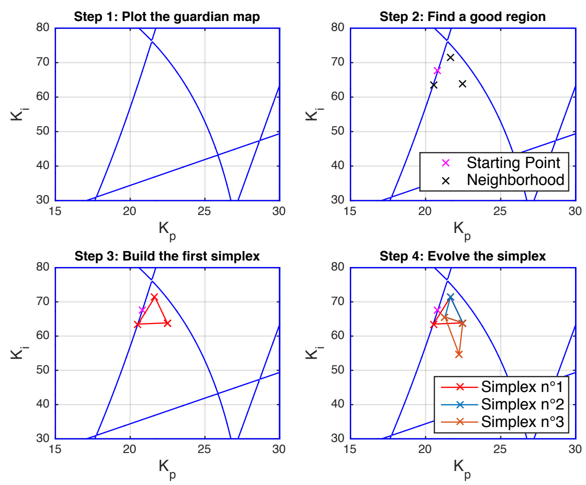

Fig. 6. Search Algorithm Illustration

- ***Step 4:*** once the starting point and the first simplex have been identified, the main intuitive idea is to move sufficiently far from the contour, hence, the resulting closed-loop poles will also move well inside the sub-region Ω_t. To do that, the algorithm uses different geometric transformations to move the simplex to the center of the region. These transformations are mainly based on the optimization algorithm proposed by Nelder-Mead in [25]. At each iteration, the algorithm selects the vertex of the simplex that is the closest from the boundary and performs a reflection with respect to the other two vertices. If the reflection is not possible, then the algorithm tries a contraction inside the simplex. The algorithm stops when all the vertices of the simplex are close to each other, which means that the simplex cannot evolve anymore.

Table 2 and Figure 7 show the results obtained after 47 iterations.

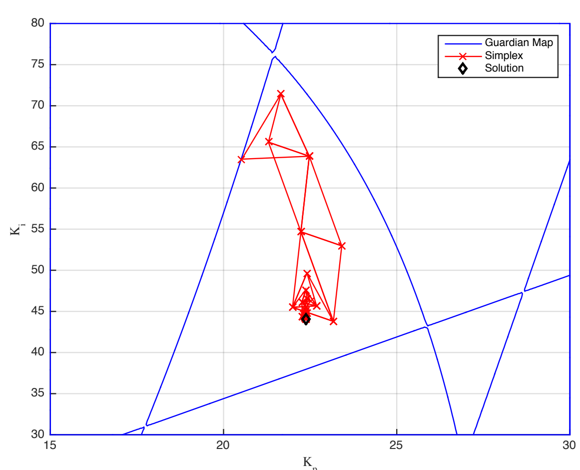

Fig. 7. Algorithm Illustration

TABLE II. CLOSED-LOOP POLES

Loop	Poles (λ)	$Re(\lambda)$	$\zeta(\lambda)$	$\lvert\lambda\rvert$
Open-Loop	$1.0 \pm 2.0i$	1.0	-0.447	2.24
Closed-Loop	-1.71 $-9.33 \pm 6.48i$	-1.71 -9.38	1.0 0.821	1.71 11.4

As it can be observed, the results are very good. In addition to stabilize the system, the algorithm finds the "center" of the sub region where the closed-loop is stable relative to Ω_t.

B. *Design Procedure for the Cessna Citation X*

The main goal of the algorithm is to tune the set of gains $\boldsymbol{K} = \{K_q, K_{nz}, K_p, K_i, K_f\}$ in order to place the closed-loop poles inside a specific sub-region Ω_t of the complex plan that represents the required closed-loop performances in terms of damping ratio and settling time. As shown in the previous section, the proposed algorithm can deal only with two parameters. Therefore, the SAS and the CAS have to be designed one at a time.

The synthesis procedure can be summarized as:

1. **Design of the SAS ($\boldsymbol{K_p = K_i = K_f = 0}$):** using the procedure described in the previous section, the gains K_q and K_{nz} are computed with $\Omega_t(-1.0, 0.5, \infty)$.

2. **Design of the CAS ($\boldsymbol{K_f = 0}$):** using the procedure described in the previous section and the results obtained in step 1, the gains K_p and K_i are computed with $\Omega_t(-0.5, 0.6, \infty)$.

3. Finally, according to Saussié *et al.* in [17], the gain K_f is chosen to set zero the dropback by solving the following equation:

$$0 = \frac{\boldsymbol{C}_{cl}\,\boldsymbol{A}_{cl}(K_f)^{-2}\boldsymbol{B}_{cl}(K_f)}{\boldsymbol{C}_{cl}\,\boldsymbol{A}_{cl}(K_f)^{-1}\boldsymbol{B}_{cl}(K_f)} \tag{10}$$

where $\boldsymbol{A}_{cl}$, $\boldsymbol{B}_{cl}$ and $\boldsymbol{C}_{cl}$ are the state matrix of the closed-loop in Fig. 2.

