RHEA

Role of the Human in the Evolution of ATM systems

Final Report

Public

Executive summary

There is a real risk that unsuitable automation concepts and systems could be implemented in the future, if automation and/or change of the controller's tasks were allowed to proceed without a detailed understanding of the optimum allocation of functions and tasks to the human and the automated system. Inappropriate automation systems may be unused or under-used by the controller (which is a waste of resources) or, more seriously, the safe and efficient performance of air traffic management could be impaired.

The RHEA project aimed at providing automation strategies which systematically guide the decision process for automating functions in an air traffic management system to accommodate the growth in air traffic. At the same time safety and efficiency levels should be maintained (or even enhanced) and air traffic controllers should have satisfying jobs. To achieve this, seven technical and one co-ordination work package (WP) were carried out.

The eight technical work packages comprised three groups. WP1, WP2 and WP3 focused on gathering information about ATM functions and automation concepts. More specifically, functions which currently play a role in air traffic management were identified and the ones that might become of interest in the future were added (WP2). Furthermore a classification of automation concepts was developed (WP3). The second group (WP4, WP5 and WP6) dealt with sophisticated evaluation methods to assess the feasibility of automation concepts and their respective consequences for the ATM functions. The third group (WP7 and WP8) discussed functional and tool requirements resulting from the automation concepts.

The RHEA project was carried out by a consortium consisting of NLR, DERA, NATS, Sofréavia and Thomson-CSF Airsys for Directorate General VII (Transport) of the European Commission.

The present document is the deliverable of WP8 and at the same time the end report of the RHEA project. It summarises the results of WP1 to WP7 (in chapter 2). Naturally, more detailed descriptions of the WP results can be found in the respective WP reports. Where appropriate, the summaries are commented upon in the light of insights gained later on in the project. Chapter 3 elaborates on the achievements of the RHEA project. Finally, in chapter 4 necessary follow-on research is discussed.

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1 Introduction

There is a real risk that unsuitable automation concepts and systems could be implemented in the future, if automation and/or change of the controller's tasks were allowed to proceed without a detailed understanding of the optimum allocation of functions and tasks to the human and the automated system. Inappropriate automation systems may be unused or under-used by the controller (which is a waste of resources) or, more seriously, the safe and efficient performance of air traffic management could be impaired.

1.1 RHEA objective

The RHEA project aims at providing automation strategies which systematically guide the decision process for automating functions in an air traffic management system to accommodate the growth in air traffic. At the same time safety and efficiency levels should be maintained (or even enhanced) and air traffic controllers should have satisfying jobs.

1.2 Meeting the RHEA objective

To achieve the overall RHEA objective, seven technical and one co-ordination work package (WP) were carried out.

The eight technical work packages comprise three groups. WP1, WP2 and WP3 focus on gathering information about ATM functions and automation concepts. More specifically, functions which currently play a role in air traffic management are identified and the ones that might become of interest in the future are added (WP2). Furthermore a classification of automation concepts is described (WP3). The second group (WP4, WP5 and WP6) deals with sophisticated evaluation methods to assess the feasibility of automation concepts and their respective consequences for the ATM functions. The third group (WP7 and WP8) discusses functional and tool requirements resulting from the automation concepts.

The present document is the deliverable of WP8 and at the same time the end report of the RHEA project. It summarises the results of WP1 to WP7 (in chapter 2). Naturally, more detailed descriptions of the WP results can be found in the respective WP reports. Where appropriate, the summaries are commented upon in the light of insights gained later on in the project. Chapter 3 elaborates on the merits of the RHEA project. Finally, in chapter 4 possible follow-on research is discussed.

2 Consolidated summaries of work carried out

This chapter summarises the results of RHEA work packages on the basis of the knowledge obtained in subsequent WPs. More details about the results can be found in the respective work package reports (RHEA WP1, 1996; RHEA WP2, 1996; RHEA WP3, 1997; RHEA WP4, 1996; RHEA WP5, 1997; RHEA WP6, 1997; RHEA WP7, 1997).

2.1 Background and Scope (WP1)

2.1.1 Objectives of WP1

The main objective of WP1, as implied by its title, was to clarify the scope of the subsequent RHEA WPs, and to generally “set the scene” for the project as a whole. In accordance with the work-plan for WP1, the report for WP1 had the following specific aims:

- to define the relevant concepts and terms;
- to identify relevant ATM research studies and programmes;
- to identify relevant automation studies and programmes;
- to clarify the scope of subsequent WPs (i.e. WP2 to WP7).

2.1.2 Technical Achievement

A 50-page report, entitled “WP1: Background and Scope”, was produced (see RHEA WP1, 1996). The report provided the following results:

- Concepts and terms of relevance to RHEA were defined and discussed. The list of terms, totalling over forty, was extracted from the text of the original project proposal, and supplemented by other terms from the general human factors, psychology, and computer science literature. One such term is, for example, ‘automation’. Two other important terms were ‘function’ and ‘task’. A new term, ‘mact’ (short for machine-act) was coined so as to distinguish machine/computer activities from human tasks.
- Under work item 2, a total of twenty ATM studies relevant for the RHEA project were identified for further consideration and analysis in later WPs. For each of the studies, a brief summary was tabulated covering the following aspects: partners (and associates), sponsor, time scale, objective(s), current status, and relevance to RHEA in terms of the automation strategies involved. The studies are listed in table 2.1 below:

AEGIS	CINCAT	FANSTIC	PHARE GHMI
ARCHIE	COMPAS	GAAS	PHARE PD1/2/3
ARC 2000	EATMS	MOZART	PHIDIAS
ATLAS	ERATO	MUFTIS	PED
CAER	AAS/AERA	ODID IV	SWIFT

Table 2.1 ATM Studies

- Under work item 3, a literature survey was carried out to identify relevant studies about automation. Several databases (e.g. INSPEC-2) were searched, and a total of over 600 potentially relevant references were found. A number of automation themes, or approaches, were extracted from the papers surveyed. A list of fourteen key references on ATM and automation were also identified for further consideration in the RHEA study (e.g. Wise, Hopkin and Smith, 1991)
- Finally, the scope of each of the RHEA WPs (WP2 to WP7) was described. Clearly, for some of the later WPs the scope was largely determined by the WP preceding it. However, important points of clarification were provided for some of the WPs.

2.2 Synthesis of Functions (WP2)

Functions are relatively broad system processes for which the precise means of implementing (i.e. by allocation to humans, automation, or a combination of both) are not initially specified.

WP2 identified the functions performed in current air traffic control systems and added the functions that are likely to play a role in the future. The functions were expressed in such a form that the consequences of their subsequent automation could be considered easily.

Functions currently performed by air traffic controllers were identified by using three task analyses and one job description as well as reports of relevant other research (e.g. Cox, 1994).

Future functions were gathered through a thorough literature survey and by interviewing several operational experts. This survey was accompanied by a search for issues that would possibly influence functions and therefore might be responsible for changes within functions.

In order to facilitate decisions on automation, a special system for the presentation of functions was realised (transformation of classifications).

2.2.1 Current functions

During the work on WP2 it became obvious that the different literature references point to different descriptions of functions in air traffic control. Those descriptions differ for example in the controller working position they observe or the level of accuracy with which the functions are described. Furthermore, the results of some of the investigations are dependent on the methods which were used.

To overcome these problems, a systematic approach, as described by Jackson in 1989, was adopted. Jackson enumerated and described the following functions:

1. sensing
2. integration
3. prediction
4. communication
5. ATC problem solving/planning
6. executive action
7. rule monitoring
8. co-ordination
9. overall system performance

This classification has its roots in cognitive psychology. Each point covers on the one hand a function which has to be performed in air traffic control and on the other hand a cognitive skill. Since this classification is built so close to controller's cognitive abilities, it can be used as a starting point for presenting functions in a way which facilitates decisions on automation.

2.2.2 Future functions

Future functions were gathered by analysing literature. In addition, 2 operational experts were interviewed. This analysis revealed several new functions which need to be added to the current functions. Some functions will vanish whereas components of other functions will either change or be subjected to a shift of interest.

2.2.3 Overall ATM functions

In the following section, new (i.e., currently non-existent) ATM functions can be distinguished from current functions by underlining. Functions that are currently existent, but which are likely to undergo substantial task structure changes in future ATM, are identified by *italics*.

2.2.3.1 Plan Flight

- A. Plan tactically

regulate local flow

generate tactical clearances for more direct, fuel-efficient routing

recognise uncertainty in trajectory prediction

generate provisional trajectory

test provisional trajectory for feasibility *modify flight plan to conform with new trajectory*

- B. Plan pre-tactically

set tactical constraints on flights
plan for runway configurations

- C. Plan strategically

collect traffic forecasts for ATFM
analyse forecasts for ATFM
analyse fuel consumption data

2.2.3.2 Predict / negotiate trajectory

- A. Predict trajectory

conduct "what if" probing
determine default a/c behaviour
check trajectory conformance
check speed conformance
check vertical conformance
check lateral conformance
check cleared level conformance
check clearance conformance (e.g., premature roll-out from turn)
integrate data
    integrate meteo data
    integrate aeronautical data
    integrate flight plan data
project current situation
calculate 4D path for an a/c
generate clearance

- B. Negotiate trajectory

generate tactical clearances for more direct, fuel-efficient routing
recognise uncertainty in trajectory prediction
generate provisional trajectory

<u>test provisional trajectory for feasibility</u>

<u>negotiate trajectory with capable a/c</u>

calculate trajectory for unequipped a/c

2.2.3.3 Detect / resolve conflicts

- A. Detect conflicts

detect short-term conflicts

detect medium-term conflicts

detect special use airspace penetrations

detect descent below lowest usable flight level

detect aircraft conflict

detect planning (i.e., schedule) discrepancies

categorise problems

determine priorities

dynamically recalculate trajectories

detect strategic conflicts

detect hypothetical conflicts

consider possible a/c manoeuvres

develop contingency plans

identify future tasks induced by traffic

assess criticality

conduct "what if" probing

- B. Resolve conflicts

consider available resolution frames

generate alternative conflict free plan

provide corrective navigation messages

verify new or modified plan

2.2.3.4 Manage air traffic sequences

- A. Manage arrivals

produce planning criteria

provide scheduled arrival times
calculate time of arrival
calculate delay
monitor slot allocations
sequencing / metering
determine optimal sequences
generate control plans

- B. Manage departures

generate criteria for determining sequence, schedule, and profile
provide estimated times, take-offs and waypoint crossings
determine scheduled times, take-offs and waypoint crossings
negotiate plan with a/c

- C. Control, general

dynamically re-sequence
provide assistance to a/c in abnormal situations
negotiate plan with a/c
automatically calculate clearance change

- D. Manage airspace (ASM)

perform strategic ASM
    collect / evaluate all requests that require airspace segregation
    plan allocation structure to accomplish segregation
        define route structure
        sectorise airspace
        configure airports
        disseminate results to all parties
perform real-time ASM
    manage restricted airspace
    dynamically restructure airspace to accommodate traffic fluctuations

2.2.3.5 Monitoring

- A. Flight Path Monitoring

monitor operational data via situational displays

observe system-generated warnings

monitor high-level, processed information

determine deviation between system plan and surveillance data

- B. Systems Monitoring

oversee automatic execution of routine functions

integrate data

filter data

exercise supervisory control

  correlate system input / output

  schedule task involvement

  schedule system activity

  determine need for intervention

2.2.3.6 Manage environmental data

- A. Manage meteo data

downlink ADS meteo data

integrate meteo data across sources

integrate meteo data into trajectory predictions

  Process meteo data

supply a/c with meteo information

delegate meteo data collection/transmission to a/c

- B. Manage aeronautical data

model aircraft performance

integrate aeronautical data into trajectory predictions

- C. Manage flight data

maintain flight plan database

process real time flight data

  integrate ADS position data

integrate ADS route data

validate flight data via ADS

manage SSR code data

integrate flight data into trajectory predictions

2.2.3.7 Manage system/position resources

- A. Communicate

communicate Ground to Air

- communicate by datalink
    - *convey requests*
    - *convey reports*
    - *convey HMI generated information*
    - *negotiate*
- communicate by RT
    - convey requests
    - convey reports
    - *convey HMI generated information*
    - *negotiate*
- interact with advanced a/c-based systems
    - *interact with conflict avoidance systems*
    - *interact with terrain avoidance systems*
    - *interact with trajectory avoidance systems*
    - *interact with meteo forecast/prediction systems*

communicate Ground to Ground

- convey outgoing flight data
- convey requests
- co-ordinate within sector
- co-ordinate between adjacent ATC sectors

- B. Regulate workload

predict workload fluctuations

re-allocate functions between controller and computer

re-allocate functions between controller and a/c *re-allocate tasks between controllers*

schedule tasks

look for new tasks

look for new data

- C Calibrate trust in automated systems

recognise information computer has used / not used

correlate system input / output

- D. Evaluate automated system advisories

- E. Manage database info

co-ordinate flight plan database with AOC

integrate database info into planning

  integrate operational data (e.g., preferred diversion routes)

  integrate navigation data (e.g., preferred diversion routes) integrate a/c performance data

All these functions were used by RHEA to build a framework of decision aids for developers and evaluators concerning automation of future ATM systems.

