Quantifying Air Traffic Controller Mental Workload

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Abstract— There are two basic, traditional approaches to reduce air traffic congestion: Adapt demand to existing capacity (e.g. regulations namely delays, re-routings or level capping) based on capacity indicators as a number of movements entering a sector in one hour; and/or adapt capacity to expected demand (e.g. through the modification of the route network or sectorization). SESAR is proposing a third one: preventing aircraft from entering locally complex areas in shorter periods of time than one hour in which separation may be difficult to achieve and with high congestion potential. Classical capacity indicators are not efficient anymore as they do not reflect the traffic complexity in short periods of time and as a consequence the declared capacity is determined with a safety buffer to mitigate the negative effect of local traffic complexity. This means that the system is underused to protect the human from complex situations in short periods of time. A key research problem associated with this third approach is the ability to quantify the complexity inside sectors or in one region of the airspace in short periods of time as well as the accuracy of the prediction of these values. This paper presents the research performed by CRIDA in this area.

SESAR defines complexity as the number of simultaneous or near-simultaneous interactions of trajectories in a given volume of airspace. In this context complexity is relevant only in terms of calculation effort, not the ability to solve a given set of problems. Complexity Management corresponds to the handling of all flights on a sector level taking into account the complexity of the traffic flow.

Estimating or measuring complexity in ATM has two facets to consider: Technical Complexity and Cognitive Complexity. Technical complexity deals with aspects such as the number of technologies involved, the number of technical interfaces or the number of system components; in this context "complex" is interpreted as having two or more components and belongs to the realm of system engineering. This paper focuses on cognitive or mental complexity and how it is assessed and predicted.

Keywords- ATC Complexity, Cognitive, Mental Workload.

I. INTRODUCTION

Cognitive complexity describes the relationship between the controller tasks to handle traffic and the corresponding mental workload [1], i.e. the relation between the task complexity and the mental workload. Its assessment is based on a three layer architecture that feeds on the flight plans, aircraft trajectories and radar tracks present in the ATM system. The layers are: Flight Events, Controller Events and Cognitive Processes. The Flight Events Layer models the traffic flows and their behaviour. The Controller Event Layers identifies and describes the actions that a controller is expected to perform. The Cognitive process layer models how the controller performs an action (operating concept) and the related cognitive process. In psychology the cognitive processes are the set of all mental abilities and processes related to knowledge: attention, memory & working memory, judgment & evaluation, reasoning & "computation", problem solving & decision making, comprehension & production of language, etc. in summary: **perception**, **central processing** and **response**.

As it is obvious, cognitive complexity prediction depends heavily on the quality of the demand, which in turn depends on the quality of the forecasted conflict resolution procedures, on the distance between the time of operation and the prediction time, and on a number of other performance areas.

The combined use of assessment and prediction opens the field for a large number of complexity management solutions in the domains of safety, capacity or human factor assessments, dynamic airspace configuration, trajectory management or training.

The concept of air traffic complexity was originally introduced to evaluate the difficulty perceived by the air traffic controllers in safely handling a certain air traffic situation (ATC workload) [2]. ATCo Mental Complexity refers to the person's ability to perceive and respond to variables based on prior experience and prior developed personal constructs[1]. ATCo mental complexity reflects the relation between the demands of a specific environment on the operator and the capability of the operator to meet those demands [3].

To quantify the complexity inside a sector we first need to define it. Hilburn [4] has provided a thorough overview of the existing literature in Air Traffic Control (ATC) complexity and workload. Hilburn defines complexity as a "…measure of the

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[1]   Personal constructs, as understood by modern psychology experts, are the basic mental structures individuals use to interpret and respond to the world. For each set of similar events, an individual develops a particular construct with the ability to adapt to future events that fit within or reasonably close to the construct. How each of these constructs relates, overlaps, and influences the others determines cognitive complexity.

difficulty that a particular traffic situation will present to an air traffic controller…" [4], [5]. SESAR builds on this statement to propose its own definition of complexity: "the number of simultaneous or near-simultaneous interactions of trajectories in a given volume of airspace" [6]. From these definitions three key factors are identified: the geometrical nature of the air traffic; the operational procedures and practices used to handle the traffic; and the characteristics and behaviour of individual controllers (experience, orderliness etc.) [7], [8]. These factors drive the Air Traffic Controller (ATCo) mental workload which is typically acknowledged to be strongly related to complexity [4], [7], [8]. In summary, the complexity inside a sector is a function of the ATCo mental workload. Thus assessing the ATCo mental workload inside a sector will provide an estimation of the associated complexity.

