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Estimation of European Airspace Capacity from a Model of Controller Workload

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This paper deals with the modelling of airspace capacity in Europe by first considering the factors that affect controller workload and then using a model, aided by the appropriate analytical techniques, to make an estimate of airspace capacity. The results show that capacity can be estimated based on the combination of different types of air traffic movement in a sector. The model has been used to provide airspace capacity estimates and utilisation measures for ATC sectors in Europe.

KEY WORDS

1. Air Traffic Control. 2. Human Factors. 3. Modelling. 4. Air Navigation.

1. INTRODUCTION. Air traffic controllers play a vital role in ensuring that all aircraft under their jurisdiction maintain a safe separation within an airspace. Airspace is divided into air traffic control (ATC) sectors each occupying a defined geographical volume. Controllers are assisted in their duties of air traffic management (ATM) by both technology and international regulations. The rapid growth in European air traffic has highlighted the crucial role of the controllers in maintaining safety. For example, in the period between 1985–1990, air traffic in Europe increased by 7·1% annually (EUROCONTROL, 1991). In 1990, 90% of the flights recorded within Western and Central Europe were internal to the area, i.e. there were 4·8 million flights within Europe in just that year. Furthermore, the traffic is unevenly distributed, with the existence of a 'core area', consisting essentially of London-Brussels-Frankfurt-Milan (including Paris), where air traffic density is greatest. Forecasts indicate both a 110% growth in European air traffic between 1990 and 2010, resulting in 11 million flights per year over Western Europe in 2010, and an increase in the size of the 'core area' by 2010 (ATAG, 1992). Consequently, controllers in the 'core area', already very busy, will need to deal with more aircraft in the future.

The major problem that underlies Europe's current airspace organisation is the lack of a single, integrated ATC system. Each European nation controls and manages its ATC infrastructure and the air traffic within its sovereign airspace. This leads to incompatibilities in technology and duplication of tasks and information across Europe. Amongst the major implications of these two factors are; a rise in flight delays in Europe, non-optimal flight profiles, extra route lengths and possible safety implications. The economic impact of delays, as well as other inefficiencies in the ATC system (e.g. non-optimal flight profiles), has been estimated to cost Europe US $5 billion a year (Lange, 1989).

In the late 1980s, at the request of the Transport Ministers of the European Civil Aviation Conference (ECAC), the European Organisation for the Safety of Air Navigation (EUROCONTROL) developed the European Air Traffic Control Harmonisation and Integration Programme (EATCHIP) (EUROCONTROL, 1991) to tackle the airspace capacity problems (ECAC, 1990). EATCHIP aimed to harmonize and integrate the diverse ATC systems progressively throughout Europe. This was to be accomplished by using a combination of new technology, such as the use of mandatory area navigation equipment on aircraft to provide greater precision in position than currently available, and innovative control procedures, such as the flexible use of airspace between civil and military ATC.

Many of the objectives of EATCHIP were achieved including some success in addressing the capacity problem. For example, there has been a 40% increase in capacity since 1990 to cope with a 35% increase in air traffic during the same period (ECAC, 1998). However, delays have not disappeared. For example, the average flight delay caused by ATC problems from January to October 2000 was 3·9 minutes (EUROCONTROL, 2000a). The continued growth in European air traffic has led EATCHIP to be succeeded by the EATMP (European Air Traffic Management Programme) (EUROCONTROL, 1998), whose main characteristic is the 'gate-to-gate' concept, in which flights are treated as a continuum from the first interaction with ATM until post-flight activities. In order to achieve this, a broad range of measures and a variety of technologies are considered that may significantly alter the way in which controllers work in the future European ATC system.

The success of the any initiative to increase airspace capacity, both currently and in the future, depends upon a reliable definition and measure of airspace capacity. This must take into account both the workload of the air traffic controllers and the aircraft performance-related spatial separation criteria. This paper provides a framework methodology for estimating airspace capacity in Europe using a simulation model of the air traffic controller's workload.

2. AIRSPACE CAPACITY AND CONTROLLER WORKLOAD.

In surface transport, capacity is relatively easy to understand. For example, the capacity of a road link is the maximum possible flow through that link for a particular period of time. This maximum flow is influenced by both the spatial-geometrical constraints (e.g. road geometry) and the composition of the road traffic. Furthermore, this maximum flow can be delivered by alternative demand patterns. The experience of a high air traffic density region, such as Europe, suggests that an appropriate and safe measure of airspace capacity should incorporate air traffic controller workload (i.e. the mental and physical work done by the controller to safely control traffic). This is in addition to the spatial separation criteria between aircraft, based upon their performance, and the traffic mix in the sector. Viewed this way, the capacity of an ATC sector can be defined as the *maximum number of aircraft controlled in that ATC sector in a specified period of time*, whilst still permitting an *acceptable level of controller workload*. This includes aircraft entering, exiting and transiting through the sector, in a given period of time. Based upon such a capacity definition, there is a need to define what is meant by *controller workload*, its *measurement* and *maximum acceptable level*.

2.1. *Controller Workload and its Measurement*. Controller workload is a confusing term and, with a multitude of definitions and models in the literature, its measurement is by no means uniform (Jorna, 1991). Workload is a construct, i.e. a process or experience that cannot be directly observed but must be inferred from what can actually be observed or measured. There are two basic approaches to measuring workload. The first is by self-assessment of the controllers, either instantaneously (for example, the SWAT (Wickens, 1992) technique) or non-instantaneously (for example, the NASA-TLX method (Hart *et al*., 1988)). The second method is based on detailed non-intrusive techniques (direct observations of the controllers, either by other controllers or ATC system experts).

There is an important methodological dimension in the two major measurement approaches, in that one method is self-assessed whilst the other is observer assessed. However, two major problems arise with these measurement techniques. One is that apart from the non-intrusive controller observations, which can be made in an operational ATC scenario, these techniques can only be conducted practically during 'real-time' simulations, i.e. when the controllers control simulated air traffic in mock-up facilities. The other is that both the controller self-assessment and the observer rating of workload techniques introduce a degree of subjective bias in the controller workload measure.

2.2. *Workload-based Airspace Capacity Measures*. Once a defined measure of controller workload has been chosen, then an acceptable maximum level workload (i.e. threshold) must be determined to enable airspace capacity estimation. Table 1 outlines a variety of workload-based airspace capacity measures used in assessment exercises in both Europe and the USA, with the threshold values associated with their underlying workload measure.

Again, the experience of airspace capacity analysis in Europe suggests that the most appropriate measure for controller workload is that based upon the tasks (both physical and mental) and the corresponding periods taken to carry them out (Stamp, 1992). Such a measure can be thought of as a *task-time measure of controller workload*. The most preferred method by which this task-time measure of controller workload can be obtained is by a *detailed non-intrusive objective record of the controller's actions*. However, in order to account properly for the non-observable cognitive tasks of a controller (such as planning), this record needs to be supplemented by controller verification of the tasks and their timings. By this method, it is possible to better account for the time controllers spend in the thinking and planning component of their tasks and thereby ascertain the 'true execution time for each task' (Lyons and Shorthose, 1993). For a task-time controller workload measure, the threshold value at capacity is defined by *the number of minutes within a given hour that the controllers are occupied in their tasks* (EUROCONTROL, 1999a).