2.2.4 Impression: future ATM retains set of functions

Future ATM will largely retain its current set of functions. In many (if not most) cases, however, the tasks involved in accomplishing these functions will be changed dramatically. Entirely new functions are likely to arise out of three broad areas of advancement: improved air-ground communications, enhanced a/c-based systems and the possibility to interact with them from the ground, and computerised strategic ATM aids.

2.3 Automation Strategies (WP3)

2.3.1 Objectives

RHEA WP3 (Automation Principles and Concepts) aimed at building a common **classification scheme of automation concepts**. The main work items concerned the building of a classification scheme, suitable for ATM, to be used for a coherent and consistent description of automation concepts, the integration and analysis of the selected ATM projects in the conceptual scheme and the analysis and evaluation of the proposed automation concepts. This work aimed at helping the selection of the automation concepts to be evaluated, and to specify the corresponding scenarios in WP5.

2.3.2 Method

2.3.2.1 Step 1: Bibliographic review

The first step in WP3 consisted of a bibliographic review on Human Factors Automation issues, based on the bibliography identified in RHEA WP1. Firstly, the identification of existing automation concept schemes (i.e., attempts to classify, categorise different automation concepts), were reviewed according to their relevance for ATM. Secondly, two major automation principles were detailed (human centred automation and dynamic allocation). Finally, the human factors automation-related issues were identified and the main themes presented and referenced. A complementary review addressed the feasibility aspects: the available techniques were reviewed and assessed against their maturity and potential use for ATM. A synthesis presents the techniques used in each ATM project.

2.3.2.2 Step 2: List automation concepts

In the second step, a list of automation concepts was elaborated, taking into account the results of the bibliographic review. The different Automation Concepts identified and their main characteristic are :

AUTONOMOUS COMPUTER / FULL AUTOMATION:	*Machine acts without informing or interacting with the operator.*
CONTROLLER AS SUPERVISOR :	*The controller monitors the system and intervenes in system dynamics only in exceptional circumstances.*
MACHINE PROPOSALS STRATEGY :	*The system offers options so as to meet high-level system goals (i.e. solutions), which human is free to evaluate. Sometimes the term advisor is used to describe the role of a machine providing recommendations (e.g. advising), or suggesting a selection.*

MACHINE AIDED EVALUATION :	*Solutions are suggested by controller and assessed using computer aids, usually graphical aids (e.g. "What-if" tools).*
Dynamic ALLOCATION	*The same tasks may be done, at different times, either by human or by machine.*
DYNAMIC ALLOCATION WITH HUMAN DELEGATION:	*Controller decides when and what task will be done by human or machine.*
DYNAMIC ALLOCATION WITH MACHINE DELEGATION:	*Machine decides when and what task will be done by one or another. The decision could be based on measurements of human workload or stress, traffic loading, or time.*
DYNAMIC AIRCRAFT DELEGATION:	*Tactical conflict resolution, for example, is delegated from the ground-side to the airborne side.*
COGNITIVE TOOLS :	*The system allows the controller to carry out the high level system functions, such as conflict detection and resolution, but the tasks are supported by the system through the design of cognitive tools.*
HMI ENHANCEMENT	*Improvement of the Controller Working Position mainly consists of enhancing HMI without adding intelligent functions.*

These concepts were first assessed for their potential advantages and disadvantages. Then, they were used as tools helping to characterise a selected set of ATM projects. These projects all focus on advanced tools for Air Traffic Controllers.

With the method involved, each ATM project was rated on each of the automation concepts. The composite pattern of ratings for each ATM project was graphically depicted, allowing the reader to characterise the major trends of each. In addition, the validation status of the ATM projects was provided, identifying, for each project the tools provided, the automated functions, the development principles, and (except for the paper studies) detailed information on validation (used or planned).

2.3.3 Results

It appears from the literature studied in WP3 that, with the exception of complete automation (which large-scale implementation, for a number of ethical, legal, and safety reasons has been ruled out) no automation strategy can be ruled out straightaway. On the other side, the more conservative strategies (e.g., less-dramatic approaches such as HMI enhancement) did not prove to greatly enhance the service criteria (increase in sector capacity, reduction of delays, etc.).

All the other Automation Strategies fall between these two extremes and differ qualitatively. A clear need was felt to explore different concepts and guidance for decision making in validation, and future tools development, as planned in subsequent WPs.

Pragmatically, experience from avionics must be taken into account in defining automation strategies for Air Traffic Control. In fact, airborne systems, with the introduction of intelligence in avionics (the so-called "glass cockpits") are more automated than ground systems. From a human factors point of view it is now recognised that advanced automation in such aircraft can raise many problems. The experience gained from the airborne side should be taken into account in order to prevent the same problems occurring in ground systems. Notably, the analysis concerning system opacity, or complacency are good examples of what must be avoided when automating. When designing tools based on dynamic allocation, for instance, it is now recognised that the change between different automation modes must not be hidden to the operator, and this kind of knowledge gained from airborne experience is of course useful for controllers as well.

In addition, unlike the cockpit situation, automation in the ATC position must include the consideration of controller's role as a member of a team of controllers. There may be teamworking aspects such as safety and social considerations which could be lost when the controller task is automated.

Research in the ATM domain has focused on the machine proposals and machine evaluation strategies. It has discovered areas such as approach control where these strategies are successful, and developed detailed methods for implementing the strategies. This focus may have been unintentional, being the obvious way to use the available technology. WP6 will explore a wider range of strategies, in various scenarios.

As well as providing input to the later RHEA work packages, WP3 included conclusions which may be of use to a wider audience: HMI enhancement and machine aided evaluation have succeeded operationally; co-operative tools and dynamic allocation are currently evaluated experimentally; complete automation failed before complete simulation. WP3 also recommends that the changes in procedures which necessarily accompany automation must be considered, and that a human centred approach is used in introducing automation.

2.4 Criteria and Applicability of Evaluation Methods (WP4)

2.4.1 Objectives of WP4

The main objective of WP4 was to review and compile a list of evaluation techniques, from which a selection would then be applied to the "ATM situations" developed in WP5. As stated in WP4 section 1.3 "Objectives of WP4" the specific aims of the WP4 report were:

- To define criteria for selecting evaluation methods and techniques.
- To perform a detailed review of existing evaluation methods and techniques to determine their areas of applicability, adaptation or validation which may be required.
- To determine ease of use of each technique.
- To specify the input requirements for each method.

2.4.2 Workplan for WP4

WP4 involved all project partners and was managed by DERA. First a literature search was completed, a database of evaluation methods and techniques was compiled with their input requirements.

Second, techniques were categorised using criteria concerning appropriateness to evaluating ATM automation concepts. The aim of categorisation was to compile a short list of recommended techniques with areas of applicability and constraints, for use in subsequent Work Packages.

Third, based on the categorisation, a short list of recommended evaluation techniques was produced.

2.4.3 Technical Achievement

2.4.3.1 List of Evaluation Methods and Techniques

Potential evaluation techniques including input requirements were identified using a specific technique classification system (Goillau, Baseley & Williams, 1991). This ranges from unstructured / informal e.g. real-time simulations, verbal protocols; to structured / formal e.g. systems engineering, human workload assessment.

"List of Evaluation Techniques Part I" contained a comprehensive tabulation of 75 individual techniques and "List of Evaluation Techniques Part II" presented an orthogonal view of 25 generic evaluation approaches with specific examples. The classification system for Parts I and II tables is explained in sections 2.2.1 to 2.2.3 of the WP4 report.

In reading the list of techniques it was important to remember what the goals of the classification are and whether the distribution of roles between people and machines was appropriate for the range of tasks at hand, which was evaluated using performance criteria. Performance criteria e.g. safety or reliability of the joint system, are mapped onto possible performance measures e.g. reported misses, physiological measures (heart rate) or psychological measures (stress). Other performance criteria classifications were noted: formal vs. informal; empirical vs. analytical.

2.4.3.2 The Systems Engineering Approach

WP4 looked at the Systems Engineering approach which organises and performs technical activities relative to the transformation of customer requirements and industrial constraints into a system specification and architecture. Activities are organised around the system life cycle following a method supported by engineering tools.

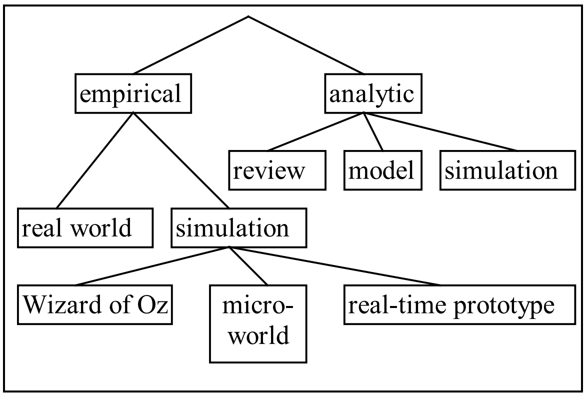
The satisfaction of client requirements, industrial constraints, risk control and complexity were stated to be key themes of systems engineering. The aim of the approach was stated to be management of technical activities allowing transformation of the operational need into system specification and design.

For example, Thomsons' Dialog Architecture and Design Method (DIADEM) aims to methodologically support HMI specification and design in all system phases. The support tool used in the Systems Engineering approach is RDD100 which:

- Formalises functional requirements.
- Constitutes scenarios according to ATM situations composed of a number of tasks.
- Defines tasks as automatic, manual or shared between man & machine and attributes them to criteria values (RDD100 can use outputs of DIADEM task analyses by using an appropriate tool).
- Integrates results of the selected evaluation methods applied to the defined tasks by assigning evaluated criteria to each task e.g. workload criteria and estimated value to evaluate system global behaviour with different automation options i.e. different scenarios.

2.4.4 Selection of evaluation techniques

To reduce the list of evaluation techniques, selection criteria were applied for evaluating appropriateness to ATM. Classification of techniques were as follows:



A number of criteria were used to evaluate appropriateness of evaluation techniques to ATM:

- Empirical vs. Analytic nature of the technique
- Primary Objective for which the technique can be used
- Previous Application of the technique (good or bad experience)
- State of Validation of the technique
- Ability to cope with non-implemented systems (typically necessary for concept validation)
- Practical (is the technique easy to apply)
- Input and Output (complexity of the input necessary and the output of the technique)

An example of an evaluation table taken from WP4 is shown overleaf (ref. WP4, section 4.2.2):

Technique		Type of technique			objective	prev. application	validation		N-I	practical				In Out		comments
NAME (when specific technique) Group of techniques (when generic)		type I	type II	Stage			P	D		U	L	T	C			
Fitt's List	b.11	analytic	ergonomics expertise	I	allocation of function	ATC automation	H	?	Y	H	H	H	H	H	M	simple list : very easy, but low results
KOMPASS	a1.21	analytic	ergonomics expertise	I	allocation of function	?	L	?	Y	H	H	H	H	H	L	simple list : very easy, but low results
Task Action Language	a1.07	analytic	modelling	I	complexity	GUI	L	?	Y	M	L	M	?	L	L	
Subjective Complexity Ratings	b.10	empirical	questionnaires	II	complexity	"commonly used"	?	?	N	L	M	M	?	L	M	
3-state model	a1.10	analytic	modelling	II, III	device use	GUI	L	?	N	M	M	M	?	H	L	low level of tasks
Quant. Display. Eval.	a1.09	analytic	ergonomics expertise	II	device use	alphanum. displays	?	?	N	L	M	L	?	H	L	not relevant
Murphy Diagrams	b.19	empirical	interviews	II, III	ease of decision making	electric power control	?	?	N	H	L	M	?	L	M	
Evaluation of decision making	b.18	empirical	observation	II, III	ease of decision making	nuclear power control	?	?	Y	L	L	L	?	L	M	
Fast-Time Simulation	SIM2 (a1.24)	analytic	simulation	I	generic	generic	M	M	Y	L	L	L	L	L	H	
Psychometric Tests	a4.08	empirical	as measured	II, III	generic	generic	M	?	N	M	L	L	?	H	H	
Real-time Simulation	SIM3 (a3.09 a4.07 b.23)	empirical	simulation	II	generic	generic	H	H	Y	L	L	L	L	L	H	Quality of output depends heavily on quality of evaluation techniques used along the simulation
Wizard-of-Oz Simulation	SIM4 (a4.07 a4.13)	empirical	simulation	I	generic	generic	?	?	?	?	?	?	?	?	?	
Link Analysis	b.21	analytic	ergonomics expertise	I	group(co-operation)	?	H	?	Y	M	M	H	?	M	M	

2.4.5 Recommended Techniques from WP4

The selection process was done in two steps. Firstly, a short list of 30 techniques was made. Techniques were selected out of each category. These techniques represent the entire range of possible techniques and scored favourably on the criteria which were established for appropriateness for validation of automation concepts. Some examples of criteria are:

- safety
- workload
- usability
- performance
- situation awareness
- allocation of function
- knowledge use
- complexity

Secondly, since it was not possible to cover the entire short list of 30 techniques within the scope of the RHEA project, a sub-selection of six evaluation techniques was chosen. The rationale behind this choice was again that the techniques applied in the RHEA project would cover the entire range, so that the automation concepts would be evaluated from a variety of different perspectives. Furthermore, this choice allowed for some simple comparison of different techniques. The resulting list of 6 techniques is shown in table 2.4.1. The table also shows that each automation concept was evaluated with at least one technique.