ATCo mental workload relates to the demand imposed by tasks on the human's limited mental resources, whether considered as single or multiple [9]. The Multiple resource theory allocates tasks to three components (demand, resource overlap, and allocation policy), estimating their interference in time-shared pairs to enable the prediction of relative differences in multitasking between different conditions or interfaces [3], thus leading to the identification of the demanded resources. Estimating ATCo mental workload is a combination of the demanded resource model, empirical research and psychological theories of human cognitive processes [10]. CRIDA's Mental Workload Models are based on the Multiple Resource Theory [10] of divided attention between tasks, which has both practical and theoretical implications. The practical implications stem from the predictions the theory makes regarding the human operator´s ability to perform in high-workload, multitask environment.

Current research is focused on the assessment of the "ATCo demanded mental resources". Work performed in this area includes the determination of ATC events [11] and the identification of the parameters related to ATCo workload [12]–[14]. There are research challenges associated mainly with operations in a structureless, dynamic environment and with the impact of the operating environment on the task load.

On the other hand, the assessment of the "available mental resources" and especially on the analysis of how psychological factors impact ATCo mental workload has barely been initiated. Seminal work has been performed by Wickens [3], [10] providing a sound basis on which to base further development.

II. MODELLING ATCo MENTAL WORKLOAD

ATCo Mental Workload is the relation between the psychological resources required by the cognitive processes that a task demands (task load) and the mental resources available. In this context workload occurs when there is an imbalance between task load and the psychological available resources that the controller has in order to perform the task without reducing the safety levels. Consequently, in order to model the mental workload model we must be able to identify both the task load and the available psychological resources, establishing their relationship.

As mentioned before, Cognitive Processes are a function of perception (Visual & Auditory), central processing (Comprehension, Strategic Thinking, Decision Making) and response (Execution: manual & verbal) [3]. As shown in Figure 1, cognitive processes are used to perceive, comprehend, think, make a decision and execute. From an ATC point of view, cognitive process are used to acquire and maintain the "situational awareness", "make a decision" and "respond" to the problem or issue at hand. As seen in the figure, it is possible to relate each cognitive process to an ATC process. This approach allows us to assume that if all ATC Events could be decomposed into a set of Controller Actions that required the use of individual Cognitive Processes, it would be possible to model the relationship between the flow of an aircraft through airspace and the mental workload associated to it. This is the basis of the ATCo Mental Workload model as developed by CRIDA.
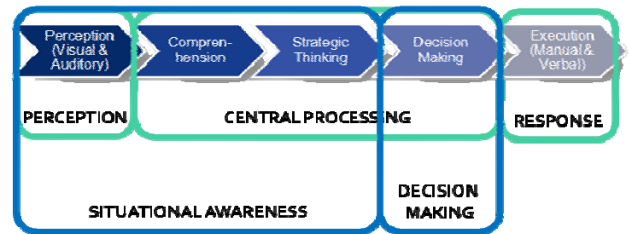

Figure 1.   Situational Awareness, Decision Making and Cognitive processes Relationship

The resulting ATCo Mental Workload framework is described in Figure 2. This framework is based on three concepts: Demanded Mental Resources, Available Mental Resources and Workload Threshold. Each of these concepts is explained below:

- *Demanded Mental Resources* (Task Load): Physical and mental activities demanded to carry out perceptual actions, cognitive actions and motor skills. It is built from empirical research and psychological theories of human cognitive processes [10]. To model this concept it is assumed that Flight Events result in Control Events that are driven by an underlying Operating Concept[2] and that their implementation requires a specific set of cognitive resources.

- *Available Mental Resources*: these are the Physical and mental abilities (perceptual actions, cognitive actions and motor skills) that an ATCo has available to provide the control service, considering only a set

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[2]   Establishes ATCo behaviour within this operational environment (Human Machine Interface, support tools, etc.)

amount of base resources[3]. The Psychological factors experienced during the controller's shift such as fatigue, stress and satisfaction with the work done are shapers of the available resources.