V. SIMULATION AND RESULTS

The algorithm was applied to 10 flight conditions in terms of altitude, speed, gross weight and center of gravity position. These flight conditions were selected within the Cessna Citation X flight envelope.

Figures 8 and 9 show the aircraft nonlinear model time response and the Bode diagram for all the 10 flight conditions. As it can be observed, the aircraft is successfully controlled. The settling time for all the ten models is less than 2 seconds and the steady state error is also less than 0.1 deg/s. Regarding the dropback it remains well below 0.3 as imposed by the performance in Table 1.

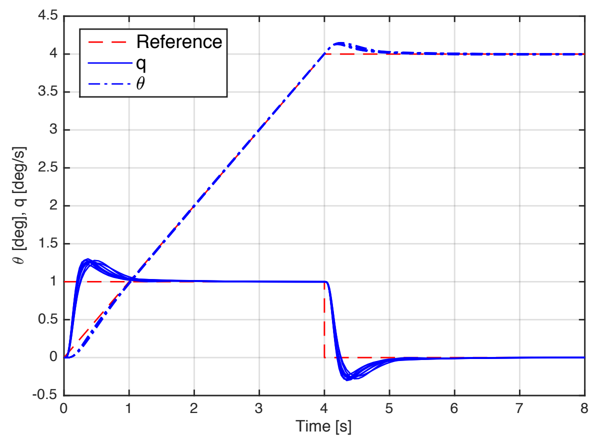

Fig. 8. Aircraft Time Response for 10 Flight Conditions

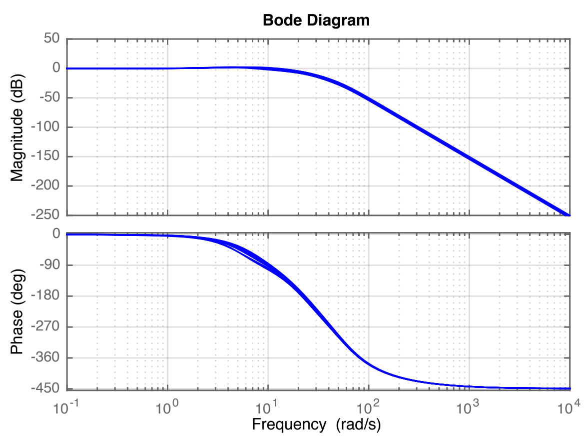

Fig. 9. Aircraft Bode Diagram for 10 Flight Conditions

Finally, as shown in Fig. 9, the gain margin and the phase margin are above the minimum values imposed by the handling qualities in Table 1.

CONCLUSION

In this paper, a new design procedure to obtain a controller to track the pitch rate command was presented. Based upon the guardian maps theory, the algorithm found the gains for a controller that satisfies several performances expressed in terms of handling qualities. The controller was successfully applied on a Cessna Citation X business aircraft nonlinear model, and very good results were obtained. To improve the algorithm, the next steps are suggested:

- The actual algorithm cannot change the space of research. If the algorithm did not find a good starting point, the algorithm stops and concludes that there are no possible solutions. To improve this part of the algorithm, a new function should be added to allow the algorithm to decide if the search area should be increased or not in order to find a better solution.
- The methodology used to select the starting point should also be improved in order to reduce the algorithm execution time.

ACKNOWLEDGMENT

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Benchmarking of airports from Central and Eastern Europe

Sorin Eugen Zaharia
Faculty of Aerospace Engineering, University POLITEHNICA of Bucharest
Bucharest, Romania
e-mail: sorin.zaharia@gmail.com

***Abstract*—Benchmarking became a powerful management tool to assist in identifying new approaches for increasing efficiency and for continuously monitoring ongoing strategic success. Applied properly, benchmarking can help reinforce an organization's vision, mission and strategies, as well as it helps create a new corporate *esprit de corps* by building employee focus, competencies and attitude.**

Our external benchmarking is focused on the performances concerning airport connectivity, passenger traffic and the relationships airport – airliners of airports from 8 countries of Central and Eastern Europe.

The target group of the airport development analyze in Central and Eastern Europe is represented by the first 20 airports from the connectivity point of view, regarding the following EU countries: Bulgaria, Croatia, Czech Republic, Hungary, Poland and Romania and 2 non EU countries: Moldova and Serbia whose traffic represents 4.1 % of passenger European traffic. The analyze concerns the macroeconomic parameters and airport operational parameters: airport connectivity, passenger traffic, aircrafts movements and also the strategy of airports in routes development.