3. AIRSPACE CAPACITY DRIVERS. The previous section has indicated that in the dense European air traffic network, air traffic controller workload is the key determinant of airspace capacity. Research studies (Mogford *et al*., 1995) show that workload is primarily dependent on the complex interaction of the air traffic and the characteristics of the ATC sectors. The workload experienced by the controllers can also be mediated by *secondary factors* including the cognitive strategies the controller uses to process air traffic information, the quality of the equipment (including the computer-human interface) and individual differences (such as age and

Table 1. A Comparison of airspace capacity measures.

Capacity Measure	Main Advantages	Main Disadvantages
Declared Capacity	A controller defined value obtained from data of actual ATC sectors.	No indication of workload saturation. Capacity estimate varies by season and new technology.
MACE Capacity Estimate	A direct subjective measure related to recent tasks.	Open to bias. Has not been validated.
FAA Sector Complexity and Density Measures	Accounts for the different control requirements of different types of traffic and combines sector and traffic features.	No justification and validation for the weightings allocated to different control requirements for different types of air traffic.
MBB Method	A simple mathematical definition to apply to obtain a workload measure.	No account of flight duration or route complexity. No recent validation.
Task-time Based Estimates	These attempt to account for the detailed usage of controller time, separating those elements of the workload that are fully defined from those less well defined.	Cognitive processes and tasks are difficult to represent accurately in these estimates.
Schmidt Model	A simple formula to apply that attempts to account for usage of the controller's time.	Task discrimination too simplistic, with tasks too difficult to assess, cognitive tasks not accounted for.
Air/Ground Communications Link Capacity	Simple definitions that account for tasks associated with a vital ATC technology.	No indication of sector characteristics, controller tasks and saturation point.

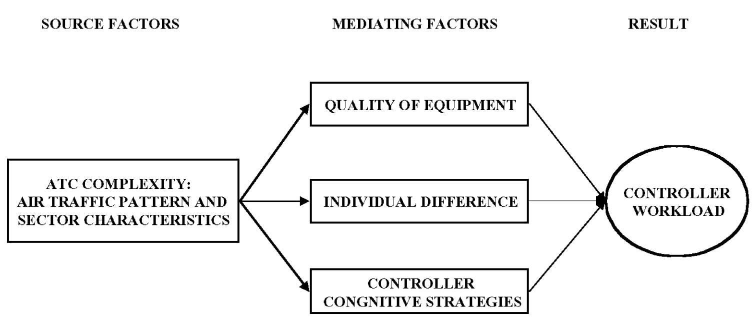

Figure 1. Factors affecting controller workload.

level of experience). These factors can be thought of as the drivers of controller workload, and consequently as drivers of airspace capacity. The effect of these factors on airspace capacity must be understood if realistic and successful strategies for increasing capacity are to be implemented. Figure 1 illustrates a model proposed by Mogford *et al.* (1995) of controller workload based upon these four factors.

Mogford *et al.* (1995) provide a useful, primarily, qualitative review of research on the effect of these factors on controller workload. There have been various recent attempts in the USA and Europe to go beyond such qualitative research and try to understand the functional relationship between controller workload and a number of these workload drivers. The methodologies for such attempts fall into two broad categories, either:

(a) 'real-time' simulations followed by controller questionnaires; for example, the 'dynamic density' concept of NASA (Laudeman *et al*., 1998). Whilst aided by major controller involvement, these studies are expensive and time-consuming; or

(b) the analysis of historic data (e.g., by the FAA human factors group (Rodgers *et al*., 1998)) on the separation loss between aircraft in Atlanta airspace, assumed to occur when controllers are under high workload conditions. Concerns arise about the transferability of the results to other airspace sectors and its limited use in studying future technology and procedural scenarios.

These two approaches have provided significant insights on the parameters influencing controller workload and airspace capacity, see Table 2.

Table 2. List of air traffic and sector factors that can affect controller workload from the literature.

Air Traffic Factors	Sector Factors
Total number of aircraft	Sector size
Peak hourly count	Sector shape
Traffic mix	Boundary location
Climbing/descending aircraft	Number of flight levels
Aircraft speeds	Number of facilities
Horizontal/vertical separation standards	Number of entry and exit points
Minimum distance between aircraft	Airway configuration
Aircraft flight direction	Proportion of unidirectional routes
Predicted closest conflict distance	Winds

An alternative approach is the use of a realistic computer simulation modelling of airspace and controller workload to vary a number of possible air traffic and ATC sector parameters systematically, i.e. carefully define the rules for the elements of the simulation in order to investigate their interaction. Subsequent analysis of the output from the model can be used to formulate a functional relationship between the controller workload and the relevant parameters at an aggregate level. Whilst various studies have been undertaken using simulation models of controller workload (EUROCONTROL, 1997), none has considered the impact of systematically varying a set of air traffic and ATC sector parameters on workload and then formulating a functional relationship. Magill (1998) notes the advantages of a simulation modelling technique over real-time simulations for capacity estimation, in particular: its economic benefits, its use over a large geographical area and its ability to investigate a wider range of traffic levels. To use such a computer simulation methodology, it is imperative to choose the appropriate controller workload simulation model.

4. CONTROLLER WORKLOAD MODELS.

The previous section noted that by using an appropriate simulation model, the functional relationship between the controller workload and the relevant parameters at an aggregate level could be estimated. This section describes alternative workload models in light of their

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appropriateness for the simulation modelling approach. Air traffic controller workload models can be either analytic or simulation models.

Analytic models are based on relatively straightforward equations, often regression equations, in which the predicted output can be rapidly generated from the mathematical analysis of a specified set of inputs. Two examples of analytic controller workload models are the Sector Design Analysis Tool (SDAT) devised in the USA (Geisinger and MacLennan, 1994), and the Capacity Indicators Model (CIM) used by EUROCONTROL (Lyons and Shorthose, 1993). Both these models determine the workload in a sector given the associated sector tasks and use probability theory to predict the expected number of conflicts in the sector and the consequent resolution strategies to resolve them.

Whilst simulation models are more complex, they are however often necessary in a system such as ATC since the great complexity of the system prevents its behaviour from being captured by analytic equations (Wickens *et al*., 1997). In addition, the inherently dynamic behaviour of an airspace is well suited for a dynamic simulation. There are two major simulation controller workload models. One of these is the DORATASK model (Stamp, 1992) that has been developed and used specifically for the UK's ATC sectors, where its results have been validated. The other is the Reorganized ATC Mathematical Simulator (RAMS) that has been widely used and validated throughout European airspace (EUROCONTROL, 1995). In addition, a model of air traffic controller workload based upon the cognitive tasks of a controller has been developed by the UK NATS, known as the Performance and Usability Modelling in ATM (PUMA) Model (Kilner *et al*., 1998). The increasingly popular Total Airspace and Airport Modelling (TAAM) simulation model is not yet appropriate as its deficiencies in workload modelling have been pointed out in a recent EUROCONTROL report (EUROCONTROL, 2000b). From this, RAMS stands out as the most appropriate simulation model for use in conducting airspace capacity assessments over a large region of European airspace. The main features of RAMS are outlined below together with a discussion of the issues to be taken into account in a simulation exercise.