Table 2.4.1 Automation concepts covered by the selected evaluation techniques

	Automation Concept						
Evaluation Technique	**CS**	**MP**	**ME**	**DH**	**DC**	**DA**	**CT**
Fast-time modelling (RDD-100)		✓(3)					✓(3)
Fast-time modelling (SIM'COOP)						✓(3)	
Real-time simulation					✓(1)		
Fast-time modelling (TOPAZ)			✓(1)				
Cognitive Walkthrough (MACAW)			✓(1)	✓(1)			✓(1)
Human Reliability Assessment	✓(2)	✓(4)	✓(2)	✓(2)	✓(2)	✓(2)	✓(2)

Queuing network modelling (RDD-100)

The main intention of this activity was to build a link between results from theoretical human factors activities and systems engineering for industry, in gathering results from RHEA activities and other studies in a unified framework, appropriate for systems engineering.

Models have been built from available information, using a systems engineering tool (RDD-100), for reference situations and the same situations with the addition of automation concepts, and various indicators computed for various levels of traffic. This evaluation was conducted by Thomson-CSF Airsys.

Cognitive modelling

The objective of this activity was to evaluate the situational awareness in the "dynamic aircraft delegation" concept, and more precisely the awareness related to the co-operative work. The measure used was the degree of "mutual manifestness" (a fact is manifest to an individual if he is capable of inferring or perceiving it).

A model has been built, based on heuristic rules determining the information that can be shared for a specific environment and a specific action; these rules takes into account different kinds of actions ("non verbal acts", "speech acts", "communicative acts"). A specialised tool (SIM'COOP) has been used. This evaluation activity was conducted by Sofréavia.

Real-time simulation experiments

The objective of using this technique was to measure controller's mental workload through physical indicators:

- pupil diameter,
- dwell time (the duration of visual fixation),
- blink rate,
- blink duration.

It has been used during RHEA to evaluate the influence of the use of a descent advisory system on mental workload. This evaluation was conducted by NLR, with the assistance of air traffic controllers.

Fast-time modelling with Petri nets

Fast time modelling has been used in WP6 to evaluate the impact of the use of STCA tools on controller's workload: the situations were modelled, then each model was evaluated, and resulting workload indicators were obtained. This evaluation activity was also conducted by NLR.

Cognitive walkthroughs

The technique has been adapted for use in RHEA, and has been given the name of MACAW (Malvern Cognitive Applied Walkthrough). Its objective is a structured and complete evaluation of automation concepts. It uses large tables to be filled during the evaluation, so that no aspect is forgotten. RHEA evaluations have used screen pictures representing tools corresponding to the various concepts. This evaluation was conducted by DERA, with the assistance of experts in the domain and air traffic controllers.

Human Reliability Assessment technique

This technique focuses on the identification of human errors likely to occur for a specific automation concept. It was based on an organised and systematic study of the possible occurrence of several categories of errors, and of their seriousness and likeliness of occurrence in each situation. All automation concepts have been evaluated with this technique. This evaluation was conducted by NATS.

2.5 Selection and Definition of ATM Situations (WP5)

2.5.1 Objectives

The major objective of WP5 was to develop a number of representative ATM scenarios. Once combined with the automation concepts identified in WP3, these would then form the basis of a set of 'ATM situations' (or 'worked examples'). These situations are to be used as a basis for the evaluation of the automation concepts in various ATC duties and tasks in WP6.

2.5.2 Development of selection criteria

Two overriding considerations were highlighted in choosing the selection criteria to be used in WP5.

Firstly, it was decided that the pan-European nature of the RHEA Project must be incorporated. Thus, it was essential that the ATM situations produced at the end of WP5 must be representative of ATM in Europe. The other overriding factor was that they must be suitable for the needs of WP6 in which the selected evaluation techniques are applied to the ATM situations.

2.5.3 The Need for a General ATC Environment

To evaluate systematically the effects of the various automation concepts upon the design of a future ATM system (and consequently upon controller performance), it is evident that broadly the same future system should be used when producing each of the ATM scenarios.

For the purposes of RHEA, a particular set of features of the future ATM system (workstations, airspace, procedures, etc.) was assumed. Consultation with air traffic control personnel responsible for future planning tended to confirm those assumptions.

2.5.4 Generation of ATM scenarios

After careful consideration, the format selected for presenting the ATM scenarios and situations was a tabular description. It was decided that in order to enable a thorough investigation of the effects of the automation concepts, the format for the scenarios and situations should include consideration of the following (cognitive) activities: communication, monitoring, planning, decision making and negotiation.

The following ATM scenarios were selected:

- En route in sector
- Crossing point between routes UG1 and UA25 (UK Strumble sector)
- European airspace - the route from X to Y within UK and Maastricht Airspace
- Control of inbound/outbound traffic
- Approach control at airport x - arrivals only runway (including control of stacks)
- Approach control at airport x - mixed-mode operations
- Arrivals/departures control - mixed-mode operations

2.5.5 The Automation Concepts to be Applied

Nine automation concepts have been identified and described in RHEA WP3.

1. Autonomous computer or full automation.
2. Controller as supervisor.
3. Machine proposal strategy.
4. Machine-aided evaluation.
5. Dynamic allocation (with human delegation).
6. Dynamic allocation (with machine delegation).
7. Dynamic aircraft delegation.

8. Cognitive tools.
9. HMI enhancement.

The first of these - Autonomous computer or full automation - would by definition not involve any human controller participation. Thus, it was concluded that from the viewpoint of RHEA it could not be usefully considered in WP5. The last automation concept - HMI enhancement - can be considered as intrinsic to all other automation concepts. Thus, it was decided that it would serve no useful purpose to consider it separately in WP5. As a result, 7 automation concepts were left for consideration in RHEA WP6.

2.5.6 Generation of ATM situations

In the course of WP5, it was necessary to decide which ATM situations should be evaluated by the RHEA partners in WP6. This information could enable the WP5 leader to extensively describe only those situations that were required later in RHEA.

The result of the deliberations of the RHEA partners is presented in table 2.5.1 below.

Table 2.5.1 Synthesis of ATM scenarios and automation concepts showing 17 resulting situations and the allocation of situations between partners

	AUTOMATION CONCEPTS								
ATM SCENARIO	Autonomous computer/full automation	Controller as supervisor	Machine proposal strategy	Machine aided evaluation	Dynamic allocation with human delegation	Dynamic allocation with machine delegation	Dynamic aircraft delegation	Cognitive tools	HMI enhancement
1. En route in sector X		1. NATS	2. NATS	3. NATS Thomson (with CT) NLR	4. NATS	5. NATS	6. Sofréavia NATS	7. Thomson (as part of ME) NATS	
2. Crossing point between routes UG1 and UA25 (UK Strumble sector)									
3. European airspace - the route from X to Y within UK and Maastricht Airspace			8. Thomson NATS	9. DERA NATS	10. DERA NATS	11. NATS	12. Sofréavia NATS	13. DERA NATS	
4. Control of inbound/outbound traffic						14. NLR			
5. Approach control at airport x - arrivals only runway (including control of stacks)			15. NATS						
6. Approach control at airport x - mixed-mode operations							16. Sofréavia		
7. Arrivals/departures control - mixed-mode operations			17. NATS						

The table shows seventeen ATM test situations for use in WP6 using a process whereby the original ATM scenarios were re-described considering the automation concepts highlighted previously in RHEA. In addition, input from air traffic controllers and ATC personnel responsible for future planning was included; their guidance was invaluable.

It was made sure that each of the automation concepts was evaluated by at least one, but preferably more techniques. This goal was met, except in the case of the "controller as supervisor concept", where only one technique was applied. The way the table was filled out, allowed for comparisons of automation concepts (evaluated with the same technique) and for comparisons of different techniques (applied on the same automation concept). Since scenario 2 has many similarities to scenario 1, it was decided to leave it out.

2.6 Application of Evaluation Techniques (WP6)

2.6.1 Objectives of WP6

The objective of WP6 was to perform evaluation activities on various automation concepts for air traffic control, from a human factors viewpoint. This was done on the basis of the previous work packages: WP3 identified the automation concepts, WP4 described evaluation techniques to be used and WP5 described situations to be evaluated. The subsequent sections will report on the evaluation results for the 7 automation concepts, which were evaluated, and on the merits of the evaluation techniques which were applied.

2.6.2 Evaluation results for each automation concept

2.6.2.1 Controller as supervisor

The 'en-route in sector X' situation was evaluated using this automation concept with one evaluation technique (HRA).

This automation concept represents an extreme of automation, in that the controller's role fundamentally changes and is reduced to that of a system monitor. However, it is a role that still demands that controllers are adequately skilled and proficient to be able to take control if the automation fails or is unable to handle a particular situation safely. Thus their level of skills must be maintained and they must be able to monitor the sector and traffic in enough detail to take control fairly seamlessly.

The advantages of CS are that certain aspects of the ATCO's workload should be lowered substantially, and potentially the ATCO can maintain a high-level picture (situation awareness). Also, many of the individual human errors (associated with recording information, communications and sub-optimised planning) are eliminated by the CS system as those activities are carried out automatically.

The disadvantages are numerous, however, and appeared to be:

- The controller made a poor monitor of the system (a general human trait). Thus, one of the main purposes of this type of automation was defeated (checking the automated system).
- As the controller was taken out of the control loop, it proved problematic to ensure that the controller maintained an adequate "picture" of the sector and traffic. This is necessary both to evaluate the machine strategy and to be able to step in should the automation develop a fault.
- Detection of machine errors was difficult, partly because of the reasons given above but also because the controller may not explore control strategies in much detail.
- When over-ride was required, the ATCO's skill-base had become at least non-fluent, and at most obsolete. Thus over-ride was not smooth and may be unsafe.
- The flexibility and intuition of the controller that currently plays an important part in problem solving and strategy formation was lost.
- There are wider implications related to the impact on the controller's job: de-skilling, motivation, moral, etc. The ATCO did not seem to enjoy this role, and this may create conflict in the human-machine system.
- The ATCO sometimes failed to update the machine system correctly.
- Shift hand-over proved to be problematical since neither the outgoing nor the incoming ATCO was able to build more than a superficial picture.

Conclusions

The issues that arose for CS are fairly central to the controller's purpose in the system. Although there may be improved reliability through fewer communication and input errors (there should be no human input in this situation), there are considerable risks for the safety of the system, as the controller becomes increasingly isolated from the system.

Controllers are unlikely to reach a level of "hands-on" experience comparable with today's controllers even with a great deal of training. With the reduced "picture" and the loss of experience, a controller would be vulnerable during high stress, high workload and emergency situations where the machine has failed.

Therefore this automation concept is not recommended.