As conclusion, some axes for politics in air transport, for a common airport-airliners strategy are presented: concentrating the airport investments according to the economic potential of the region correlated with the foreign investor's interest and the existing infrastructure of the airports in that region and the improvement of the intercontinental connectivity.

Keywords— airport development; benchmarking; Central and Eastern Europe; passenger traffic; airport connectivity.

I. INTRODUCTION

The air transport brings a major contributor to global economic prosperity. The air transport system provides jobs, trade, connectivity, tourism, vital lifelines towards many remote communities and also rapid disaster response.

Every day, airlines transport 8.6 million passengers within 99,700 flights and carry $17.5 billion worth of goods. In 2013, nearly 3.1 billion passengers arrived on and departed from the 3864 airports of the world, 49.8 million tones of cargo and 36.4 million commercial flights were processed. Consequently, aerospace industry represents overall a major direct generator of employment and economic activity, creating 8.7 million direct jobs and 9.9 million indirect jobs in 2012. The ACI Report from February 2015 reveals that during 2014, passenger traffic at Europe's airports grew by an average of +5.4%.

Less tangibly, but as well important, a better connectivity increases passenger traffic and trade. This, in turn, can lead to a more favorable environment for foreign firms to operate in — greater links to the outside world often drive a more conducive global business environment. A better connectivity together with a bigger number of passengers lead to the development of national, regional and global economy.

II. AIRPORT BENCHMARKING

Benchmarking became a powerful management tool to assist in identifying new approaches for increasing efficiency and for continuously monitoring ongoing strategic success. Applied properly, benchmarking can help to reinforce an organization's vision, its mission and strategies, as well as it can help to create a new corporate "*esprit de corps*" by building employee focus, competencies and attitude.

Airport benchmarking is a component of an airport's strategic planning process. It is a statistical and an accounting process used to monitor and compare airport economic, operational and service performance. Benchmarking assesses the implementation of an airport's strategic planning objectives to measure the performance of discrete airport functions and identifies best practices for possible incorporation into the organization's procedures to increase efficiency, quality and customer satisfaction. Thus benchmarking links day-to-day operations and management with an airport's short and long-term strategic initiatives and action plans.

The airport benchmarking presented in this paper groups measurable parameters according to area of airport activity: economical context, operational activity and quality of community airline service. The parameters for economical context are GDP for the period 2004-2014, the number of airports of the country, the number of passenger traffic per country, the average of passenger per airport For the operational activity, the parameters consist in the passenger traffic per each airport, the rate of passenger traffic growth and the total, direct and indirect airport connectivity and also the hub connectivity. Regarding the quality of community airline service, the parameters are: the number of airlines, airline routes and frequencies and the type of airlines.

III. THE TARGET GROUP OF ANALYZE

In our paper, we achieve an external benchmarking, which compares performance across the 20 airports of 8 countries from Eastern and Central Europe during the last 10 years and for some performances only the results for 2014. In the last 10 years, in the mentioned region, there has been recorded a very important increasing in traffic and in airport connectivity, by this way, the aviation brings its contribution to sustaining economic growth and the involvement of the countries above in the global economy.

The target group of the airport development analyze is represented by the first 20 airports ranked from the connectivity point of view from the following EU countries: Bulgaria, Croatia, Czech Republic, Hungary, Poland and Romania and from 2 non EU countries**:** Moldova and Serbia whose traffic represents 4.1 % of passenger European traffic.

In figure 1, we present the number of airports of the analyzed countries. Romania comes first having a number of 16 airports, followed by Poland with 14, while all other countries have less than 10 airports. In total there are 61 airports with 70 806 899 passengers in 2014, representing 4.1 % from European passenger traffic.

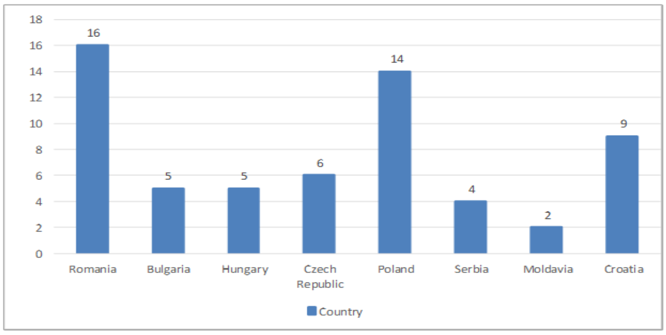

Figure 1 Number of airports per country

If we go further with our analyse and we calculate the average surface from the country which correspond to an airport, we notice that the bigger average surface is in Poland 22,335 km^2, followed by Bulgaria with 22,180 km^2, Serbia 19,363 km2, Hungary 18,606, Moldova, 16,923 km^2, Romania 14,900 km^2, Czech Republic 13,144 km^2 and Croatia with 6288 km^2. In term of the average of passengers per airport, the situation is presented in table 1 and on the graphic from figure 2.