5. THE REORGANIZED ATC MATHEMATICAL SIMULATOR (RAMS).

The RAMS model is a discrete-event simulation model that has been used widely for over 25 years in Europe for airspace planning, and has been verified by controllers (EUROCONTROL, 1999). In the RAMS model, each control area is associated with a sector, which is a 3-D volume of airspace as defined in the real airspace situation. Each sector has associated with it a RAMS Planning Control and a RAMS Tactical Control, see Figure 2. These control areas maintain information regarding the flights that wish to penetrate them, and have associated separation minima and conflict resolution rules that need to be applied for each of the two RAMS control elements. The use of the Planning and Tactical control elements reflects the teamwork aspect of control seen in practice. The simulation engine also permits the input of rules that mimic reality. The tasks for the controllers in RAMS are based on a total of 109 tasks, together with their timings and position, grouped into five major areas. These tasks are derived from a number of reference airspace regions of Europe, which include sectors in the London region, Benelux countries, France and Germany. Furthermore, a cloning engine enables future traffic demands to be generated, based upon the current air traffic patterns.

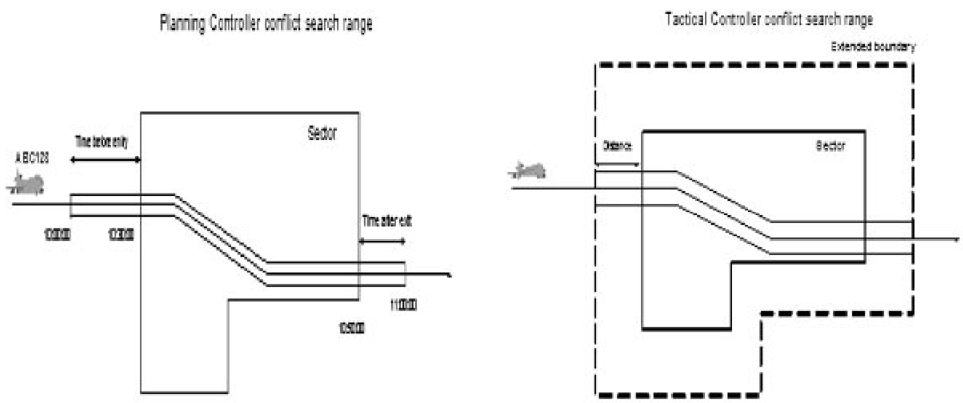

Figure 2. The control elements in RAMS.

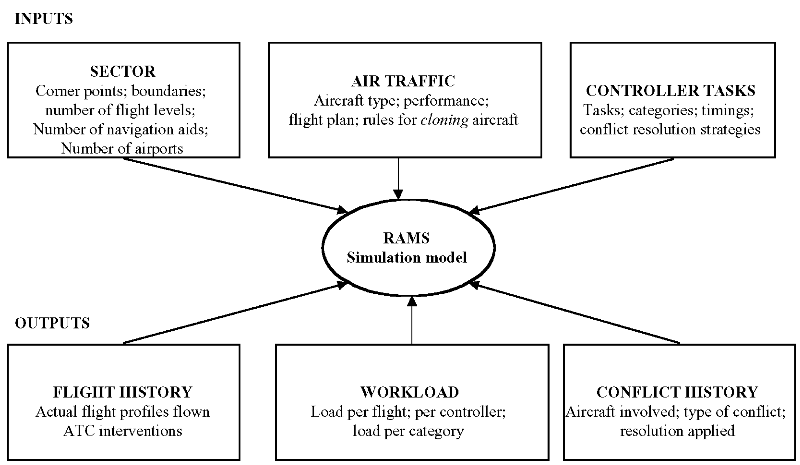

Figure 3. The inputs and outputs into the RAMS model.

A range of methodological issues must be addressed with the use of such a simulation modelling technique, especially the need to ensure that the simulation replicates the conditions in European airspace as closely as possible. Figure 3 shows the major inputs and outputs of the RAMS model. The application of appropriate 'rules' for the inputs of RAMS, deals with the following simulation issues:

(a) the area of airspace simulated – the characteristics of the ATC sectors and the air routes through them are contained in the sector data input files;
(b) the air traffic simulated – the characteristics of the aircraft and their performance capabilities are contained in the air traffic data input files;
(c) the simulated controller tasks and procedures – the set of controller's tasks and their timings are contained in the controller task input files. The choice of an appropriate set and its implications are of the utmost importance in both undertaking as well as understanding the simulation results.

Having ensured that RAMS reflects the real airspace environment being simulated as closely as possible, attention must then be paid to the workload estimates from the model. Magill (1998) notes that to make effective use of the simulation modelling technique, 'it is desirable to have a simple means to characterise the work done by the ATC system.' The workload estimates obtained from the RAMS model are based upon task-time definitions derived from a detailed non-intrusive objective record of the controller's actions, aided by controller verification. Based upon these task-time definitions, threshold controller loadings of a control team (Tactical and Planning) at capacity being 42 minutes/hour must be utilised for RAMS (EUROCONTROL, 1999). This task time threshold has been validated by several real-time studies and the experience gained from previous simulation results, as well as from field studies (e.g. EUROCONTROL, 1999).

6. A SCHEME FOR ESTIMATING AIRSPACE CAPACITY. Based on the previous sections, it is possible to generate a perfectly adequate general capacity model, which will be used in the forthcoming sections. The procedure, summarised by Figure 4, is as follows:

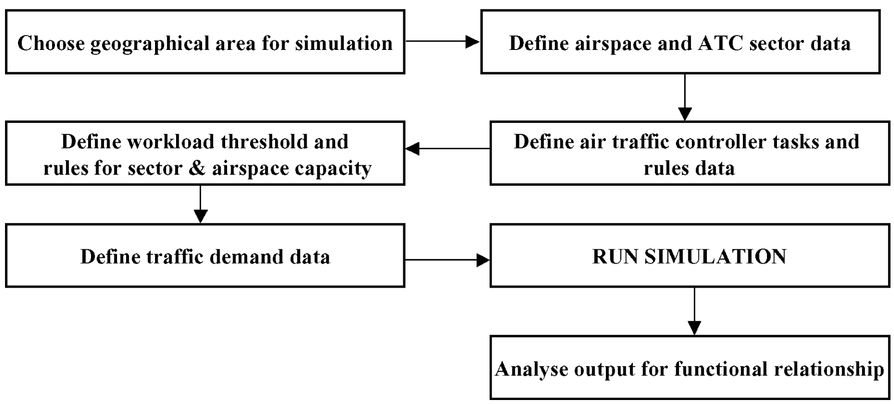

Figure 4. A scheme for estimating airspace capacity.