2.6.2.2 Machine-proposal strategy

The MP strategy attempts to offer the advantages of CS in terms of the computer power and machine sophistication, without taking the controller out of the control loop completely. The results of the Queuing Network Simulation for MP showed a trend for improvements in the controller's workload and safety at the expense of the level of skill. The results were consistent for en-route, approach and aerodrome control phases of a flight.

On the positive side,

- The machine proposals were more accurate or timelier.
- When the requests for information from the ATCO were preformatted, they seemed to overcome the problem of failing to consider side effects of actions.
- MP could also help overcome any narrowing of situation awareness or tunnel vision, by prompting the ATCO with proposals on aspects of the picture the ATCO was ignoring.
- In theory, MP will leave more time for the ATCO, as is demonstrated in the results of the Queuing Network Simulation. However, in reality, the ATCO may have to consider a back-up plan anyway, so this time will only be real if the MP is perceived to be highly reliable and highly useful. This was assumed in the Queuing Network Simulation.

HRA was performed for en-route, approach control and arrivals/departures control. There are a number of human reliability issues that indicated that caution might be required. The issues include:

- Over-confidence or under-confidence in the output of the MP system.
- Loss of core skills, which subsequently became a problem when trying to compensate for system malfunctions or faulty predictions or proposals.
- The controllers' “picture” did not develop fully as they are removed from the control loop. It is not clear how MP will affect the picture. On the one hand, the ATCO may lose the longer-term planning picture, and on the other the MP system might actually enhance the long-term vision of the picture by lengthening the effective planning and prediction interval of the ATCO. This will depend on the way in which MP is implemented.
- MP offers optimisation of air traffic, but only within restricted rules. Flexibility that the ATCO brings to the job was lost.
- The ATCO will need to develop management skills to ensure that the output of the MP system does not interfere with the safe and expeditious control of traffic.
- The MP can prompt the controller for certain actions thereby reducing the likelihood of actions being taken too early or too late. However, this may lead to long-term skills being lost should the MP produce a script (or “procedures”) for the controller.
- The MP system relies on ATCO input of information, allowing the chance for data entry errors and subsequently erroneous proposals

All the potential sources for human error listed above will apply to the situation of an en-route sector. However, the approach control task is likely to require more precise timeliness of proposals than en-route, to be useful. In addition, the ATCO will need time to read and judge the proposals even though almost continuously busy.

The task of approach control, however, is arguably more skill- and rule-based, and is primarily one of optimising ‘feed’ towards the airport. It may be therefore that MP amounts to a *sequencing* tool that helps the sequencing of the aircraft and stack control. Such tools would be useful to the ATCO, and might require less evaluation, as they would give fairly straightforward advice on sequencing of operations.

Given the time-pressured nature of the arrivals/departures control task, it is difficult to see how MP would be used or useful. Much of arrival control appears to be tactical in nature, and requires frequent confirmation activities, such as that planes have in fact turned off the runway at the nearest exit. MP may disrupt the fluency of such a dynamic task, or may distract the ATCO from critical R/T communications and visual checks. Furthermore, any computerised system would probably contain algorithms that would be conservatively safe. Use of such a system might result in more 'go-arounds' than with human controllers. Controllers perform well on the tactical task of landing planes in very tight time-compressed scenarios. If the machine made a mistake, there would probably not be sufficient time to detect and correct it.

The HRA analysis points to a rejection of the MP automation concept. It may be noteworthy that the cognitive walkthrough assessment (MACAW) suggested that MP could be an improvement of the ME concept. However, the MP concept *per se* was not assessed using MACAW.

2.6.2.3 Machine-aided evaluation

A number of common points were found by each of the three partners involved in the investigation of the ME concept.

Both NATS and DERA expressed a concern about the controller becoming too reliant upon the tool and "losing the picture". DERA suggested that regular retraining in ATC procedures could help to retain basic skills and prevent complacency with tool use.

Both NATS and DERA were concerned about the trustworthiness of the tool and the confidence in using it. Both agreed that errors are more likely to occur as a result.

NATS and DERA mentioned that ME could be advantageous if used to sequence air traffic, enabling optimisation of routing.

Opinions about workload were varied. NATS found that using ME to make plans could increase the workload. This meant that ME use would not be beneficial in higher traffic levels. DERA found that ME would reduce the workload. NLR agreed that both of these extremes occurred: ME reduced the workload in low to medium traffic levels but increased the workload in medium to high traffic levels. The increased number of controller resources being used to make decisions and plans explained this.

Regarding performance, partners had different opinions. NATS did not really evaluate ATCO performance, but thought it was uncertain whether ME offered improved reliability. The majority of DERA subjects on the other hand thought that performance would increase and capacity would also increase as ME could reduce workload.

The three assessment techniques of NATS, DERA and NLR were different from each other, which meant that comparisons of findings were difficult. Some similar criteria were observed by NATS and DERA e.g. the issue of losing the picture. NLR looked at different criteria e.g. safety. Although safety was a major issue for other partners (e.g. HRA is a safety assessment), it was looked at in the overall goals of actions rather than as an individual criterion. This phenomenon shows that the use of different techniques for the evaluation of one automation concept can be beneficial. Each technique may highlight different aspects of the concept. The goal of the automation concept should guide the choice of a technique. Some techniques will reveal more about safety, while others are better suited to evaluate workload.

2.6.2.4 Dynamic allocation with machine delegation

The purpose of Dynamic Allocation with machine delegation (DC) is that the machine determines at what moment which tasks should be undertaken by the human controller in order to achieve optimum system performance. The machine bases this decision on the controller's workload. In this way, the controller will undertake the majority of the ATM tasks, with the machine "lending a hand".

The results from the different evaluation activities were consistent over the two applied scenarios (En-route in sector X and Control of inbound/outbound traffic), although the precise use of the automation concept differed slightly between the two activities.

The main drawbacks derived from both evaluations are:

- The principle advantage of DC is thought to be that it optimises the controller's workload, and moreover the variations in workload. These advantages were not confirmed in the conducted experiments.
- A cognitive mismatch was found between the automation concept and controller's behaviour (the controller did not behave as the machine "expected").
- This mismatch made it hard for the ATCO to keep his/her mental model of situation under control and to integrate the concept into his/her natural strategy.
- Reviewing the advise generated by the automation caused extra mental workload.
- System performance also decreased under conditions of low mental workload. Within DC, the automation does not take over any tasks under conditions of low mental workload.
- The controller did not know who was controlling the system at specific moments.
- There were problems with acceptance of the system by the controller because he/she was out of control.
- Measuring physiological workload during task performance might influence task performance.

A general conclusion from these evaluations was that this automation concept has some problems that might be too great to overcome. These problems were mostly related to the concept of mental workload, acceptance of the concept by the controller because he/she is not in control, and the cognitive mismatch between the concept and human behaviour.

2.6.2.5 Dynamic allocation with human delegation

There is a number of common discussion areas from NATS and DERA results.

The ATCO has a chance to predict high workload peaks and prepare delegation of tasks beforehand. NATS found that the individual choice and self-pacing may prevent loss of worth and job satisfaction. The sequencing of tasks / air traffic was also liked by DERA.

NATS thought that individual preferences should be allowed in delegation of tasks. This may help controllers to become more proficient at delegating to the machine. However, DERA thought that standardisation of tasks is necessary to maximise safety. This avoids confusion during hand-overs resulting from an individual preferences system. Further research will be needed to clarify what the trade-off between those two arguments is.

DERA's research into locus of control indicated that under the standardised DH system, ATCOs felt that job satisfaction was reduced when tasks were delegated to the machine.

NATS suggested that the ATCO could also have an effective ATM control picture, as she/he still needs to be aware of what is happening. On the other side, DERA found circumstances under which the picture would be lost, namely during times of heavy work due to mental overloading. This is supported by NATS' point that the controller only has time to use the DH concept during low to medium workloads. Therefore both partners have found a potential mismatch with tool use and time to function.

A main area of agreement between the two partners was the "trade off" issue between work required to use the tool and work gained from using the tool. This is centred around the issue of trust. If the tool can be trusted to function without continuous monitoring, then capacity is gained from the work performed by the machine. If the tool has to be continuously monitored, this extra work may contribute to a higher workload than not using the tool.

Both partners looked at the tool at a highly conceptual, low level of detail. The results must therefore be interpreted carefully. Both partners advised further research into this concept.

2.6.2.6 Dynamic aircraft delegation

Three scenarios (1, 3 & 6) were evaluated using the DA automation concept, with two evaluation techniques (HRA, SIM'COOP.

The purpose of the DA automation concept is to transfer a part of the tasks usually under the control of the ground systems to the cockpit (separation, manoeuvres, and trajectories).

The results obtained showed the following:

- The ATCO experienced some difficulties in building a proper internal representation of the situation. The behaviour of the aircraft can be rather unpredictable (in ASAS-like situations for instance), and the ATCO may have difficulty to anticipate the evolution of the situation. This loss of system and situation awareness may not affect the individual ATCO only; it can also have an impact on the shared cognition across the ATM system.
- The effect of the DA on workload seems to be ubiquitous. On the positive side the ATCO is supposed to be relieved of some of the workload; on the negative side, the additional tasks imposed by the delegation process (preparation and monitoring) may prove resource demanding, and hence increase the workload.
- From the MA perspective, these additional tasks can be seen as positive features since they increase the shared context between ATCOs by providing new opportunities to co-ordinate and exchange information.
- The effect of the required externalisation of representations and strategies is not so clear. It may prove non-suitable to the way ATCOs actually perform their tasks and may lead to a loss of flexibility. On the other hand, some information left ignored in the existing situation becomes visible and therefore improves the mutual awareness between agents.
- Obviously the DA automation concept gives more autonomy to the cockpit systems and more responsibility to the pilots. The difficulty raised by this approach is the distribution of decision-making between aircraft and controllers and how the whole system is co-ordinated. Providing more autonomy to aircraft is a trendy idea at the present time, but so far no empirical answers based on experimental or observational data have been brought. Little is known for example on how this new organisation would impact the mutual adjustment process of each agent's representation of the others.
- The role of the tools, required as a framework for supporting DA automation is very significant. One should keep in mind that the potential advantage offered by DA depends highly on the way the concept is technologically embodied. Potential benefits gained from an automation concept could be lost because of an inaccurate implementation.

A conclusion from these evaluations is that DA automation concept can be seen as promising and actually one of the most innovative ones, as it involves both ATCOs and the airborne side, and requires a set of sophisticated tools. But due to the prospective nature of DA, it is essential to have a general thinking on the role of each component of the ATC system based on additional empirical studies that have not been performed yet. These studies should address many relevant points, including questions related to the consequences of the shift from planning to tactical side induced by DA. The nature of co-ordination mechanisms between the air and the ground, the way different variations of DA could have an influence on situation awareness, the problem of the trade-off between MA and workload.

2.6.2.7 Cognitive tools

The concept of cognitive assistance tools is a human-centred concept, which should fit well in the structure of the present job. However, will the controller have the time to use it? Most advantages and drawbacks detected relate to these two points.

Cognitive tools assist the controller's job, without changing it in principle, and are adapted to the controller's way of thinking. It even helps as a support for using automation (concept of controller's agenda). This is seen as a serious advantage, because this means that, in theory, there should be little reluctance to use of the tool. It also facilitates interpretation of the machine outputs, evaluation of the situation, anticipation and prioritisation of problems.

But these advantages also appeared to bring drawbacks:

- Controllers developed over-confidence, and over-reliance in the tools.
- If individual controllers' strategies are implemented in the tools, as has been understood, there is a problem of the lack of standardisation of the tools.
- If tools fail, there is a concern that there will be a problem over the recovery of the situation (although controllers also generally think that skills will be maintained).
- Trusting the tools may be a good thing only in so far as the tools are trustworthy and accurate enough (this depends on the implementation). If the tools are not trustworthy, they will not be used.

There were several concerns about the time necessary to use the tools:

- The tools need to respond instantaneously, which not always happened. This caused additional workload for the controllers.
- Selective attention on some aircraft or problem was at the expense of others, or at the expense of monitoring.
- If there is time enough to use the tools only in low workload configurations, they will not reduce the controller's workload (but one of the goals of the tool is to avoid overloading...)

A general conclusion from evaluations was that this automation concept has a high potential. The way it is implemented is important (to avoid the tools cluttering the screen, or responding too slowly). Typical automation-related issues (overconfidence, ability to restore the situation in case of tool failure) should be carefully addressed. At first sight, the problems seemed to be minor in comparison to other concepts. However, In the RHEA project there was not sufficient time to address the cognitive tools in such depth, that the occurrence of problems can be totally excluded.