Table 1 The average of passengers per airport by country

Country	Average of passenger per airport	
	2013	2014
Czech Republic	1981969	2028776
Poland	1662441	1944590
Hungary	1691803	1867792
Bulgaria	1415659	1567304
Serbia	330232	1168228
Moldova	660618	893009
Romania	671588	728856
Croatia	635781	531566

The bigger average number of passenger per airport in 2014 was recorded by Czech Republic with 2028776, while the lowest average is that of Croatia with 531 566. Regarding the dynamic of this parameter, the most important growth was achieved by Serbia which passed from 330 232 in 2013 to 1 168 228 in 2015. Romania is placed on the last but one with an overage of 728 856 passengers per airport.

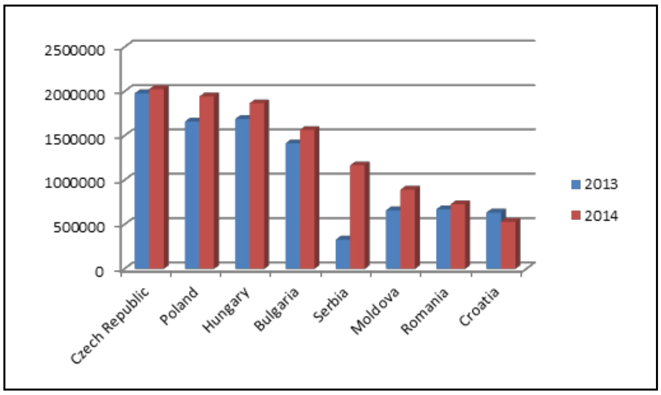

Fig. 2 The average of passenger per airport by country

The best efficiency in using airport in 2014 was obtain by Czech Republic with the bigger average number of passenger per airport 2 028 776, fallowed by Poland with 1 994 590, while the lowest average is that of Croatia with 531 566.

Regarding the dynamic of this parameter, the most important growth was achieved by Serbia which passed from 330 232 in 2013 to 1 168 228 in 2015, having a growth of 253.8%. Romania is placed on the last but one with an overage of 728 856 passengers per airport, the growth of 8.52% reporting to 2014 .

The top 10 airports, having in view the airport connectivity criteria are: 3 from Poland, 1 from Romania, 1 from Bulgaria, 1 from Croatia, 1 from Czech Republic, 1 from Hungary, 1 from Serbia and 1 from Moldova. Passing to top 20 airports, capitals and other regionals, from connectivity point of view, the repartition by countries is the following: 6 in Poland, 4 in Romania, 3 in Bulgaria, 3 in Croatia, 1 in Czech Republic, 1 in Hungary, 1 in Serbia and 1in Moldova. According to the ACI airports classification [1], the analyses airports are placed as follow: Group 2: Prague and Warsaw; Group 3: Budapest and Bucharest and Group 4: Belgrade, Sofia, Zagreb, Krakow, Wroclaw, Chisinau, Poznan, Dubrovnik, Katowice, Bourgas, Varna, Timisoara, Warsaw Mlodin, Cluj and Sibiu.

IV. THE ECONOMICAL CONTEXT

In the figure 3, we present the evolution of GDP during the period 2004 – 2013. The highest value is recorded by Poland for all period, followed by Czech Republic and Romania.

Gross Domestic Product positively influences the Gross Domestic Product positively influences the connectedness of a country and shows also a heath economy which is able to attire new foreign investments with an important influence on the increase of passenger and cargo traffic and foreword an important airport development.

On the figure 4, we can see the evolution of passenger traffic in the 8 analyzed countries.