(a) *Step 1*. Define the physical characteristics of the air traffic system. This is conceptually simple for the existing ATC network. There is a need to define:
   (i) the airspace sectors and their horizontal and vertical boundaries (locations);
   (ii) the number of flight levels in each sector;
   (iii) the air routes through the sectors, comprising of a series of navigation aids defined by geographic coordinates;
   (iv) the airport locations, in geographic coordinates

Whilst these are directly observable, data collection and analysis can be time consuming

(b) *Step 2*. Define the traffic demand through the sectors. This involves definition of the aircraft types and their associated performance characteristics, e.g. speed characteristics, climb and descend rates, as well as their chosen routes. This also applies for the any traffic demand forecast known.
(c) *Step 3*. Define the rules for assessing the capacity of an individual ATC sector for use in the simulation model of air traffic controller workload. This requires a base of tasks and timings for the controller's work and the definition of controller workload threshold for capacity based upon these tasks.

(d) *Step 4*. From the output of the simulation runs, undertake statistical analysis to derive a functional relationship between airspace capacity and the *airspace capacity drivers*, mentioned in Section 3.

The use of a technique based upon the use of a simulation model of controller workload, defines the capacity of an ATC sector as the *maximum number of aircraft controlled in a particular ATC sector in a specified period*, while still permitting an *acceptable level of controller workload.*

7. THE SIMULATION EXPERIMENTS. A number of simulation experiments were conducted with RAMS to test the effects of certain variables on the workload obtained from it. The salient points of the simulations are outlined below. In these simulations, it is the air traffic data that is systematically varied (Figure 3).

The simulation area covered the 122 en-route sectors of continental Europe, excluding the United Kingdom due to its unique ATC procedures. Figures 5 and 6

Figure 5. European ATC sectors.

Figure 6. Navigation aids and airports.

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show the geographical location of the sectors and the distribution of navigation aids (navaids) throughout Europe (an indicator of the route density). Four different traffic patterns were modelled as shown in Table 3.

Table 3. The basic air traffic demand simulation scenarios.

Traffic Demand Simulated	Airspace Region	Number of sectors
Current (1996)	*Germany, France, Italy, Central Europe, Spain, Portugal, S.E. Mediterranean, Denmark*	122
+25% Current	*Germany, France*	67
+50% Current	*Italy, Central Europe, Spain, Portugal, S.E. Mediterranean, Denmark*	64
+100% Current	*Italy, Central Europe, Spain, Portugal, S.E. Mediterranean, Denmark*	22

The logic behind this is as follows. Computational constraints meant that Europe was sub-divided into geographic regions for the simulations, such as German airspace and French airspace, depending upon the traffic flow pattern. When any sector in such a geographical sub-division reached workload at capacity (i.e. workload of the control team reached 70% of an hour in that sector) that geographical airspace was assumed to be at capacity. After all, that particular sector is related to all others adjacent to it and forms a bottleneck in that particular airspace. A minimum of ten replications per geographical scenario was run to account for randomness in the model.

The flight data is contained in traffic profiles of the scheduled flight data for a particular day. Individual flights are defined by an entry time, entry cruise and exit levels into a sector, aircraft performance model, and a flight plan of navaids, airports and runways (i.e. the route of the flight). Flight profiles are dictated by the flight plan and aircraft performance. The flight path is 4-dimensional, containing 3-dimensional positions in space, each associated with time of arrival. Aircraft performance is defined by the cruise, climb and descent speeds and rates and by wake turbulence separations. The *cloning* engine replicated the current air traffic to allow future traffic scenarios to be explored under the assumption that the pattern of current air traffic demands and routes remain, e.g. demand for London to Paris flights and their timings remain the same at present.

The choice of an appropriate controller task base is essential for confidence in the results. To this end, the task base for controllers of the Bordeaux Area (South West France) Air Traffic Control centre was utilised. The advantage of this task-base was that it contained the timings given by the controllers for all their tasks, including those required in their strategies to resolve the various types of air traffic conflicts. This task base was sub-divided into the five control task categories: internal and external co-ordinations tasks; flight data management tasks; radio/telephone communications tasks; conflict planning and resolution tasks; and radar tasks. This particular task set has been validated and used in sector planning (EUROCONTROL, 1996). A consequence of choosing this task base is that all sectors are assumed to have the same equipment and level of technology as the Bordeaux sector. This is not necessarily the case across Europe, e.g. in sectors in Greece and Cyprus.

Given the accuracy and reliability of ATC position equipment, the dynamic nature of ATC and the difficulty in maintaining constant distance separation between aircraft of varying speeds, common practice in European airspace is for controllers to maintain a time based separation of 2 or 3 minutes between aircraft rather than the 5 nautical miles separation permitted in areas of radar coverage by international regulations. This is modelled by a greater longitudinal and lateral separation between aircraft of ten nautical miles. The use of dynamic separation multipliers in RAMS further increases the aircraft separation based upon the relative positions between the two flights during the simulation, and thereby provide increased realism into the conflict detection, e.g. providing greater separation between aircraft approaching each other than when aircraft are parallel to each other.

8. A GENERAL FUNCTIONAL MODELLING STRATEGY.

The output data from the RAMS simulations of interest in this capacity analysis are those for the workload and the history of the flights through the sectors, Figure 4. In order to derive a functional relationship between the controller workload and the relevant air traffic and ATC sector variables obtained from the RAMS output, the appropriate analytical techniques need to be used.

The most usual method of obtaining such a functional model is to use classical – ordinary least squares (OLS) and fit a linear regression model to the data (Gujerati, 1995). The assumption underlying regression models is that the observed value of dependent response variable Y can be explained by a function (often a simple linear combination) of the independent X variables, e.g.:

$$y = X\beta + \epsilon, \tag{1}$$

where: y is the response variable, i.e. workload,
X is the matrix of regressor variables, i.e. traffic and sector variables,
β are the unknown parameters,
$\epsilon \sim \mathrm{N}(0, \Sigma)$, the error or disturbance term.

The OLS procedure is usually chosen to estimate the parameters β as it has certain optimal properties, encapsulated under the Gauss-Markov theorem. This makes the estimators obtained by OLS the best linear unbiased estimators (BLUE) in the class of linear unbiased estimators. However, the Gauss-Markov conditions can be violated if the Y values are not measured with equal accuracy or there is correlation between the error terms.

Should either of these situations occur, then whilst the estimators obtained by OLS may be unbiased they will not have the minimum variance property, and thus will not be BLUE. Hence any hypothesis tests on the parameters will produce misleading results as to the apparent significance of the X variables. The solution in such cases is to use Generalised Least Squares (GLS), a technique that in effect makes use of 'information' that OLS does not, and transforms the variables on which OLS can then be conducted so that the estimators are BLUE. Two situations where GLS must be used are in the presence of heteroskedasticity and autocorrelation, outlined below. Figure 7 provides the functional modelling strategy and analytical techniques to be used in the capacity assessment exercises.