2.6.2.8 Further considerations about automation concepts

WP6 highlighted how multifaceted the problem of automation and automation concepts is. It must be addressed with care: safety is at stake. Currently, controllers take decisions taking into account regulations, their experience, but also their available (mental) "resources". If they lack time to analyse a complex situation, they may make a satisfactory (in terms of safety) instead of an optimal decision, sometimes at the expense of efficiency. In this context, a possible solution for automation might be to favour partnership between controllers and machines, rather than a strict allocation of tasks. A good solution should:

- ensure that controllers themselves always perform tasks that are necessary to maintain their situation awareness and their skills,
- contribute to the avoidance of errors. This is mainly by regulating workload (in theory, automation concepts based on delegation are useful here) and providing assistance tools to help ATCOs to organise their work and to find good solutions (cognitive tools are useful here),
- design to tolerate remaining human errors. This may be through the development of very advanced, "intelligent" and timely warnings and alarms, the machine acting as a supervisor of human work.

2.6.3 On the applicability of the used techniques

In addition to comparisons of different automation concepts in the previous section, this section addresses the different evaluation techniques. First each technique will be evaluated individually. In the last section, the different techniques will be compared.

2.6.3.1 Human Reliability Assessment

The Human Reliability Assessment of the automation concepts has highlighted how little is known about the detailed cognitive processes used by controllers. This is one of a number of issues and areas related to the use of automation in ATM, which should be investigated as part of the development of new automated tools. The important issues identified by the present study are listed in the following paragraphs.

There is currently little understanding of controllers' cognitive processing and the limits of their resources. It would be beneficial to determine the scope of controllers' strategy formulation and pattern recognition, and how far ahead they plan strategically (versus more opportunistic planning). Without this, the automation developed may place demands on controllers that exceed their maximum potential resource use.

The impact of automation on Team Resources Management (TRM) is an important consideration as the ATCO is part of a team, which may include machines and other humans. Part of the philosophy of TRM, is the notion of compliance, or accepting authority. For an automation strategy that advises or tells the ATCO what to do, or does not require "permission" from the ATCO, the issue of TRM and compliance needs to be addressed. There is sufficient experience with human non-compliance in industrial systems and of the introduction of *clumsy automation*, to make this an issue of considerable importance and one that should not be ignored. Failure to do so may result in the lowering of controller morale and well-being, increased staff turnover, etc., with consequences for reliability.

This assessment has focused on the *human* reliability issues. A further analysis of *system* reliability is required. Although controller reliability may be degraded, overall system performance may be improved, or vice versa. Such an assessment would also indicate specific aspects of control activities that remain vulnerable to human unreliability. Action could then be taken to design out, mitigate against or control the human reliability.

It should be noted that automation frequently changes the very nature of the task. Most pilots fly because they want to fly, and not because they wish to work with computers. Similarly with ATCOs, they wish to control the traffic, to 'wheel and deal' in complex traffic situations. They are almost always very good at it, possibly due as much to being intrinsically motivated by the task as any other reason. If the nature of the task changes significantly, then this motivation and high performance may be lost.

The benefits of automation are easy to identify, but difficult in practice to realise fully. It is all too easy to be wooed by the potential for major benefits of automation without giving full consideration to the possible negative impacts on human reliability, human well-being and the reliability and flexibility of the system. It should also be remembered that, if the automation fails, it is still left to the controller to handle the situation safely.

2.6.3.2 Cognitive walkthrough

The Malvern Cognitive Applied Walkthrough (MACAW) method is novel and has not yet been validated, but it is possible to look at what this study has shown.

The MACAW technique was found to be effective, involving real controllers and incorporating their operational experience into the study. The interviews provided a valuable insight into the controllers' opinions about the three RHEA WP5 automation concepts under review. Usefully combined with the opinions of human factors experts / system designers, an optimum user-friendly design for automation tools should be possible.

There are three main issues to be discussed which arise from MACAW data analysis: problems with MACAW; automation issues; and scenario issues.

Problems with MACAW

First, although subjects used for this study had similar career training and experience, their opinions were very varied. It would be interesting to discover if any definite patterns emerged from data with a larger sample of subjects. Further study is required to look at subjects performing user trials in a simulated ATC situation. Second, ATM researchers, such as human factors experts and system designers, need contact with operational controllers. This yields operational experience, which is essential to task analysis of ATM and to the design of automation tools. The lack of experience in this study is evident from some apparent operational discrepancies of ATM tasks in the WP5 situation specifications ***[WP5]***, around which the tasks employed in the present MACAW evaluations were based.

The experimental procedure was refined, less useful questions were deleted and more useful questions were added to the MACAW questionnaire pro-forma during the pilot study.

Automation issues

All subjects emphasised the issue of trust, whether the automation concept tools be trustworthy enough to be implemented into the ATM system. ATCOs stated that the tool must work faster than the controller 99% of the time. Lastly, while some controllers were unsure of the safety aspects of receiving automated assistance, others welcomed it. Those who welcomed automation thought that if it were to be used, standardisation would be important to guarantee safety.

Scenario Issues

First, there is a limit to the quality of comments that can be gleaned from a paper specification and a picture of an exemplar screen interface. Second, although these automation concepts were construed as providing benefits, each ATCO suggested different potential improvements to the concepts which might be implemented in the design. Third, although slips and lapse errors may occur with these tools, all can be recovered tactically from the resultant STCAs (Short-Term Conflict Alerts) and through the maintenance of manual skills. Finally, it was found that there was not enough detail in the WP5 scenario / situation specifications for MACAW purposes, and so the specifications were refined during the course of this study.

2.6.3.3 Real time experiments with physiological workload measurements

Workload

The most reliable indicator of the eye measurements is the pupil diameter. This indicator confirms that more traffic results in a higher workload. Furthermore these results show, maybe surprisingly, that the static manual session results in the lowest workload. These findings are in accordance with the dwell time data.

These two indicators are contradictory with the blink rate and blink duration data. They indicate that during the manual sessions the controllers need more time to monitor and have less time to blink. These results seem to indicate a higher workload for the static manual session.

These seemingly contradictory results can be explained by the multidimensional nature of workload. Eye pupil diameter is a global indicator for workload and is sensitive to a great diversity of tasks. The blink data on the other hand have a strong relationship with visual workload, which is only part of the overall workload. It seems as if the dynamic allocated automation increases the global workload but decreases the visual workload of the controller. So, apparently the higher workload in the automation conditions requires mental processes, which put a high load on the mental processes, which put a high load on the mental processing resources of the controllers.

Another explanation is that the number of blink data was insufficient to provide a good image of the relations and correlation with workload. Because the controllers have their eyes more open than closed, the number of blink data is always small compared to the other eye track data.

Workload variation

The objective of dynamic allocation is not only to lower workload but also to lower variations in workload. Only the blink rate data shows stable values with the dynamic allocated sessions. The other three indicators provide, sometimes even significantly, differences between the low and high traffic sessions. From this, it can be concluded that the dynamic allocation of the descent advisory is not used successfully. The variation of the controller's workload is not decreased within this ATC scenario.

Descent Advisory usage

The use of the Descent Advisory indicates the same trend: with high traffic the advice are less used by the controllers. Instead of assisting the controllers when they need support, the advice is not used in conditions of high traffic flow. From this analysis, it is not clear whether they do not evaluate the advice by ignoring or blindly rejecting the advice, or whether they use another strategy whereby the controller evaluates the advice and adapts them to their mental model. This last strategy can be the explanation why the (dynamically) automated sessions result in higher workload and the same or even more variations in workload. If controllers do not trust the advice, they need to evaluate the advice and then decide whether they will accept or reject the advice. This strategy contains extra tasks, which might result in extra workload.

2.6.3.4 Fast Time Modelling with Petri nets

This was the first study in which this type of fast time human performance modelling was used in combination with existing safety analysis methods. Despite the acknowledged shortcomings of such modelling (e.g. it is only as useful as the underlying probabilities and models of human behaviour), it can provide some converging evidence, when used in addition to techniques specially related to human operator characteristics, e.g. mental workload, scanning strategies. It seems feasible to evaluate ATM scenarios with this type of technique, although the method needs to be validated. Additionally, the described technique might also be useful for other purposes: function allocation and reliability determination.

2.6.3.5 Cognitive modelling

The results of the simulations put into evidence one of the main methodological interests of SIM'COOP: the versatility of the data that can be used as inputs. In reference situations, the scenario of activity is an excerpt from observations performed in real work-settings; in "tools" and DA situations, the scenario of expected activity (which does not exist yet) is a theoretical task model.

Figures may provide a practical synthesis to express results from simulations, but they are definitely not the best way for putting into evidence some relevant aspects of these results. For example in a particular situation, a slight shift in the level of Mutual Awareness may lead to dramatic consequences that are not properly resumed by the decrease of the amount of Mutual Awareness. There is an obvious need for defining a better external representation of the outputs of the simulation that would make visible the possible effects of adding or deleting regulation loops supported by Mutual Awareness (Bressolle, Decortis, Pavard & Salembier, 1997).

2.6.3.6 Queuing Network modelling

The activity has applied the queuing network modelling technique to the evaluation of automation concepts applied to controllers' work. This implies that human tasks were to be modelled. Generally speaking, this technique is more specially used when evaluating performance or behaviour of predictive systems rather than complex human behaviours. But the way controllers work can be modelled in the same way than it is done for computers, although this modelling can obviously not be as precise and reliable as computer modelling, and is much more difficult. This analogy with computers is used in the EUROCONTROL's model of cognitive aspects of ATC. However, when human behaviour is involved, all problems highlighted above are still more of concern.

The first point that must be stressed about the realism of the model is that it can try to model controllers' work, not how the controller's *brain* works.

The second point is that the level of detail cannot be very fine, because figures (on the duration of tasks, for example) are very difficult to get at a low level of detail without practical experiments (all the more so, of course, when the automation concept is not implemented yet).

Nonetheless, even when remaining at a fairly high level, there are still problems. For example, does a general framework that describes the work of all controllers really exist, or are there many different ways of doing the same work?

Another problem is that most figures are highly variable.

For example, it is obvious that measures might vary from one controller to another, from a moment of the shift to another, and so on. Furthermore, the methods of measurement may also strongly influence measures themselves. Accurate data would need the use of a sample of controllers.

Therefore, the interpretation of results must be very careful. But, in spite of all that, it seemed worthwhile to experiment the technique for comparing different automation concepts (especially to get tendencies on various evaluation criteria, or to perform “what if” analyses). This is because of a specific advantage of choosing RDD-100 as the modelling tool: a model of the controller's work, based on existing human factors studies, could be a first basis for the design of the automated part of a computer-based ATM system. Using the same tool for the model presented here and for further steps (such as performance modelling of the system) would help things: in a first step. The human part would be privileged, in order to make main choices for automation concepts to be implemented, without detailing the automated part; in a second step, using the same tool, the automated part would be designed, through successive refinements, and modelled in detail. However, this possibility of using a single model as the basis for these two activities, with a focus on different parts, still has to be experimented.

Establishing such a kind of relationship between validation techniques was considered important in recommendations from the VAPORETO work package report dedicated to validation techniques.

2.6.4 Which technique?

2.6.4.1 Problems associated with techniques

It is evident from the results of WP6 that it was not always straightforward to apply the evaluation techniques, and that a variety of problems were encountered. For example: all of the techniques required, in one form or another, detailed task descriptions of the scenarios and resulting ATM situations (i.e. scenario + automation concept). Although being an excellent starting point, the scenario descriptions in WP5 did not always prove to be sufficient for application with every technique.

Second, and related to the first point, it is evident that several of the techniques, particularly the fast-time modelling, required the specification of a “reference situation”. However, it was not possible to use the same reference situation for each technique, thus creating some problems when comparing the results. To counter possible methodological objections against the results of the RHEA study, it would have been better to use a common reference situation for each automation concept and each technique. However within the given budget and time frame, this was impossible. Furthermore, some little tests that were done to see if a common reference situation would have made any difference, did not show any significant result. This gave the consortium confidence in the results.

Third, there was the problem of the validity of the data for the fast-time modelling. This is nothing new, since any modelling exercise is only as good as the data fed into it, and the assumptions being made (and this was recognised by the partners concerned). As a consequence the results must be interpreted carefully. Also, it should be pointed out, that the analytical techniques are prone to problems of validity. A technique such as MACAW is only as good as the ability of the controllers (or other participants) to conceptualise the implications of the automation concept.