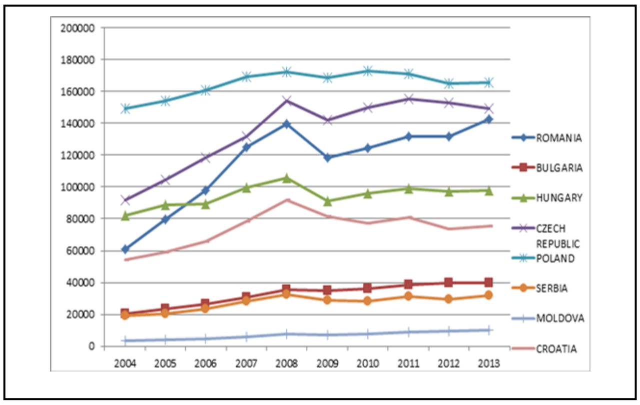

Fig 3 The GDP's evolution in Eastern and Central Europe

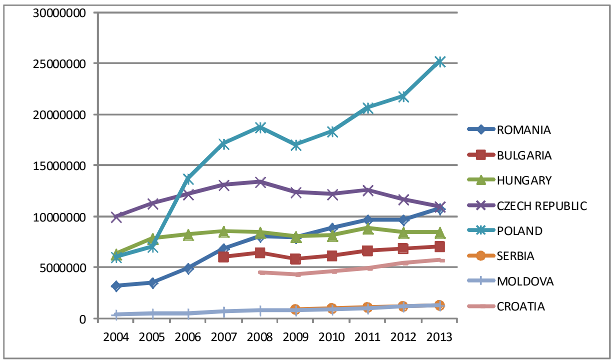

Fig. 4 The passenger traffic evolution during 2004-2013

The highest passenger traffic was registered in Poland, followed by Czech Republic and Romania. From the figures number 2 and 3, we can observe how the important growth of the Poland's GDP is in concordance with the highest traffic level from all the compared countries. The evolution of the traffic follows the GDP's evolution of each country. Poland is an exception. Although Poland didn't register a drop of the GDP's value in 2009 and 2010, the passenger traffic is still affected by the worldwide crisis.

Table 2 Connectivity in Central and Eastern European Countries in 2015

Country	**Connectivity**							
	Absolute in 2015				**Average annual growth 2004 – 2014**			
	Total	Direct	Indi-rect	Hub	Total	Dire ct	Indi-rect	**Hub**
Poland	7539	2280	5260	2242	5%	4 %	5 %	**5 %**
Czech Republic	4595	1262	3363	1246	3 %	1 %	4 %	**-3 %**
Romania	4044	962	3082	261	6%	4 %	7%	**6%**
Hungary	3427	814	2613	77	1 %	-2 %	2%	**-21%**
Croatia	3424	964	2460	9	7 %	7 %	8 %	**1 %**
Bulgaria	2205	542	1663	27	8 %	7 %	8%	**8 %**
Serbia	2595	634	1961	301	9%	5%	11%	**18%**
Moldova	638	191	446	30	9%	5%	11%	**17%**

Concerning the evolution of connectivity in 2015, the highest growth was obtained by Hungary by 9.8%. In regard to non-EU countries, during 2004- 2014, the most important growth of connectivity Y-o-T, by 9%, was achieved by Moldova and Serbia. Serbia keep also for 2015 the best growth of the group in relative terms, by 37.5% (fig. 5).

By correlating the values of the airport connectivity (Table 2), the passenger traffic (fig. 4), the evolution of the GDP (fig. 3) and the number of airports from the analyzed countries (fig 1), we can observe that the essential element which generates the traffic's growth and the connectivity is the growth of the GPD, meaning the economic growth and not the number of airports.

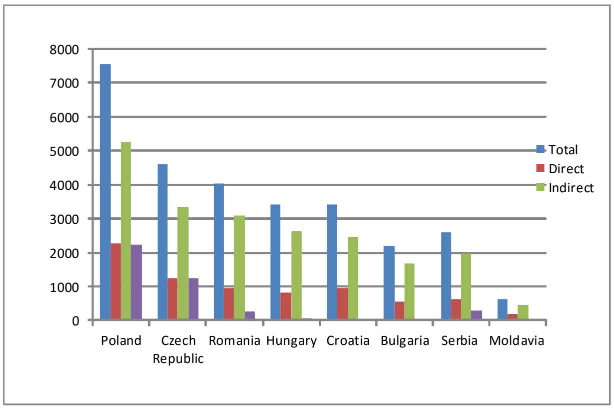

Fig. 5 The airport connectivity for Eastern and Central European countries

V. Operational Activities

For the operational activities, the parameters analyzed consist in the number of passenger traffic per each airport, the rate of passenger traffic growth and the total, direct and indirect airport connectivity and also the hub connectivity.

Europe's connectivity grows in 2015 over past year with +8.9%. This trend is reflected in direct connectivity which has grown by +4.6% this year. The most important value being obtained by United Kingdom, 54981, with a growth of 10,38 %, keeping the first position in Europe as in 2014.