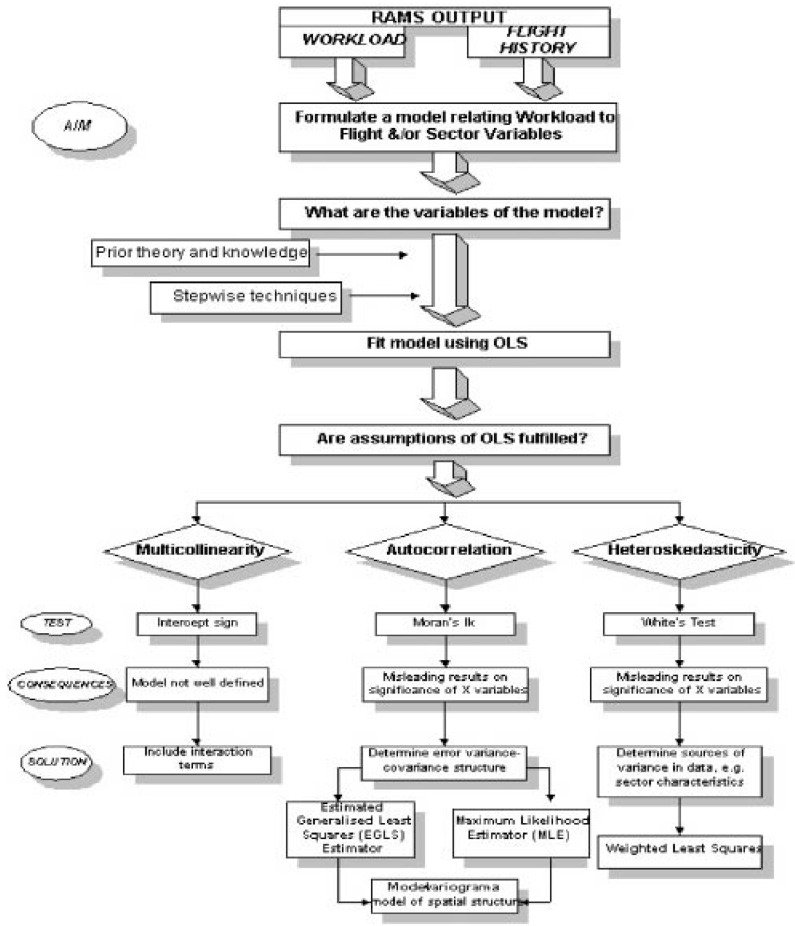

Figure 7. The modelling strategy used in this research.

Table 4. List of possible regressors obtained from the RAMS model.

Sector Design	Traffic Structure
1. Volume of airspace	1. Total flight time
2. Number of airports	2. Average flight time
3. Number of navigation aids	3. Number of aircraft in cruise attitude
4. Number of intersection points	4. Number of aircraft in ascent attitude
5. Dimension of maximum side	5. Number of aircraft in descent attitude
6. Perimeter	
7. Number of vertical sectors	
8. Number of surrounding sectors	

9. ANALYSIS OF RESULTS AND MODEL SPECIFICATION. Based on the strategy of Figure 7, Table 4 outlines a list of possible regressors (subdivided into sector design and traffic structure) obtained from the RAMS simulation model. For each traffic demand pattern, the requirement is to fit the most

Table 5. OLS for the current air traffic for six-variable interaction model (122 sectors).

Attitude Variable	$\hat{\beta}$	SE	t
Intercept	158·78	50·80	3·13
Cruise	55·48	6·06	9·15
Ascent	44·51	8·41	5·29
Cruise^2	−0·56	0·063	−8·84
Descent × Cruise	4·09	0·762	5·38
Ascent × Cruise	2·07	0·659	3·15
Descent × Ascent	4·86	0·923	5·26
Adjusted R^2	0·9282		
Regression F	261·55		
White's Test, χ^2	21·7085	Pr. = 0·5967	

Table 6. WLS for the current air traffic for six-variable interaction model (122 sectors).

Weight	Surrounding Sectors		
Attitude Variable	$\hat{\beta}$	SE	t
Intercept	148·54	54·73	2·71
Cruise	56·95	6·25	9·11
Ascent	46·54	8·527	5·46
Cruise^2	−0·57	0·069	−8·26
Descent × Cruise	4·27	0·746	5·73
Ascent × Cruise	1·67	0·634	2·62
Descent × Ascent	4·98	0·947	5·26
Adjusted R^2	0·9241		
Regression F	246·62		

appropriate analytical model to the RAMS output data to determine the link between the workload obtained and the various flight and sector data.

Consider the analysis for the *base or current air traffic simulation*, covering 122 sectors. Forward selection and stepwise procedures for the selection of regressors indicate that the following five variables only are significant to the 5% level of significance: number of aircraft in cruise, number of aircraft in ascent, number aircraft in descent, the total flight time and the average flight time. It is noteworthy that these variables are all traffic related, with no sector related variable is significant.

Based upon these five variables, a variety of regression models were fitted to the output data from RAMS for the current traffic simulation, and the most appropriate model is shown in Table 5. This table shows the results of a linear regression (OLS) for a 6-term model incorporating interactions between the different types of air traffic movement, i.e. ascend, cruise and descend.

The presence of a positive intercept is essential and implies that, even if there were no aircraft in a sector, controllers would have work to do in the sector, such as in-sector communications.

9.1. *The heteroskedasticity correction.* Table 5 also shows the results of White's Test conducted to determine the presence of heteroskedasticity (Gujerati, 1995), i.e. the case when the error variance is not constant across all observations. The results seem to indicate the presence of heteroskedasticity, which is not surprising given that

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the current traffic simulation covers the whole of Europe's airspace and presents a wide variety in the characteristics of the ATC sectors. Since the true variance σ_i^2 is unknown, assumptions are made about the heteroskedasticity pattern. From a variety of possible sources, the numbers of sectors that surround any given sector were chosen, as this can cause varying workload. The rationale behind this is as follows. If many sectors surround a particular sector, this may well provide more entry and exit points and lead to a complicated traffic pattern within the sector. Should this be the case, the workload can be greater than if there are few sectors to provide entry and exit points. However, it could be that the more surrounding sectors there are, the less conflicts there will be within the sector as there are many more alternative routes provided for the air traffic. Table 6 shows the results of a weighted regression (WLS), which indicates in comparison to Table 5 that there does not appear to be much difference in parameter and intercept values between unweighted OLS and the WLS with surrounding sectors. This implies that the heteroskedastic effect in the data, whilst not negligible, is not very great. In the WLS analysis, each observation (sector) is assigned a weight, w_t:

$$w_t = \frac{1}{\sqrt{SS}}, \tag{2}$$

where: SS = number of sectors that surround a sector. The weight is selected to ensure that the variance of the weighted data is constant.