At first sight some techniques appear to be more useful and productive than others. However, as has been explained previously, the techniques all differed in their data requirements, and in the quality of the evaluations they yielded.

If anything has become clear in the RHEA study, then it is that there is not one technique outperforming all the others. Fast time simulations are particularly useful if a quick and cheap evaluation of an automation concept is needed. Their speed goes on the expense of precision of course: the most precise model of the reality would be the reality itself. Fast time simulations are particularly useful in the early stages of concept development.

The same accounts for techniques like MACAW. They are very useful in the early stages of concept development. Furthermore, they are cheap, since they require only a limited preparation time.

On the other side, there is real time simulation. If done properly, a simulation can be a very precise representation of reality. Thus, a broad range of operational issues can be studied. However, real time simulations are expensive and cost a lot of time. They are only useful if an automation concept has reached a certain stage of maturity.

2.7 Functional Requirements (WP7)

The reader will agree that it would be very crude to identify one specific “optimal” automation concept that fits an entire ATM application. Within an ATM system often several automation concepts are combined.

To help in such a situation, WP7 analysed the six ATM automation concepts evaluated in RHEA to derive requirements for each concept. This enables the designer or evaluator to choose the relevant items for the ATM system under assessment.

In WP7 a trade off had to be made between the need for global requirements (which will be of help for any ATM system), and very specific ones. This delicate question is well known in the area of guidelines, style guides and requirements.

Requirements on automation can be derived from various sources. In WP7 two different perspectives were used: **automation related issues** and **basis controller functions**. With this approach both the system and the human side of ATM was covered.

2.7.1 Requirements derived from automation related issues

In WP3 eleven automation issues were identified that can be used to distinguish the automation concepts from each other:

1. high level design principles;
2. training;
3. skill degradation;
4. system transparency;
5. mental model;
6. controller's roles, workload and capabilities;
7. error management;
8. co-operation and teamwork;
9. decision management and trust;
10. psycho-sociological aspects;
11. co-operation and delegation of responsibility.

Next, in WP6 the following six different automation concepts were evaluated:

1. machine proposal strategy;
2. machine aided evaluation;
3. dynamic allocation with human delegation;
4. dynamic allocation with machine delegation;
5. dynamic aircraft delegation;
6. cognitive tools.

In the following paragraphs, firstly a number of requirements feasible for each automation concept will be presented. Secondly, each relevant automation issue will be discussed for each of the 6 concepts. The issues were expressed as requirements. A more comprehensive discussion of each requirement can be found in the WP7 final report.

2.7.2 General requirements for all automation concepts

2.7.2.1 Skill degradation

> *Requirement*: When necessary, alternative means must be used to maintain the controller's "picture".

Requirement: Frequent training must be applied to maintain skills that the controller might need in case of emergency.

2.7.2.2 System Transparency

Requirement: The controller must be provided with optional information on system actions.

2.7.2.3 Controller's roles, workload and human capabilities

Requirement: Stressors in the automated system have to be isolated and their intensity has to be reduced.

Requirement: Changes in capabilities with automation have to be identified and the controller has to be trained in those capabilities.

Requirement: It must be tried (!) to introduce only automation features requiring capabilities which the human can easily acquire.

2.7.2.4 Error management

Requirement: With each of the concepts the controller should have the possibility to take over the task and recover from the error, if he has detected one.

Requirement: Information, which is relevant for delegation, has to be provided visually and logically.

Requirement: Errors, which are typical for certain automation concepts, must be isolated and dealt with.

2.7.2.5 Man-machine co-operation and delegation of responsibility

Requirement: The controller must be able to take over responsibility at any time.

2.7.3 Requirements specific for the respective automation concepts

2.7.3.1 Requirements for machine proposal strategy (MP)

2.7.3.1.1 High level design principles

Requirement: The controller must be able to overrule a machine proposal at any time.

2.7.3.1.2 Training

Requirement: Controllers need to be trained to recognise that machine proposals are not equally valid.

2.7.3.1.3 System transparency

Requirement: The machine must provide the controller with a history on how the proposal was developed.

2.7.3.1.4 Mental model - ‘the picture’

Requirement: MP must not disturb controller’s mental model.

2.7.3.1.5 Error management

Requirement: If the controller action is contradictory to the machine proposal, the machine should give a message in case the controller action contains aspects that are contradictory to safety.

2.7.3.1.6 Co-operation and teamwork

Requirement: Controllers working in a team must be informed about each other's relevant interaction with the machine.

2.7.3.1.7 Decision making and trust

Requirement: An explanation accompanying a machine proposal must be kept simple.

2.7.3.1.8 The effect of automation on the psycho-sociological aspects

Requirement: Avoid that controller exaggerates competition with machine.

2.7.3.1.9 Man-machine co-operation and delegation of responsibility

Requirement: During the whole interaction process the controller must be aware of his overall responsibility for the situation.

2.7.3.2 Requirements for machine aided evaluation (ME)

2.7.3.2.1 High level design principles

Requirement: It must be clearly defined what the controller has to do after the machine has evaluated a proposal.

2.7.3.2.2 Training

Requirement: The controller must be able to learn to think of ME as a safety system.

2.7.3.2.3 System transparency

Requirement: The system must reply on the same level of detail as the controller did in order to maintain transparency.

2.7.3.2.4 Mental model - 'the picture'

Requirement: ME judgement may not interfere with the controller's mental model.

2.7.3.2.5 Error management

Requirement: The machine should give a message if the controller action is contradictory to the machine solution.

2.7.3.2.6 Co-operation and teamwork

Requirement: The use of ME in a team of controllers must cover aspects that are vital for a good team atmosphere.

2.7.3.2.7 Decision making and trust

Requirement: It must be prevented that the use of ME is dependent on the trust the controller has in the machine.

Requirement: Integrate the use of ME into the controller's normal chain-of-actions.

2.7.3.2.8 The effect of automation on the psycho-sociological aspects

Requirement: Avoid that the human is feeling controlled.

2.7.3.2.9 Man-machine co-operation and delegation of responsibility

Requirement: The control of a ME evaluation must be possible.

2.7.3.3 Requirements for dynamic allocation with human delegation (DH)

2.7.3.3.1 High level design principles

Requirement: Smooth switching between delegation and re-delegation must be supported.

2.7.3.3.2 Training

Requirement: The controller has to learn to anticipate own overload.

Requirement: The controller has to learn how to interact efficiently with DH.

2.7.3.3.3 System transparency

Requirement: Delegating information may not lead to high workload.

2.7.3.3.4 Mental model - ‘the picture’

Requirement: With task delegation during high workload the machine must not introduce a different mental model.

Requirement: Cues for the controller to use his mental model again have to be provided.

Requirement: A mental model that allows delegating and switching of tasks must be introduced.

2.7.3.3.5 Error management

Requirement: Before delegation, delegation-constraints must be defined which have to be met.

2.7.3.3.6 Co-operation and teamwork

Requirement: Harmonisation of work must be guaranteed during delegation in teamwork constructions.

2.7.3.3.7 Decision making and trust

Requirement: It must be possible to re-delegate a task.

2.7.3.3.8 The effect of automation on the psycho-sociological aspects

Requirement: Introduce low threshold for delegation.

2.7.3.3.9 Man-machine co-operation and delegation of responsibility

Requirement: A timely switch of responsibilities has to be provided.

2.7.3.4 Requirements for dynamic allocation with machine delegation (DC)

2.7.3.4.1 High level design principles

Requirement: System actions must be transparent to the controller.

Requirement: The controller must be informed at the appropriate time when he has to take a task over.

2.7.3.4.2 Training

Requirement: A redefinition of the controller's role has to be accomplished.

2.7.3.4.3 System transparency

Requirement: The controller has to be informed about task-take-over at the appropriate time.

2.7.3.4.4 Mental model - 'the picture'

Requirement: The controller has to be informed over what the system is doing.

Requirement: The controller has to be informed in time that he has to resume a task.

2.7.3.4.5 Error management

Requirement: The controller must confirm that he has taken over or delegated a task.

Requirement: A possibility has to be implemented to check whether the controller has taken control over a certain task.

Requirement: It must be possible to re-delegate a task.

2.7.3.4.6 Co-operation and teamwork

Requirement: Precautions have to be taken in case a teamworking controller leaves the teamwork-situation.

2.7.3.4.7 Decision making and trust

Requirement: With DC not all decision processes must be taken away from the controller.

2.7.3.4.8 The effect of automation on the psycho-sociological aspects

Requirement: Keep the controller informed.

2.7.3.4.9 Man-machine co-operation and delegation of responsibility

Requirement: A proper warning by the machine before taking over responsibility must be accomplished.

2.7.3.5 Requirements for dynamic aircraft delegation (DA)

2.7.3.5.1 High level design principles

Requirement: Communication between the human and the system must be supported.

2.7.3.5.2 Training

Requirement: Controllers must learn to accept the increasing amount (and change in quality) of contributions coming from multiple a/c.

2.7.3.5.3 System transparency

Requirement: The same delegation-relevant information has to be provided for air and ground.

2.7.3.5.4 Mental model - 'the picture'

Requirement: The mental model of airborne and ground must be matched.

2.7.3.5.5 Error management

Requirement: The same information has to be provided to both sides (ground and air) to prevent misinterpretations.

2.7.3.5.6 Co-operation and teamwork

Requirement: It must be identified who should work on DA information.

2.7.3.5.7 Decision making and trust

Requirement: Corresponding goals for ground and airborne side must be defined.

2.7.3.5.8 The effect of automation on the psycho-sociological aspects

Requirement: The controller must get used to a new role.

2.7.3.5.9 Man-machine co-operation and delegation of responsibility

Requirement: Rules for switching process and final responsibility must be provided.

2.7.3.6 Requirements for cognitive tools (CT)

2.7.3.6.1 High level design principles

Requirement: The controller must not be flooded with information.

Requirement: Keep information provision flexible.

2.7.3.6.2 Training

Requirement: The controller must learn to interact with CT without neglecting other interface items.

2.7.3.6.3 System transparency

Requirement: A mechanism for intuitive filtering of CT information has to be provided.

2.7.3.6.4 Mental model - ‘the picture’

Requirement: The special support CT gives to the controller’s mental model must not lead to “mental isolation”.

2.7.3.6.5 Error management

Requirement: A feature has to be provided to the machine to check the controller’s actions before giving him accompanying information.

2.7.3.6.6 Co-operation and teamwork

Requirement: Teamworking controllers must have co-operating machine support.

2.7.3.6.7 Decision making and trust

Requirement: Decision making must not be hampered by displaying too much information.

Requirement: The controller must realise that even the CT information sometimes might not be sufficient.

2.7.3.6.8 The effect of automation on the psycho-sociological aspects

Requirement: Avoid the controller seeing CT as an annoying intruder.

2.7.3.6.9 Man-machine co-operation and delegation of responsibility

Requirement: The possibility to tune or filter the amount of contributions from CT must be provided.

2.7.4 Requirements developed from controller tasks

In addition to the requirements derived for each of the 6 automation concepts, a second approach took the different controller functions as distinguished in WP 2 as a starting point. Those functions were:

- sensing
- integration
- prediction
- communication
- ATC problem solving/planning
- executive action
- rule monitoring
- co-ordination
- overall system performance

Each of these basic functions has its own requirements when it is applied to an automated system. These requirements are listed below in the following paragraphs.