In 2015, as between 2004 and 2014, all groups of airports recorded an increase of connectivity and of the passenger traffic. The different size categories of airports registered significantly higher year-on-year growth in direct, indirect and total airport connectivity. In 2015, the group 1 obtained an increase of total connectivity by 8.7% while during the period 2004 – 2014, the average was only of 3%. The highest growth in relative terms continues to be recorded in 2015 by group 4 by 9.5%, more than a double value reported to the average growth Y-o-Y, during 2004-2014. In 2015, the group 1 obtained the best growth of direct connectivity by 4.8%, while the group 4 due the increase of total connectivity to the growth of indirect connectivity by 12.5%. The airports from Eastern and Central Europe also significantly building up their connectivity which could be an important premises for an economic growth.

The Traffic report for December, Q4 and Full Year 2014 of ACI Europe [4] reveals that during 2014, passenger traffic at Europe's airports grew by an average +5.4%.

A. Airports by groups

The analyze by groups of airports, of the evolution of performances shows the following:

- **GROUP 2**: The group average of the passenger traffic growth in 2014 is + 7.4% compared with 2013 and the airport connectivity recorded in 2015 an increase of 8 % versus 2014. The studied airports belonging to this group recorded the following results: in terms of passenger traffic, Prague got in 2014 a growth of +1.6%, under the average of the group, while Warsaw had even a decrease of – 0.9%. From the connectivity point of view, Prague arrived in 2015 on the first position with a growth of 7% over the past year.
- **GROUP 3**: The group average of the passenger traffic growth in 2014 is + 2.8 % compared with 2013 and the airport connectivity recorded in 2015 an increase of 9.4% reported to 2014. **I**n this group, in 2014**,** Bucharest OTP has an important growth in terms of passengers traffic, over the average of the group, recording an increase of +8.8% fallowed by Budapest with an increase of 7.5%, which is also over the average. In terms of airport connectivity, Budapest has the best increase of 10%, while the Bucharest's airport connectivity rose only by 5%.
- **GROUP 4**: The group average of the increase passenger traffic in 2014 is + 6.3 % compared with 2013 and the airport connectivity recorded in 2015 an increase of 9.5% versus 2014. In this group, in 2014**,** Chisinau has an important growth in terms of passengers traffic, over the average of the group, recording an increase of +34.8% fallowed by Belgrad with an increase of 30.9% and Sofia with 8.9% which are also over the average.

Among the capitals, in terms of airport connectivity, Chisinau keeps the position of the leader with an increase of 18% in 2015, while the highest airport connectivity in the group 4 was achieved by Bourgas with 38%. The situation of passenger traffic for the others airports analyzed of the group is shown on the figures 6 and 7.

B. The airport connectivity and the passenger traffic in East and Central European Countries

In the table 4, we present the situation of total airport connectivity for 2015 and the evolution of connectivity during the period 2004 – 2015 and also the passenger traffic for year 2014 and in fig. 6, its evolution for 2004 – 2014 for airports of the analyzed countries capitals.

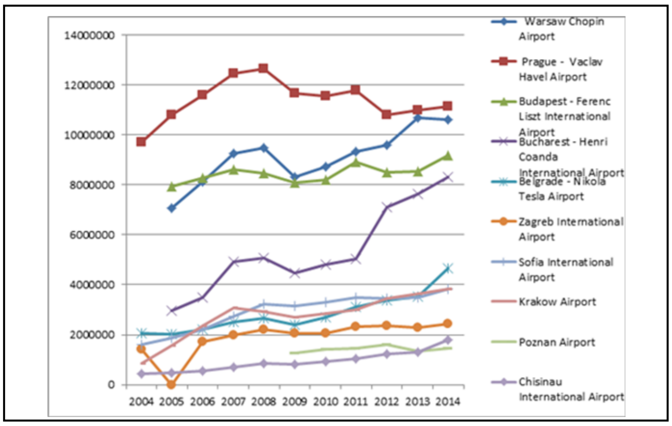

Fig. 6 Passenger traffic for top 10 airports for 2004 – 2014

Concerning the position from connectivity point of view, in 2015, Prague, Belgrade and Zagreb recorded a better position, while Warsaw and Bucharest lost 3 places. The ranked of airport from capitals, regarding the connectivity, in 2015 is the same as the classification from passenger traffic in 2014,

TABLE 4 CONNECTIVITY AND PASSENGER TRAFFIC FOR CAPITALS

Airport	Toatal connectivity 2014/2015	Growth of total connectivity 2004 – 2014/ 2015 vs 2014	Connectivity position in European classification 2014/2015	Passenger traffic in 2014	Traffic pozition	Traffic evolution 2014/2013 2014/2004
Prague	4162 / 4437	29 % / 7%	31 / 29	11.149.926	38	+ 1.6% + 14.9%
Warsaw	**4265 / 4161**	31 % / -2%	30 / 33	10.590.473		**- 0.9%** + 49.7 %
Budapest	3121/3427	11 % /10%	41 / 41	9.146.723	48	+ 7.5% + 15.4 %
Bucharest	3083/3231	82 % / 5%	40 / 43	8.316.705	54	+ 8.8% + 179 %