9.2. *The spatial autocorrelation correction.* In addition to heteroskedasticity, there is a likelihood of spatial correlation in the data given the geographic nature of air traffic flow patterns. Again a correction needs to be made if such correlation occurs. A formal method of testing for spatial correlation is by means of Moran's I_k test for the residuals obtained from an OLS or WLS analysis, using:

$$I_k = \frac{\hat{e} W \hat{e}'}{\hat{e}\hat{e}'}, \tag{3}$$

where: $\hat{e}$ = the error residuals from an OLS or WLS.

Equation (3) requires the specification of a Weights matrix (W) for the data. Cliff and Ord (1981) suggest that a binary weights proximity W matrix is appropriate, where:

$w_{ij} = 1$ if ATC sectors i and j had a common boundary length,
$w_{ij} = 0$ if otherwise.

Under the assumption of normality, the mean and variance of I_k are:

$$E(I_k) = \frac{trace((I - P_x)W)}{n-k}, \text{ and} \tag{4}$$

$$Var(I_k) = \frac{trace\{(I-P_x)W(I-P_x)W'\} + trace\{[(I-P_x)W]^2\} + [trace(I-P_x)W]^2}{(n-k)(n-k-2)} - [E(I_k)]^2, \tag{5}$$

where: $P_x = X(X'X)^{-1}X'$ and k is the number of parameters in the regression model. As the standardized I_k statistic is asymptotically normal, a one-sided test procedure for large samples is:

Test $H_0: \rho = 0$ versus $H_a: \rho \neq 0$

Reject H_0 if:

$$z^* = \frac{I_k - E(I_k)}{\sqrt{Var(I_k)}} > z_{1-\alpha}, \tag{6}$$

where: ρ is a constant and is a measure of the *overall level of spatial autocorrelation* amongst the elements of the error term (e_i, e_k) for which $W_{ik} > 0$. If $\rho > 0$, then one has *positive* spatial autocorrelation among the residuals, whereas $\rho < 0$ implies *negative* spatial autocorrelation. The results from the residuals obtained from the OLS and WLS regressions carried out for the six variable model relating to the different attitudes of air traffic in a sector are given in Table 7.

Table 7. Results of Moran's I_k test for the 6-variable model.

	OLS	WLS (Surrounding Sectors)
Moran's I_K	0·458666	0·388073
$E(I_K)$	−0·06473	−0·06473
$var(I_K)$	0·078534	0·078534
Z*	1·867653	1·615752

A z-value of 1·86 corresponds to a one-sided probability of 3·07%, whilst a z-value of 1·62 corresponds to a one-sided probability of 5·26%. These results suggest the marginal presence of spatial autocorrelation amongst the residuals at a 5% level. For the completeness of further analysis, the presence of spatial autocorrelation has been assumed.

10. CORRECTION FOR SPATIAL AUTOCORRELATION.

The presence of spatial correlation noted in the previous section requires correction. Returning to regression equation (1) again, the aim here is to estimate the parameters β and the fact that the workload is spatially correlated is a nuisance factor whose influence needs to be accounted for in the analysis. If the variance-covariance matrix (Σ) is known, then the best unbiased estimator for β is the generalized least squares estimator since this has the smallest variance of any linear estimator:

$$\hat{\beta}_{GLS} = (X'\Sigma^{-1}X)^{-1}X^{-1}\Sigma^{-1}y. \tag{7}$$

However, since β *and* Σ are unknown in this case, they can both be estimated simultaneously using the method of maximum likelihood. This method involves the calculation of the joint likelihood that the observed response values, i.e. workload, given the values assigned to certain parameters. The likelihood function is given by:

$$L(\phi|y) = f(y|\phi), \tag{8}$$

and the aim is to find the value of ϕ which is most likely to have generated the observed data set.

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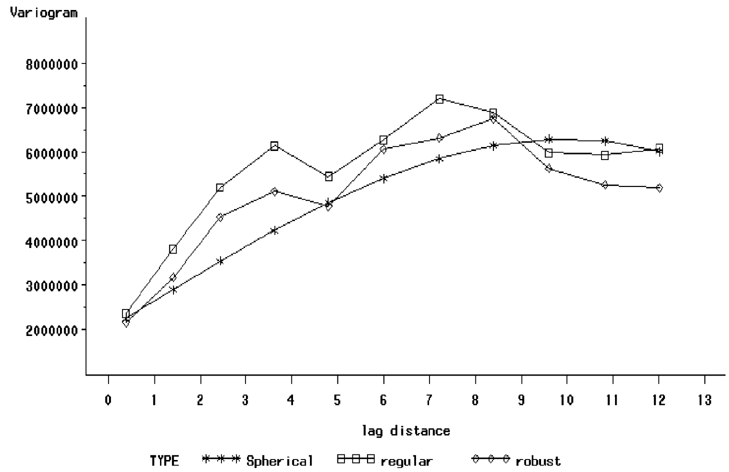

Figure 8. Covariogram of current traffic data for the ATC sectors of Europe compared with a theoretical spherical covariogram.

Maximum likelihood estimators (MLE) have desirable properties in that they are asymptotically normally distributed, consistent (as sample size increases the MLE tends towards the true value) and asymptotically efficient (as sample size tends to infinity, the MLE has the smallest possible variance). However, MLE estimators are not necessarily unbiased and require assumptions about the form of the distribution.

10.1. *The variogram function.* Information about the error covariance structure can be obtained from a *residual correlogram* that shows the variation in residual correlation with inter-locality distance. In the case of residuals, Cook and Pocock (1983), in their analysis of geographical mortality studies in the UK, use the distance definition $(\hat{\epsilon}_i - \hat{\epsilon}_j)^2$ to derive an estimate of the correlation between errors at i and j occurring at distance d_{ij}. They use an algebraic identity, so that:

$$E\{(\epsilon_i - \epsilon_j)^2\} = 2\sigma^2\{1 - \rho(d_{ij})\}, \tag{9}$$

where: ρ is a constant and is a measure of the overall level of spatial autocorrelation amongst the elements of the error term. In order to estimate $\rho(d_{ij})$, estimates of σ^2 and of $E\{(\epsilon_i - \epsilon_j)^2\}$ are needed. With the former independent of distance, attention turns on the estimate of the expectation:

$$E\{(\epsilon_i - \epsilon_j)^2\} \approx \frac{1}{n_d} \Sigma \left(\hat{\epsilon}_i - \hat{\epsilon}_j\right)^2, \tag{10}$$

where the summation is taken over all those locality pairs occupying distance class d. For convenience denote the sample estimate given on the right hand side of equation (10) as G.

A correlogram is provided by plotting G against $(\Sigma d_{ij})/n_d$, the mean inter-locality distance of the locality pairs belonging to distance class d. The variation in G with d will provide a clear idea of the extent to which the residuals display autocorrelation and, with an accurate estimate of σ^2, it is possible to obtain $\rho(d_{ij})$ from Equation (9) to show explicitly how $\rho(d_{ij})$ varies with d_{ij}. Cook and Pocock (1983) obtain their estimate of $\hat{\sigma}^2$ by identifying from the G correlogram the distance u at which errors are evidently uncorrelated. This will correspond to the point where the correlogram flattens to approximately a zero slope.