- *Threshold*: Value beyond which Demanded Mental Resources (Task Load) exceeds the Available Mental Resources. There is a direct impact on safety and the ATCo will need to be trained to cope with these situations or supported by technology.
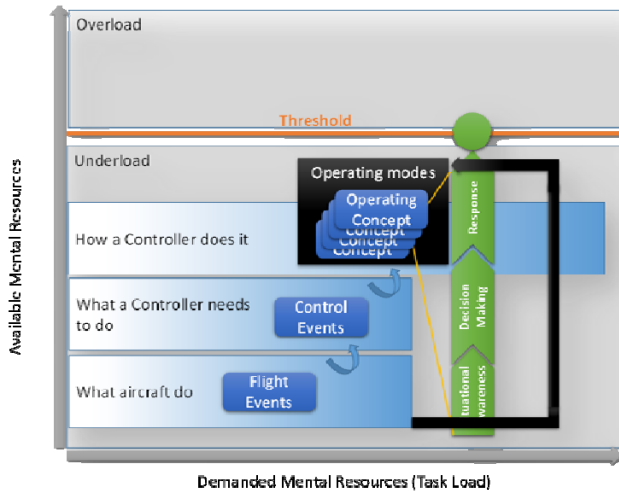

Figure 2. Mental Workload Model Framework

To represent the three concepts a layer framework has been used. The framework has three layers that collect a core set of components associated with the underlying mental workload model framework concepts:

- **Flight Event Layer**: this layer gathers the components related to the identification and use of flight events. It includes aspects such as the traffic demand (or actual traffic data depending on whether archived or real-time information is used) or sector configuration data. The layer models the aircraft behaviour within a specific airspace.

- **Controller Event Layer**: Components in this layer include those related to the actions expected from an ATCo (e.g. solve conflict). This layer identifies the actions that a controller must take to address a specific issue. To either estimate or measure mental workload, we need to identify these control events[4]. Control events might be (a) acquired real-time to measure system performance[5], (b) used in post-processing to

calibrate the measurements or (c) generated through a simulation to enable the prediction of the system performance.

- **Cognitive Process Layer**: Components in this layer include those related to the manner in which an ATCo performs a specific action (operating concept) and those related to the mental processes required to perform said actions. It must be noted that usually there is no single way to address a specific action. ATCo have different Operating Modes (a catalogue associated to specific operating concepts) depending on the traffic situation or on personal preferences.

This framework has been successfully used by CRIDA to develop an experimental system that is able to use a list of flight events (obtained either from archived or simulated data) to identify the associated control events. These are used as input to a Multiple Resources Workload Model (MWM) algorithm that is able to estimate the associated workload.

The MWM algorithm starts from an initial state defined by the set of ATCo actions required to address a control event. From this state, the algorithm identifies the required cognitive channels using the available automation features and the time at which the cognition is required to be used. This information is used to construct an interference matrix. The resolution of this matrix leads to the estimation of the demanded resources required to address a control event.

Available resources are estimated by setting up the workload threshold upon which it is considered that the controllers are not able to fulfil their tasks within an adequate safety level. Currently the MWM assumes a fixed amount of available resources.

Figure 3 presents the logical architecture that CRIDA has used to develop an experimental system that implements the MWM algorithm.
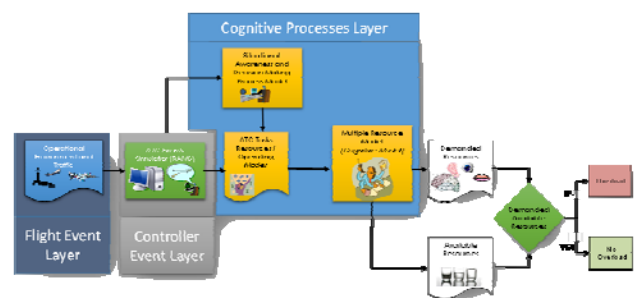

Figure 3. Logical Architecture of the ATCo Mental Workload experimental system

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[3]   Initial physical and mental abilities (perceptual actions, cognitive actions and motor skills) ATCo have available to control an air traffic situation without considering psychological factors

[4]   Control events represent those situations in which the ATCo must perform a control action.

[5]   CRIDA uses ATON (an automated control event parser and detection system) to generate the list of control events in real-time.