Belgrade	1887/2011	**144 % / 7%**	61/ 60	4.640.879	79	+ 30.9% + 126.7 %
Zagreb (IV)	1694/1923	59 % / 14%	67 / 64	2.425.889	109	+ 5.7% + 72.6 %
Sofia (IV)	1596/1725	**84 % / 8%**	68 / 68	3.815.192	94	+ 8.9% + 136.3 %
Chisinau (IV)	538/638	136 %/ 18%	122 /115	1.781.169	122	**+ 34.8%** **+ 323.4 %**

excepted Zagreb Airport which is much better situated from connectivity point of view.

Concerning the total airport connectivity, Praga Airport becomes the best performer with a total connectivity of 4437, this means an increasing by 7% reporting to 2014. Vaclav Havel Airport recorde also the highest passengers traffic of 11 149 926 in 2014. In term in hub connectivity, Warsaw keep the position of leader absolute with 2217, with a decrease of – 4% reporting to 2014.

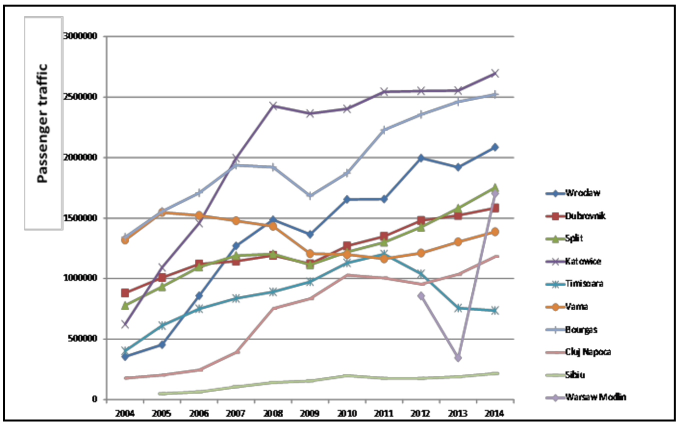

Fig. 7 The passenger traffic for top 11 - 20 airports

The performer in terms of the dynamic of passenger traffic, it is Henri Coanda Airport from Bucharest which recorded in 2014 the highest increase in passenger traffic by 8.8%. Between 2004 and 2014 there was also the highest growth by 179 %, with a good dynamic of total connectivity, recording a growth by 6%. In terms of traffic growth from non-EU countries, the best is Chisinau Airport with an increase by 323,4% between 2004 and 2014 and by 34,8% during 2014. In figure 6 and table 5, we present the situation of total airport connectivity for the next top 12 airports excepted capitals.

Krakow Airport from Poland recorded the best position both in total airport connectivity, 1298 and in passenger traffic, 3 817 792. Wroclaw had also a good evolution in connectivity in 2015 arriving in the second position, wining 12 position in the general ranking of European airports, having also an important passenger traffic. In 2015, airports with a good evolution in connectivity are Split, Bourgas and Warsaw Mlodin. They have also important passenger traffic in 2014.

In terms of passenger traffic, the most important **evolutions between 2004 – 2014** are those of the following airports: Cluj Napoca 564%, Wroclaw 486 %, Krakow 353 %, Sibiu 341 % and Katowice 332%. In general it is a concordance between the position in terms of connectivity in 2015 with the position in the ranking from volume of passenger traffic in 2014.

C. Intercontinental connectivity

From the point of view of intercontinental connectivity, the most important absolute values were obtained by Poland, Czech Republic and Romania .

From the total direct connectivity in the case of the analysed countries, the intercontinental connectivity still a small percentage as follow: Serbia 7.14% (Etihad), Poland 3.03% (4 continents), Hungary 2.86% (2 continents), Czech Republic 2.46% (4 continents), Romania 1.55% , Bulgaria 1.27%, Moldova 1.2%, Croatia 0,6%.

One can notice that the intercontinental connectivity of the majority of the countries, such as Serbia, Romania, Bulgaria, Moldova and Croatia, is made only with Middle East. The most significant intercontinental connectivity is that of Poland and Czech Republic which are linked to 4 continents. The superior connectivity between Serbia and Middle East could be explained by the fact that Etihad Air Company holds the majority of shares and the management of Air Serbia.