Equation (10) defines the *variogram function* and is simply a model of the spatial dependence or continuity, of the residual terms obtained from the OLS analysis of the data. Geostatistical theory has a considerable body of literature detailing with the intricacies of variogram estimation (e.g. Journel and Huijbregts, 1978) either visually or by analysis.

The *isotropic* or direction-invariant variogram estimated for the ATC sectors of Europe is shown, for the current traffic scenario, in Figure 8. Note that it is the behaviour of the variogram near the origin that is of interest and, in Figure 8, there appears to be a strong local (nugget) effect with (lag distance 1) a spherical variogram whose formulation is given by:

$$\gamma_z(h) = c_0 \left[\frac{3}{2} \frac{h}{a_0} - \frac{1}{2} \left(\frac{h}{a_0} \right)^3 \right] \text{ for } h \leqslant a_0 \tag{11a}$$

$$\gamma_z(h) = c_0 \quad \text{for } h > a_0 \tag{11b}$$

where: a_0 is the range and c_0 is the scale of the covariogram. For further details of such variogram estimation, see Majumdar (2002).

Estimating by maximum likelihood of the model in Table 6 with both a spherical variogram and nugget to account for the spatial nature of the error term as well as for heteroskadasticity indicated that the Cruise^2 variable was not significant. Removing this variable gives the parameter values for the resulting five-variable model shown in Table 8. When comparing the results of the MLE analysis to the OLS

Table 8. MLEs for 5-variable model with a spherical variogram structure and nugget.

Attitude Variable	$\hat{\beta}$	SE	t
Intercept	193·921	46·269	4·19
Cruise	45·225	4·446	10·17
Ascend	46·201	7·946	5·81
Descend × Cruise	3·820	0·713	5·35
Ascend × Cruise	1·560	0·596	2·61
Descend × Ascend	5·337	0·895	5·96
Log Likelihood	−828·602		
AIC (model fit measure)	−831·602		

analysis (Table 6), it can be seen that the intercept term is much higher than for OLS (by 45 seconds), whilst the cruise variable parameter is nine seconds lower and the ascent variable parameter is nearly the same.

11. MODEL ESTIMATION FOR +25% AND +50% CURRENT TRAFFIC DEMAND.

On the basis of a similar analysis to that in Sections 9 and 10 for the other traffic demand patterns, Table 9 summarizes the significant

Table 9. Summary of relevant variables for each demand pattern.

Demand	Current		+25%		+50%		+100%	
Variable	WLS	ML	WLS	ML	WLS	ML	WLS	ML
Cruise	√	√	√	√	√	√		
Ascent	√	√			√	√		√
Cruise^2	√							
Descent							√	√
Descent^2							√	√
Descent × Cruise	√	√	√	√	√	√		
Ascent × Cruise	√	√	√	√			√	√
Descent × Ascent	√	√	√	√	√	√		

variables (indicated by √ sign) relating controller workload to the air traffic movement variables, for each demand pattern. Note the following about Table 9:

(a) WLS indicates weighted least squares estimation, where a correction for heteroskedasticity is made by using the number of surrounding sectors as the appropriate weight;
(b) ML indicates maximum likelihood estimation where a correction is made both for heteroskedasticity and for spatial autocorrelation (spherical covariogram model).

If the +100% current traffic demand model is ignored because of the problems associated with such a small, disparate data set, then certain interesting observations can be made from Table 9:

(c) the functional models for the +25% and +50% of current traffic data, the MLE data, involve a sub-set of variables of the five variables determined with the model for the current traffic demand data;
(d) the Cruise, (Descent x Ascent) and the (Descent x Cruise) variables are present in all models, and all three types of aircraft movement are incorporated as the significant variables of models for each of the three traffic demand data;
(e) the Descent variable exists only in interaction with the other aircraft movements in all three models. Two such Descent-based interaction variables are significant for each traffic demand.

12. USE OF THE MODELLING FRAMEWORK. This modelling framework can be used in a variety of ways. With the parameters given by Table 8, for the current travel demand, a curve of the workload when the control team is assumed to be at capacity, i.e. 70% of an hour (see Section 2 for the choice of this threshold) can be plotted. For example, in the case of the current traffic demand, one has the following equation:

$$W = 193{\cdot}92 + 45{\cdot}23C + 46{\cdot}2A + 3{\cdot}82DC + 5{\cdot}34DA + 1{\cdot}56AC, \quad (12)$$

where: C = the number of aircraft in cruise attitude in the peak hour;
A = the number of aircraft in ascent attitude in the peak hour;
D = the number of aircraft in descent attitude in the peak hour.

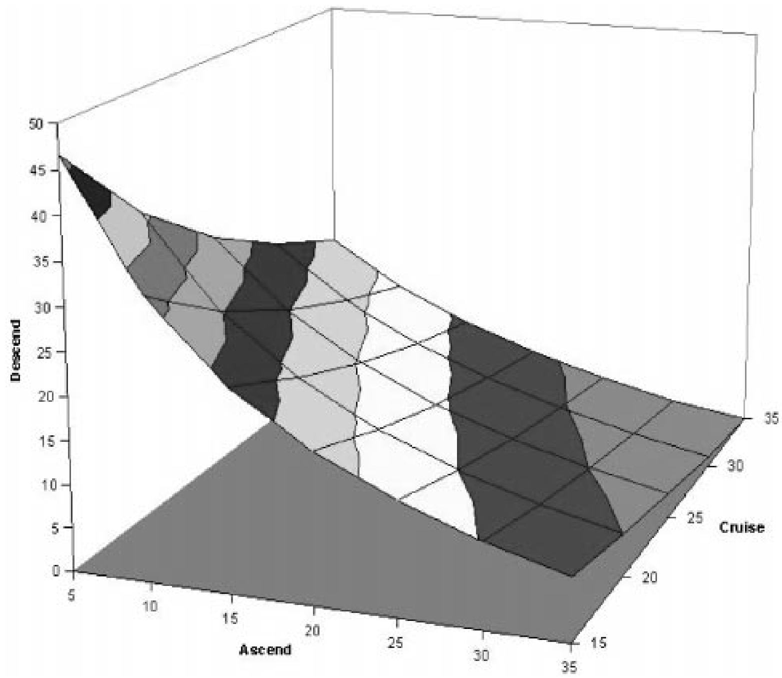

Figure 9. Capacity Curve (70% of hour workload) for current traffic, 5-term interactions model weighted by surrounding sectors (ML).

Table 10. The workload values calculated for four sectors based on the 100 ML Model.