III. WAC – Workload Analysis Component

To perform both the validation of the mental workload model and to enable the prototyping of new applications, CRIDA has developed the WAC (Workload Analysis Component) platform prototype. WAC is a workload estimation and measurement tool which calculates the workload required per sector for a set of predefined Sector configurations. WAC integrates the following modules:

- A Pre-Processor module that receives the Traffic Predicted Trajectories and transforms them in a traffic demand scenario that can be used by the Fast Time Simulator (FTS) module.

- A Fast Time Simulator that simulates the traffic demand scenario and generates the set of Control Events that the simulated traffic demand is expected to require.

- A Sector Translator module that maps basic volumes to sectors. It link each Control Event to the sector it applies depending on the implemented sector configuration.

- A WL Calculator that delivers the WL Matrix applicable to all the predefined sector configurations. Predicted WL in each sector is calculated by using the set of Control Events provided by the Sector Translator for each given sector configuration and applying the Operational Concept.

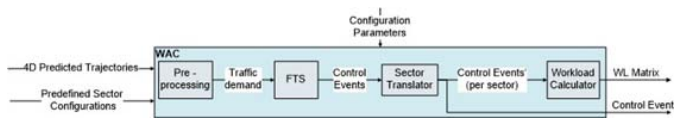Figure 4 presents the pipe flow associated to the aforementioned modules.

Figure 4.   WAC main data flows

In order to configure WAC, several off-line and on line parameters can be set. These parameters will determine amongst others the:

- Workload calculation parameters such as Number of iterations to be performed, Calculation Window Size, Sliding Window Size or Time Horizon (in terms of number of lines of the WL matrix),

- Cognitive operating concept being used,

- Filters applied to the sector translator module,

- Impacts that the fast-time simulation will apply between Flight and Control events.

WAC is implemented within an ATM system that allows the prediction, assessment and resolution of workload imbalances in real time simulation. Figure 2 shows the Mental Workload Framework on which the architecture of the system has been built.

WAC provides workload predictions to the ATM system over a three hour period. This prediction is used to elaborate and propose an optimized sectorization in which the workload is distributed amongst the sectors following a pre-established criteria.

IV. Validation

It is obvious that validating an ATCo mental workload model is a daunting task because of the inherent difficulty of measuring the actual mental workload of a person. To circumvent this problem CRIDA has devised a strategy based on the performance of two types of validation exercises: Validation of the application's ability to calculate sector capacity, and identification of the correlation between ISA[15] measurements and the normalized mental workload model estimations.

A. Use of Mental Workload to Estimate Sector Capacity

The use of mental workload to estimate sector capacity in ENAIRE started in 2005 [16] and continues today. The results obtained from this continued use have enabled the calibration of the mental workload models to the operational environment and operating concepts present in Spain.

The mental workload model was initially calibrated by comparing the results obtained from PUMA [17] with the results obtained from the mental workload model. These results were later refined through the comparison of the capacity values obtained through direct observation and those obtained from the application of the mental workload model [18].

The prototype calculates the workload corresponding to a representative traffic sample, grouping it in one hour periods. At this point Sector Capacity is defined as the number of aircraft controlled in a one hour period that produce a workload lower than a static workload threshold established by the operator.

Instead of validating the mental workload model per se, CRIDA has validated its application. To this end CRIDA has developed a prototype based on the ATCo Mental Workload framework and based on the RAMS fast-time simulator to estimate the capacity of a specific sector. The values obtained from the prototype are compared to the actual measured sector capacity values. The validation hypothesis is that *if the prototype is able to estimate the capacity correctly, then its components will be correct, and thus the ATCo mental workload model would be feasible*.

B. Assessment of the coherency of mental workload results through the comparisson of Predicted and Perceived Workload

To complete the validation, CRIDA (through the SESAR Joint Undertaking research programme) has established the relationship between the mental workload perceived by the

ATCo and the workload estimated by WAC. Through the SESAR programme, CRIDA (in close collaboration with other SESAR partners) performed an experiment to establish this relationship [19]. The experiment recorded the ISA tool inputs from a set of ATCos during a standard operation day. These values were compared with the values calculated using the WAC tool and the actual traffic flown.

The statistical analysis suggests the existence of a linear relationship between the perceived and predicted workloads. It must be noted that the analysis of the results showed that there was a time-shift between the workload predicted by WAC and the actual workload experience by the ATCo (WAC would consistently predict the time of occurrence of overloads and underloads before they actually took place).