2.7.4.1 Significant requirements for sensing

1. Information sources should be clearly detectable/available
2. Information should easily be extractable from the sources
3. The information should be presented in such a way as to facilitate its gathering, recognising and remembering
4. It should be clear for the provision of which information a source is meant, and unintended use should be prevented
5. If different information needs to be combined to obtain a clear picture (to decide what information has to be obtained next), it should be presented in such a way as to enable/facilitate this (mental) process
6. The human should be timely informed about information updates
7. Extreme values of the information or information that requires

immediate action should be clearly indicated, by means fit to usage of the information and at a location appropriate to the actions to be undertaken (e.g. colour coding, visual or aural alerting)

8. Information should contain a 'code' to enable checking whether it is recent/valid
9. The system should support the controller by filtering, pre-processing and integrating the information where applicable
10. The system should provide means to (temporarily) store the information
11. The system should provide means to recall or check on previous information
12. Integrity checks should be provided to inspire controller confidence in the system

2.7.4.2 Significant requirements for integration

1. The format in which the information is presented should facilitate integration
2. The location of the information should facilitate integration
3. It should be clear what information needs to be combined (e.g. which information considers which a/c)
4. The human should be informed at the appropriate time about information updates
5. Extreme values of the information that requires immediate action should be clearly indicated, by means fit to usage of the information and at a location appropriate to the actions to be undertaken (e.g. colour coding, visual or aural alerting)
6. The system should support the controller by integrating the information where applicable
7. The system should provide means to (temporarily) store the information
8. The system should provide means to recall or check on previous information

2.7.4.3 Significant requirements for prediction

1. Prediction information should be clearly isolated from remaining information
2. The system should support the controller by filtering prediction information
3. The system should present anticipations which have to be used for a certain prediction issue as interconnected elements

4. The human should be timely informed about situation updates
5. The system should pre-process 3D information for the human
6. The system should provide an explicit and pre-processed link between information between 3D issues and issues covering time aspects
7. The prediction data should be transformed into information at reasonable places in the system

2.7.4.4 Significant automation requirements for communication

1. The messages to send/receive should be easy to understand (good quality, clear coding)
2. The messages sent/received should be stored and should be easy to look up

2.7.4.5 Significant requirements for ATC problem solving/planning

1. The human should be timely informed about information updates
2. The system should support the human in the decision making process
3. The information regarding a certain subject has to be clearly indicated
4. The rules, regulations and constraints concerning each planning and problem solving issue have to be clear (e.g. a/c performance information)
5. The system should provide means to (temporarily) store information
6. The system should provide means to (quickly) recall or check on previous information

2.7.4.6 Significant requirements for executive action

1. It should be clear to the human when executive actions should be taken
2. It should be clear to the human what executive actions to take
3. The environment should be fit for the actions to be (timely) executed
4. The system should indicate the wrong execution of actions if possible
5. The system should be able to recover the system state as it was before the execution of a certain action
6. The controller should be able to store/look up any previous taken actions

2.7.4.7 Significant requirements for rule monitoring

1. The information regarding a certain subject has to be clearly indicated
2. Deviations from the planned situation should be easy to detect (e.g. within a certain time or distance range)
3. The system should support the human with the detection of deviations from the required situation (e.g. by means of alerting)
4. The 3D situational information should easily be derived and monitored
5. The 3D situational information should be pre-processed for the human (trend-vectors e.g.)

2.7.4.8 Significant requirements for co-ordination

1. It has to be clear what tasks should be performed by whom
2. The system should support in the smoothly transferring of information

2.7.4.9 Significant requirements for overall system performance

1. The human should be familiar with the items to check, to examine the system state
2. The system should support the human by alerting when deviations from the required situation occur
3. The system should provide integrity checks to give the controller confidence in the system

2.7.5 Requirements for automation tools

The following paragraphs contain requirements for automation tools. They are a translation from the relatively theoretical requirements in the earlier sections into a form that can be used directly by system designers.

All requirements were named with standardised references, and terminated with a ## paragraph. This is to facilitate their automatic processing for storage into an RDD-100 requirements database. The reference begins with RHEA, followed by a category of reference (three letters; the first letter is T for the section on "Requirements for automation tools), and ends with a reference number in the category.

In practice, as specific systems already have a lot of requirements, possibly contradicting some of those expressed below, all requirements should be considered as recommendations, rather than as strict requirements.

The following requirements are very general, and do not apply to specific ATC tools to be developed. Therefore, they must be considered as guidelines, and adapted, for defining requirements to be applied to specific tools.

The requirements should not be considered as an exhaustive set: most of them originate from the evaluations performed during **WP6**. They are classified as follows:

- requirements about specific automation tool issues
- requirements depending on what is automated
- requirements depending on the level of automation

2.7.5.1 Requirements about specific automation tool issues

2.7.5.1.1 Requirements about comprehensibility of tools

RHEA-TCO-001

Raw data should be processed to avoid the display of a too large amount of data.

##

RHEA-TCO-002

The controller should be notified when information displayed is degraded for a flight (or for all flights).

##

RHEA-TCO-003

The uncertainty of displayed data must be made clear to controllers.

##

RHEA-TCO-004

The interface should prevent misreading errors.

##

RHEA-TCO-005

HMIs displaying aircraft should make clear which aircraft are under the control of the controller.

##

2.7.5.1.2 Requirements about flexibility of tools

RHEA-TFL-001

Tools should be adaptable to unusual circumstances, such as a physical delay (e.g. aircraft blocks runway) or very high workload situations.

##

RHEA-TFL-002

It should be possible to tailor tools, to make them more flexible.

##

RHEA-TFL-003

The system should be flexible enough to be able to work in the absence of some tools.

##

RHEA-TFL-004

Providing a tool, or making it mandatory, should take into account operational situations involved.

##

RHEA-TFL-005

Automation tools should encourage standard practices.

##

2.7.5.1.3 Requirements about distinctness of tools

RHEA-TDI-001

The design of a tool should not lead to any ambiguity on its role.

##

RHEA-TDI-002

It should be possible to distinguish different tools easily.

Of course, this requirement does not mean that inconsistent principles should be used for different tools!

##

2.7.5.1.4 Requirements about communication between a tool and the controller

RHEA-TCC-001

The controller should get a feedback on who does what, what is being done, what has already been done, and what still has to be done. There should be an indication that a plan to avoid a conflict has been safely executed, and the potential conflict avoided.

##

RHEA-TCC-002

Trust in tools should be addressed when designing them.

##

RHEA-TCC-003

A tool should meet the cognitive capabilities of the human for the function the tool stands for.

##

RHEA-TCC-004

Tools should facilitate the externalisation of the controller's plans.

##

RHEA-TCC-005

The interface should prevent overlooking certain data.

##

RHEA-TCC-006

The interface should prevent accidental activation of functions.

##

RHEA-TCC-007

The speed of response should appear to be instantaneous.

##

RHEA-TCC-008

Tools have to adapt to the controller's capabilities, taking into account the workload.

##

2.7.5.1.5 Requirements about communication (multi-tool issues)

RHEA-TCM-001

Standardised colours should be used in HMI.

##

RHEA-TCM-002

Windows of automation tools should not clutter screens.

##

RHEA-TCM-003

The interaction modes for the different tools used by the controller should be consistent (e.g. a tool should not be based on keyboard input, while another one is based on mouse).

##

RHEA-TCM-004

The units used by different tools should be consistent (e.g. not nautical miles in one tool and kilometres in another one), except when no inconvenience results of this situation.

For example, it should never be necessary to convert one figure displayed by a tool from a unit to another one for its use in a second tool.

##

RHEA-TCM-005

Communication between tools and the HMI should take care of the possible different degrees of automation present in the tools.

##

2.7.5.1.6 Requirements about tools reliability

RHEA-TRE-001

Tools should be reliable, i.e. provide a correct service, according to their specification.

##

RHEA-TRE-002

There should be no invisible failure. A warning should be issued for any automation failure.

##

2.7.5.2 Requirements depending on automated tasks

2.7.5.2.1 Communication between humans

RHEA-TCH-001

Tools automating communication between humans should make up for identified human limitations.

##

2.7.5.2.2 Communication between humans and machine

RHEA-THM-001

New automation tools for communication with the machine should make this communication easier, safer, or more efficient, and should not be detrimental to any of these points.

##

2.7.5.2.3 Negotiation

RHEA-TNE-001

The tools should ensure the application of agreed negotiation protocols.

##

RHEA-TNE-002

If controllers have to take decisions during the negotiation, tools should assist them in their decisions (e.g. "what if" conflict detection tools).

##

2.7.5.2.4 Monitoring

RHEA-TMO-001

Tools should warn controllers when an aircraft trajectory is not as expected (and the deviation is significant)

##

RHEA-TMO-002

Conflict detection tools should warn of conflicts, but should also in some cases indicate the absence of conflict (when the controller might be unsure, or thinks that there is a conflict).

##

2.7.5.2.5 Planning

RHEA-TPL-001

Tools proposing an agenda for future controller's tasks could list everything, including straightforward tasks.

##

2.7.5.2.6 Decision-making

RHEA-TDM-001

Decision-making tools should inform controllers of their decisions.

##

2.7.5.3 Requirements depending on the level of automation

2.7.5.3.1 No automation

No automation requirement on tools.

2.7.5.3.2 Only digitisation

RHEA-TDG-001

No useful information in communication should be lost due to automation.

##

RHEA-TDG-002

Situational awareness of third parties should not be reduced due to automation.

##

2.7.5.3.3 Data processing for improvement in accuracy

RHEA-TDP-001

New data processing for improving accuracy should never result in a lower accuracy.

##

RHEA-TDP-002

New data processing for improving accuracy through the use and fusion of several input sources should continue to work even in the case of failure of some of the sources.

##

2.7.5.3.4 Assistance

RHEA-TAS-001

When a tool proposes solutions, a measure of confidence should be associated to proposals.

##

2.7.5.3.5 Automated task sharing between controller and machine

RHEA-TTS-001

The status of task sharing between a controller and the machine must be made clear to this controller.

##

RHEA-TTS-002

The status of task sharing between controllers and the machine in the adjacent sector should be useful (WP6).

##

RHEA-TTS-003

Clear limits of delegation should be defined (WP6).

##

2.7.5.3.6 Supervision of human work

RHEA-TSH-001

The supervision tool should provide warnings in potentially unsafe situations only.

##

2.7.5.3.7 Complete automation, with human supervision

RHEA-THS-001

The automation tools should take into consideration, that controllers are able to take charge at any moment, should the tools fail.

##

2.7.5.3.8 Complete automation, without human supervision

RHEA-TCA-001

In this case, the overall system should be extremely reliable, and faults in automation have to be tolerated.

##

The requirements identified in WP7 form a basis, from which further investigations on integration requirements can profit. With the decision for a level of detail which enables the developer/evaluator to identify at least whether the requirements apply to a certain product or not, the work package contributed to building up a framework for the role of the human in the evolution of ATM.

3 RHEA achievements

Chapter 2 of this document summarised the results of the RHEA work packages. This chapter 3 will highlight the merits of the RHEA project and where justified, attempt to generalise these results to application areas beyond RHEA.

3.1 Common understanding and adopting common terminology

The RHEA consortium consists of a broad range of key players in the field of ATM, representing academia, industry, regulatory authorities and research establishments. Their co-operation on such an important subject like automation concepts in ATM in itself, enhances a common understanding of the problems related to the subject and of the best ways in dealing with them. Furthermore, RHEA provides an agreed terminology and a classification scheme for automation concepts. This will diminish confusion and repeated efforts in future ATM automation research.

3.2 Comprehensive function analysis

RHEAWP2 identified the functions performed in different current air traffic control systems (en route, approach) and added the functions that are likely to play a role in the future. The functions were expressed in such a form that the consequences of their subsequent automation could be considered easily. The WP2 function analysis can also be used for signalling, analysing and solving bottlenecks in current air traffic control and for development of new ATC procedures. The application area of the results of WP2 is thus much broader than the scope of RHEA (e.g. nuclear industry).

3.3 Techniques for evaluation, validation and certification

WP4 provided an extensive and up-to-date list of techniques available for evaluating automation concepts. For each automation concept several techniques were listed. These techniques were not unique to ATM and could be applied to automation studies outside this field as well. Except for most of the fast time simulation techniques (which are mostly in an experimental stage), most of techniques are suited for validation and even certification studies. For example, when introducing new air traffic control procedures, one or several of the techniques listed in the RHEA WP4 report could be chosen to carry out validation of the procedures. Criteria for choosing techniques have been extensively described (e.g. cost of technique, ease of applicability), thereby facilitating the best choice of a technique for the validation case at hand.

3.4 Broad applicability of RHEA scenarios

The major objective of WP5 was to develop a number of representative ATM scenarios. In WP6 these scenarios were combined with the automation concepts identified in WP3, thus forming the basis of a set of 'ATM situations' (or 'worked examples'). The pan-European nature of the RHEA Project was stressed in that the ATM scenarios produced at the end of WP5 were representative of ATM in Europe. The generic nature of the RHEA scenarios allows their application in other European projects, like CINCAT, PATIO, MANTEA, PHARE, which need very similar scenarios. This would safe time and funds.

3.5 Suitable automation concepts

RHEA WP3 provided a framework within which each automation concept may in principle be categorised. Once again, this framework does not only apply to ATM but also to automation in other areas, for example the aircraft, nuclear or defence industry. For each automation concept the major benefits and drawbacks are once again summarised in the following sections.