Sector	Declared Capacity	Declared Cruise Aircraft	Declared Ascent Aircraft	Declared Descent Aircraft	MODEL 100 ML Workload (seconds)
EDDYLNO	51	26·52	11·73	12·75	4510·35
A	41	22·14	7·79	11·07	3220·64
B	35	23·8	5·25	5·95	2415·42
C	32	22·72	6·4	2·88	2091·28

At capacity, W is 42 minutes (2520 seconds) in equation 12, it is possible to determine the combination of cruise, ascent and descent aircraft that produces this workload. This 'capacity curve' is shown in Figure 9, and indicates the theoretical maximum number of aircraft in their various possible attitudes, based upon equation (12). The resulting surface shows the traffic combinations that could be obtained when the control team is at capacity.

The value of such a curve is as follows. For a number of ATC sectors in European airspace, there exists a capacity measure known as the *declared capacity*, which is declared by the controllers of the sector as the maximum number of aircraft handled by them in the peak hour over a six-month period. As an example of the use of these curves, consider the declared capacity values for four sectors in 1996, one of which is the EDDYLNO sector in the Maastricht area control centre, which had the highest declared capacity of any in Europe with 51 aircraft in the peak hour outlined in Table 10. (This information was kindly supplied by Soenke Mahlich, Head of Airspace Indicators Division, EUROCONTROL, Bretigny-sur-Orge, France.)

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In Table 10, the columns have the following meaning:

(a) Column 1 gives the sector/airspace for which declared capacity figures are available. Due to the political sensitivities associated with sector capacity issues in Europe, the geographical location of sectors referred to as Sectors A, B and C are not identified;
(b) Column 2 gives the declared capacity – the peak hour traffic handled as declared by controllers in their sector, over a six month period in 1996;
(c) Column 3 gives the average number of declared cruising aircraft handled in the peak hour from the controllers' declared capacity breakdown;
(d) Column 4 gives the average number declared ascending aircraft handled in the peak hour from the controllers' declared capacity breakdown;
(e) Column 5 gives the average number declared descending traffic handled in the peak hour from the controllers' declared capacity breakdown; and,
(f) Column 6 indicates the workload calculated for the sectors based upon the functional model derived for the current traffic demand.

The information from equation (12) and Table 10 can be used in one of two ways, outlined below.

12.1. *Sector Utilization.* Given that the maximum workload at capacity for the ATC team, using the 70 % workload threshold, is 2520 seconds, then the workload utilization of a sector, U, can be defined as:

$$U = \frac{W_{MOD}}{W_{MAX}}, \tag{13}$$

where: W_{MOD} = workload derived from the functional model;
W_{MAX} = maximum possible workload.

The results of using this equation (13) on sector utilization can be seen in Table 11.

Table 11. Percentage sector utilization and difference in number of aircraft for four sectors based on the 100 ML Model.

Sector	Declared Capacity	% Utilisation of MODEL 100 ML	Declared Descent Aircraft	100 ML Descent Aircraft	Difference Descent 100 ML – Declared
EDDYLNO	51	89·5	12·75	15·98	3·23
A	41	63·9	11·07	25·49	14·42
B	35	48·0	5·95	28·02	22·07
C	32	41·5	2·88	27·25	24·37

12.2. *The Theoretical Number of Aircraft in the Sector.* Alternatively, the capacity can be determined in terms of the number of aircraft theoretically possible in the sector using the equations derived earlier. For the current demand model, given the number of declared cruising and ascending aircraft, the theoretical maximum number of descending aircraft possible at the workload capacity of 2520 seconds can be determined, Table 11.

In Table 11, the columns have the following meaning:

(a) Column 1 gives the sector/airspace for which declared capacity figures are available;
(b) Column 2 gives the sector utilization when calculated using the current traffic demand model;

(c) Column 3 gives the declared number of aircraft in descent for the sector;
(d) Column 4 gives the calculated maximum number of aircraft in descent at capacity, based upon the parameters for the functional model of the current traffic demand;
(e) Column 5 gives the difference between the calculated number of aircraft in descent, based upon the current traffic functional model and the declared number of aircraft in descent for the sector.

These results of both the sector utilization and theoretical number of aircraft possible seem to indicate that the sector EDDYLNO in the Maastricht airspace seem to be approaching the capacity that can be achieved using existing control technology and procedures. Sector B also appears to be at high sector utilization. For the other sectors, there seems to be scope for an increase in the workload/descending traffic, so there appears to be spare capacity. However, the declared capacity relates to air traffic conditions relevant to that particular sector, and it could be that factors such as unique traffic difficulties or demanding conditions could explain why the certain sectors appear to have spare capacity. Alternatively, the assumptions behind the declared capacity figures need to be examined.

For the four traffic demand patterns, each with its own functional relationship between the controller workload and the air traffic variables, it is possible to draw a curve for each demand pattern to indicate the traffic combinations that may be obtained when the control team is at capacity.

13. CONCLUSIONS AND FUTURE ATC/ATM CONSIDERATIONS.

This paper has given a framework by which the capacity of Europe's airspace can be estimated, given that this capacity is limited by the air traffic controller's workload. This method relies upon a well-validated simulation model of the air traffic controller's workload, RAMS, together with the use of appropriate definitions of controller workload and threshold workload value at capacity. Based upon a series of controlled experiments, the output from the RAMS model is used for a functional analysis to relate workload, and hence capacity, to its various possible drivers. Of interest in the functional analysis is the fact that simple classical OLS regression appears to be inadequate. Corrections have to be made for both heteroskedasticity and for spatial autocorrelation in the data. Whilst these effects are not individually large, they are not negligible, and in combination their effect does need to be accounted for. Having obtained a suitable functional model between the workload and the various air traffic movements, a 'capacity curve' can be obtained to indicate the combinations of air traffic movements in a sector when the control team is at capacity. Such a curve can greatly aid planning by indicating any spare capacity in a sector, though the assumptions underlying the curve need to be noted.

With air traffic over Europe forecast to increase considerably during the next decade, various programmes have been proposed by EUROCONTROL, with the political support of ECAC, to increase airspace capacity in steps (EUROCONTROL, 1998). Amongst the methods proposed are those based upon the introduction of new technology to aid the controllers in their tasks. As an example, automatic conflict detection and resolution tools should reduce the amount of time and effort controllers spend on these tasks. More accurate positioning equipment on-board aircraft as well as the introduction of satellite navigation, should enable the controllers to know more accurately and with a higher reliability, the position of the aircraft in airspace and to

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be able to predict their future trajectories. The introduction of a digital data-link between controller and pilot should make communications between them much more efficient. All of these could radically alter the nature of controllers' tasks.

In addition new airspace procedures are proposed, especially 'free flight' and 'direct routing'. Free flight, reliant upon accurate pilot knowledge of aircraft position and navigation capabilities, has the potential to completely revolutionize the controllers' work, in that ATM may move away from the current active control to a role more based on monitoring movements for possible conflicts. However, controllers will always have the opportunity to intervene and revert to active control when they deem the situation demands it. Given that these ideas have been proposed, their impact on the controller's tasks and workload need to be researched. This in turn will have a major impact upon the framework by which to estimate airspace capacity. Research on this is currently ongoing at Imperial.

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