Table 1 shows the comparison between the estimated workload (*Cognitive)* and the perceived workload (ISA) without applying the time-shift (in this case the correlation factor was 0.75). Table 2 shows the same data with the time-shift applied (in this case the correlation factor was 0.93).

TABLE I.   50 MINUTE MENTAL WL PREDICTION (NO TIME SHIFT)

Time	Cognitive (Normalized WL Units)	ISA (Normalized WL Units)
15:30:00	39	48,00
15:35:00	39	48,00
15:40:00	39	32,00
15:45:00	39	24,00
15:50:00	39	20,00
15:55:00	20	20,00
16:00:00	22	24,00
16:05:00	22	40,00
16:10:00	22	36,00
16:15:00	22	28,00

TABLE II.   50 MINUTE MENTAL WL PREDICTION (TIME SHIFT)

Time	Cognitive (Normalized WL Units)	ISA (Normalized WL Units)
15:30:00	39	48,00
15:35:00	39	48,00
15:40:00	39	32,00
15:45:00	20	24,00
15:50:00	22	20,00
15:55:00	22	20,00
16:00:00	22	24,00
16:05:00	22	40,00
16:10:00	18	36,00

The analysis indicates that the predictions generated by WAC are strongly dependent on the appropriateness and consistent usage of the operating concept; when deviations from the baseline operating concept occur, WAC shows a strong degradation in performance, leading to large inaccuracies in the estimations.

These results have led to the initiation of research activities to improve the mental workload model through both internal research projects and projects funded through international bodies. These activities include the introduction of psychological factors to estimate the available resources, and the use of dynamic thresholds and operating concept's catalogues to account for the dynamic operating environment.

To ensure that the mental workload model is fully adapted to the future ATM needs, research has also been initiated to establish the full impact of automation onto mental workload and to develop models for both situational awareness and decision making processes (both are considered essential to the future ATM operational concept).

V.   CONCLUSIONS

The close relationship between ATC complexity and mental workload "simplifies" the problem of estimating complexity to a problem of estimating mental workload.

The availability of a method for the estimation of ATC complexity is an enabler for several key SESAR concepts (Automated Controller Support for Trajectory Management in dynamic airspace management environments, Ground based Automated Support for Managing Traffic Complexity Across Several Sectors, Full integration of Dynamic Airspace Configurations into Demand and Capacity Balancing (DCB), Traffic & Demand Forecast in a 4D trajectory Management Context, and Network Performance Assessment for Distributed Network Operation).

CRIDA has developed a Mental Workload framework based on the existence of three components: Demanded resources, Available resources and Thresholds. The framework has been used to develop both a workload estimation algorithm (MWM) and a Workload Analysis Component (WAC) that are used to test and validate the mental workload and its applications.

Validation is based on a strategy that focuses on the assessment of the quality of the applications of the mental workload model to estimate sector capacity and on the establishment of the relationships between perceived and estimated mental workload. The results obtained show that even though workload estimations are accurate a number of improvements must be made on both the framework and the algorithm.

The analysis of the validation results has proven that it is possible to use mental workload estimations to perform airspace management. Specifically, data has shown that it is

possible to calculate hourly sector capacities using mental workload estimations.

Validation results also suggest a linear relationship between the perceived and the predicted mental workload results, thus validating the use of the Mental Workload Model as a tool to estimate ATCo workload.

The analysis of the mental workload model validation data indicates the need to upgrade the mental workload model to take into account the variability of human behaviour in a dynamic environment. This will be achieved through the introduction of dynamic thresholds, the enhancement of the definition of operating modes and the development of situational awareness and decision-making processes' models.

The aspects of the framework and of the algorithm that are currently being improved in different internal and external projects are:

- Introducing psychological factors (fatigue, stress and emotion) as modifiers of the available resources to account for dynamic operating environments.

- Introducing dynamic thresholds as functions of used resources and psychological factors to account for dynamic operating environments and for distinct operating modes.

- Enhancement of the operating mode definition to take into account the different "styles" of control and the traffic situations.

- Impact of system automation features on ATCo mental workload to increase adaptation to future ATM systems.

- Full development and integration of situational awareness and decision making processes to increase compatibility with the future SESAR operational concepts.

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