D. Quality of community airline service

Low cost companies are the main actor in the increasing traffic in countries from Central and Eastern Europe. For the majority of capitals of analyzed countries, the number of

TABLE 5 AIRPORT CONNECTIVITY AND PASSENGER TRAFFIC FOR TOP 12 AIRPORTS EXCEPTED CAPITALS

No.	Airport	Connectivity position 2014/2015	Total Conectivity in 2014/2015	Passenger traffic 2014	Traffic Pozition	Traffic evolution 2014/2013 2014/ 2004
1	Krakow (Po)	81 / 83	**1188/1298**	3817792	93	+ 4.6 % / **353.9%**

2	Wroclaw (PO)	123 /111	534/663	2085638	117	+ 8.61 % / 486.8%
3	Split (Hr)	125 / 113	522 / 660	1752657	125	+10.9 % / 125.1%
4	Poznan (PO)	120/ 119	554 / 596	1445350	131	+6.7% / 13.6%
5	Dubrovnik (Hr)	124 / 125	532/570	1584471	129	+ 4.1 % / 79.8%
6	Katowice (PO)	152	340/455	2695732	103	+ 6.0 % / 332.9 %
7	Bourgas (BG)	204/189	177/224	2522319	105	+2.0 % / 87.9 %
8	Varna (BG)	201/ 192	187 / 230	1387494	133	+5.2% / 5.2 %
9	Timisoara (RO)	190 / 194	240/224	736191	154	-2.76 % / 82.6 %
10	Warsaw Modlin (PO)	229/ 201	144/214	1703324	124	+394.4% / 98.8%
11	Cluj Napoca (RO)	206/ 210	175/194	1182047	138	+ 14.0 % / 564.6 %
12	Sibiu	207 / 221	175/172	215941	185	+ 12.4% / 341.6 %

destinations operated by LCC is bigger than the number of destinations operated by legacy companies (LC). The situation is the following:

TABLE 6 NUMBER OF COMPANIES ON AIRPORTS CAPITALS

Airport	Total air companies	Low cost companies (LCC)		Legacy companies (LC)	
		Number	Desti-nations	Number	Desti-nations
Prague	65	38	120	27	83
Warsaw	45	24	120	21	63
Budapest	37	14	74	23	27
Bucharest	33	15	78	18	53
Belgrade	28	16	27	12	51
Zagreb	25	9	16	16	34
Sofia	25	7	28	18	33
Chisinau	18	9	13	9	35

On the airports with the bigest passenger traffic and the best connectivity, **as for example, Vaclav Havel Airport – Prague** and Chopin Airport – Warsaw, the number of destinations operated by LCC is about 5 times bigger than thenumber of destinations operated by legacy companies.

We have a similar situation, a much bigger number of destinations operated by LCC, on the smaler airports which have the most important growth in terms of passenger traffic during 2004 – 2014. In this situation there are the folowing airports: Cluj from Romania : 2 LCC with 19 destinations and 3 LC with 6 destinations; Wroclaw from Poland: 3 LCC with 29 destinations and LC 3 with 4 destinations; Krakow from Poland: 6 LCC with 45 destinations and 9 LC with 11 destinations; Sibiu from Romania : 2 LCC with 3 destinations and 3 LC with 3 destinations; Katowice from Poland: 3 LCC with 32 destinations and 2 LC with 2 destinations.

On Katowice Airport, for example, which has the bigger passenger traffic in 2014, we can observe that the number of destinations operated by LC is totally insignificant in comparison with the 102 destinations operated by LCCs.

VI. CONCLUSIONS

In the last 10 years, one can notice a very important increasing in passenger traffic and in airport connectivity in Central and East Europe. In 2014, the majority of airports from Central or East European countries had an increasing traffic Thanks to this increasing, there are created the premises for an important economic growth and a world wider opening of these countries, bringing a more considerable contribution to the global economy. At the same time, this improvement in connectivity is appealing for foreign investments in the area. The growth of traffic in the region is due especially to the low cost companies. The airport connectivity is very sensitive to the evolution of dominant companies. The case of Budapest and Timisoara airports, stresses the effect caused by disappearing of the two dominant companies Malev and respectively Carpatair, which led to an important decrease in connectivity.

The development airport investments have to be concentrated according to the **economic potential** of the region, the foreign investor's interest in that region and the existing infrastructure of the airports. There are good practices in this regard, such as the airports Bourgas and Varna from Bulgaria, developed and managed by the German company Fraport, which invested in the mention airports, after the important investments made by other German companies in the tourism of the region. Another similar case is that of the airport Cluj from Romania, where there has been an excellent correlation between the investment both in the airport and the one made by foreign and national investors in the region. The results of these good strategies are mirrored in the important rate of passenger traffic growth.

One of the priorities of East and Central European countries could be **the improvement of intercontinental connectivity.**

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Contact	University of Žilina
	Air Transport Department
	Univerzitná 8215/1
	010 26 Žilina, Slovakia

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