3.5.1 Full automation

There is no role for the human in a fully automated system, so it was not studied in detail in the RHEA project. ATM studies which attempted to build a fully automated ATC system, were all abandoned (e.g. EUROCONTROL's ARC2000). Whether the reason for lack of success is the unfeasibility of the concept or the unavailability of the technique to build such a system remains unclear to date.

- Benefit: complete predictability of airspace capacity;
- Drawback: if system fails, there are no fall-back options.

3.5.2 Controller as supervisor of the system

- Benefit: unaffected traffic load and allows high productivity and reliability;

- Drawbacks: the concept is deemed not suitable because of de-skilling of air traffic controllers (no practice of skills necessary for operation if system fails), adverse impact on motivation, poor situation awareness and their related negative impact on safety.

3.5.3 Machine-aided evaluation

The system assists in getting the picture, but never makes or even suggests any decision.

- Benefit: decrease in controller workload;
- Potential drawbacks: superficial situation awareness, possible complacency caused by over-confidence in the output of the tools.

3.5.4 Cognitive tools

Machine assistance for organising controller tasks based on typical controller's heuristics.

- Benefits: no fundamental change in control principles (core skills are preserved, facilitation of acceptance), decreases memory load, saves human cognitive resources;
- Drawbacks: workload overhead when using the tools if they are incompatible with high traffic load, development of selective attention at the expense of monitoring, less global situation awareness, possible complacency by over-confidence in the outputs of the tools.

3.5.5 Machine-proposal strategy

The system suggests "solutions" that the controller may choose to implement or not.

- Benefits: save human resources, remains indifferent to traffic load, never fails to consider side-effects of actions, overcomes any narrowing of situation awareness or tunnel-vision;
- Drawbacks: work overload because of under-confidence in the output of the system, more superficial situation awareness, loss of core skills, loss of flexibility, possible complacency by over-confidence in the output of the system.

3.5.6 Dynamic allocation with machine delegation

The system regulates workload by deciding which tasks the controller should perform, and by performing the remaining tasks by itself.

- Benefits: capacity gain by work performed by the machine, constant controller workload, core skills are preserved;
- Drawbacks: operators are out of control (loss of job satisfaction), risk of poor acceptance, more superficial situation awareness, ambiguity over who is responsible for what at any time, mismatch between system- and controller- behaviour, poor relevance of definition and assessment of workload criteria, impairing of task performance by physiological workload measuring.

3.5.7 Dynamic allocation with human delegation

The operator regulates his or her own workload through allocating tasks to the system.

- Benefits: capacity gain by work performed by the machine, the controller is still much in control, core skills are preserved since the controller keeps a performing role;
- Drawbacks: ambiguity over who is responsible for what at any time, additional workload from manipulation and monitoring of the system, loss of job satisfaction when tasks are delegated.

3.5.8 Dynamic aircraft delegation

The operator delegates some control tasks to the pilot.

- Benefits: possible optimisation of control actions when performed airborne, reduced controller workload, core skills are preserved since the controller keeps a performing role, shared context is increased through explicit co-ordination;
- Drawbacks: the behaviour of the aircraft can be unpredictable (loss of anticipation and situation awareness), additional workload from co-ordination with pilots and monitoring of aircraft behaviour, loss of job satisfaction when tasks are delegated, ambiguity over who is responsible for what at any time, increased pilot workload.

3.5.9 HMI enhancement

A good Human Machine Interface is essential for each automation concept. An automation concept may be very well thought through on a conceptual level and even be implemented successfully from a system's point of view, if the HMI has not been considered sufficiently, there is a big chance of failure of the automation concept.

3.5.10 What is the best automation concept?

It depends, is the obvious answer, but on what? Firstly on the fact of the new system is developed from scratch or if an existing system needs adaptation. The former case is rare, certainly in the air traffic control field, where evolution and not revolution is the standard. For these rare cases, *cognitive tools* seemed to be the most promising automation concept. The analysis of WP3 associated major advantages and only minor problems with cognitive tools. Although the validation of the cognitive tools concept is not complete, this theoretical analysis was largely confirmed in the concept evaluation performed in WP6 (see also section 2.6

In the case where an adaptation of an existing concept rather than developing a new system from scratch is being proposed, the choice for a particular automation concept is less obvious. It is mainly finding the optimal match between the concept of the existing system and an automation concept that solves the drawbacks of the original. The automation concepts framework from WP3 provides 9 concepts with their respective benefits and drawbacks. This framework can help to perform a thorough analysis of existing operational problems. The resulting list with problems should guide the decision about the required future automation concept. Drawbacks of the current implementation can be solved by choosing an automation concept that supplements these drawbacks. This strategy may sound surprisingly simple, but is hardly ever used when choosing an automation concept for ATM. The WP3 report provides numerous examples of analysing automation concepts, but for reasons of clarity one more example, namely for the CINCAT concept, will be described in the following section (3.5.11).

The benefits and drawbacks of each automation concept as indicated in WP3, are all related to human factors. Naturally, the choice for a particular automation concept is not only based on human factors considerations but also on factors like cost, technical complexity, political considerations, etc. Those were not explicitly covered in RHEA.

3.5.11 A worked example: CINCAT

In WP3 a number of existing ATM projects was rated according to the automation concepts scheme. As an example, in the following paragraphs CINCAT will be rated on each of the 9 automation concepts. Therefore, the 9 automation concepts are considered to be dimensions that allow to characterise more precisely the underlying principles upon which the CINCAT automation concept is built.

A five point rating system was used. The ratings on the scale have the following meaning:

- 2 : Project wholly or deliberately disregards this automation concept

- 1 : Project shows moderate disregard for the concept

- 0 : Concept has no relevance to the ATM project.

- +1: Project pays moderate or implied consideration to this automation concept;

+ 2 : Project completely and deliberately embraces the automation concept.

CINCAT was rated on each of the 9 automation concepts. The results can be found in the following table.

Table 3.1 CINCAT rating on each of the 9 automation concepts

	CINCAT
1. Autonomous Computer/Full automation	-2
2. Controller as supervisor	-2
3. Machine proposal strategy	0
4. Machine aided evaluation	+1
5. Dynamic allocation with human delegation	0
6. Dynamic allocation with machine delegation	0
7. Dynamic aircraft delegation	-2
8. Cognitive tools	+1
9. HMI enhancement	-1

So, what does this table tell us about the CINCAT project? In the first place it shows that the CINCAT project is not based on one particular automation concept. As a consequence there is a risk of confounding advantages and problems of the different automation concepts. It highlights the fact that before the CINCAT project started, no thorough explicit automation conceptualisation was carried out.

One could systematically go through the benefits and drawbacks of each automation concept (as laid down in the WP3 report). For example, ‘autonomous computer/full automation’ scored -2 on the rating scale, meaning the CINCAT project never even considered this concept. It therefore misses an opportunity for error-free ATC and prevents a major drawback of the full automation concept, namely that there is no human back-up in case the automated system fails. For each of the other 8 concepts a similar way of reasoning could be set up. If done systematically and thoroughly, a comprehensive list with possible gains and problems of the CINCAT project could be made, with a predictive value. E.g. the score of -1 on HMI enhancement indicates that CINCAT paid very little attention to the design of an appropriate HMI. This ignorance could seriously endanger the potential of the automation concepts that are present in CINCAT.

As the worked example indicates, analysing an automation concept before implementing it, could prevent the occurrence of predictable drawbacks, usually associated with the automation concept under study.

4 Epilogue and follow-on work

There is a real risk that unsuitable automation concepts and systems could be implemented in the future, if automation and/or change of the controller's tasks were allowed to proceed without a detailed understanding of the optimum allocation of functions and tasks to the human and the automated system. Inappropriate automation systems may be unused or under-used by the controller (which is a waste of resources) or, more seriously, the safe and efficient performance of air traffic management could be impaired.

The RHEA project attempted to reduce these risks, by providing a framework that allows predictions about the chances of success of an automation concept. Most of the 9 proposed concepts underwent some form of evaluation, but none of them has been completely validated. HMI enhancement and machine aided evaluation have been successfully applied; co-operative tools and dynamic allocation have only just begun experimental evaluation while complete automation failed before complete simulation. The benefits and drawbacks predictions that can be made by using the RHEA WP3 framework, can reduce the risk of projects which seek to explore a particular automation concept. However, further validation of the RHEA framework and of the respective automation concepts is absolutely necessary.

It would be interesting to conduct an evaluation study in the future which concentrated on the four most promising automation concepts (based on the results of WP6): cognitive tools, dynamic allocation with human delegation, machine aided evaluation and machine proposal. A Real Time Simulation of each concept built into one scenario could be carried out. This particular scenario should have a particular focus on crossing points, approach and departure control. Some physiological measures e.g. eye indicators, could be taken to gauge mental workload during the simulation runs. Parts of the other more time-consuming techniques would cover many criteria. For example, MACAW could be adapted to provide a structured interview to take place after the simulation trials. Fast time simulations could be performed alongside the main real-time simulation. This multi-technique project could generate more information about the potentially most promising automation concepts. As part of the study, the exact nature of automation concepts investigated would need to be clarified. In RHEA, certain assumptions about what certain tools/interfaces would look like, were made.

5 References

ATLAS *ATLAS, Outline of the vision for the future European unified CNS/ATM system*, Interim report, Volume 2.05 of the ATLAS study, European Union DGXIII, 1993.

Cox M. *Task analysis of selected operating positions within UK Air Traffic Control.* IAM Report No. 749. Defence Research Agency, Farnborough, United Kingdom, 1994.

Goillau P.J., Baseley D.A. and Williams N.J. Practical experience of rapid prototyping for user interface design in ATC. In *Proceedings of Ergonomics Society Annual Conference*, Southampton University, April 1991.

Jackson, A. Internal EUROCONTROL document. 1989.

Jentsch, F.G. Problems of systematic safety assessments: lessons learned from aircraft accidents. In Wise, J., Hopkin, V.D. & P. Stager (Eds.). *Verification and validation of complex systems*: Human factors issues, Springer, 1993.

O'Hara, J., Wachtel, J. Advanced control room evaluation: General approach and rationale. *Proceedings of the Human Factors Society 35th Annual Meeting*, Santa Monica (CA), 1991, pp. 1243-1247.

Reason, J. *Human error*, Cambridge University Press, Cambridge, 1990.

RHEA WP1, Kelly, C., Goillau, P.& G. Banks: *Background and scope*, Final report, 1996.

RHEA WP2, Buck, S.: *Synthesis of functions*, Final report, 1997.

RHEA WP3, Sofréavia, DERA, NLR, Thomson-CSF Airsys: *Automation strategies*, Final main document, 1997.

RHEA WP4, Goillau, P., Biemans, M., Chupeau, F., Foot, P., Tremblay, B.*: Criteria and applicability of evaluation methods*, Final report, 1996.

RHEA WP5, Cox, M., Kelly, C., Banks, G., Goillau, P.: *Selection and definition of ATM situations*, Final report, 1997.

RHEA WP6, Thomson-CSF Airsys, DERA, NATS, NLR, Sofréavia: *Application of Evaluation Techniques*, Final report, 1997.

RHEA WP7, NLR, Thomson-CSF Airsys: *Integration requirements for ATC-functions*, Final report, 1998.

Wise J.A., Hopkin V.D., and Smith M.L. (eds) (1991) *Automation and systems issues in Air Traffic Control*, Springer Verlag, Berlin.

6 Glossary of acronyms

ASM	Air Space Management
ATC	Air Traffic Control
ATLAS	Air Traffic Land and Airborne Study
ATM	Air Traffic Management
CAA	Civil Aviation Authority
CENA	Centre d'Études de la Navigation Aérienne
CINCAT	Capacity Increase through Computer Assistance Tools
CT	Co-operative Tools
DG	Directorate General
DH	Dynamic allocation with human Delegation
HMI	Human Machine Interface, Human Machine Interaction
MACAW	Malvern Cognitive Applied Walkthrough
ME	Machine aided Evaluation
MP	Machine Proposal
NATS	National Air Traffic Service
NLR	Nationaal Lucht- en Ruimtevaartlaboratorium
RHEA	Role of the Human in the Evolution of ATM
Sofréavia	Société Française d'Études et de Réalisations d' Équipements Aéronautiques
STCA	Short Term Conflict Alert
WD	Working Document
WP#	Numbered Work Package