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DOI
10.1109/DASC43569.2019.9081689

Publication date
2019

Document Version
Final published version

Published in
DASC 2019 - 38th Digital Avionics Systems Conference, Proceedings

Cognitive Work Analysis of the Sectorless ATM Concept with the Introduction of Teams

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***Abstract*—In this paper the cognitive work analysis for the sectorless ATM environment will be presented. The analysis includes the abstraction hierarchy, decision ladder and information flow maps. This analysis will form the basis for development of tools and display designs within the sectorless ATM environment.**

***Index Terms*—sectorless, air traffic management, cognitive work analysis**

I. Introduction

The amount of IFR flights grows every year. In 2017 an increase of 4.0% was observed with respect to 2016 for the ECAC member states [1]. In the period from 2017 to 2024 an additional growth of 17% is expected [1].

The current ATM system will eventually not be able to deal with such increases in air traffic. The main problem to deal with this increase in traffic lies within the limiting factors of the airspace capacity. This airspace capacity is limited by the capacity of the individual sectors. When the workload within the sector becomes too high, the sector is split up into smaller sectors. The side effects of splitting up sectors are that communication increases with smaller sectors and that smaller sectors decrease the possibilities for tactical and strategic control [2]. If a sector gets too small, further splitting it up might result in a higher workload due to these side effects.

Two solutions to increase the capacity of the current ATM system have been proposed: dynamic sectorization [3] and introduction of automation [4]–[6]. Even though these concepts are able to increase the capacity of the airspace, they do not tackle this limiting factor for the capacity increase.

Over the past ten years DLR has been developing a new concept in air traffic management: sectorless ATM. In sectorless ATM, controllers are no longer responsible for a given sector, as in the current ATM system, but are instead responsible for a certain number of aircraft regardless of their position in the airspace [7]–[11]. The controllers are responsible for these aircraft from entry into the airspace until the aircraft exits the airspace [2], [12]. The change from the current environment to the sectorless ATM concept is visually presented in Figure 1.

Currently new research is being conducted on introducing teams to the sectorless concept in order to increase the efficiency of the concept.

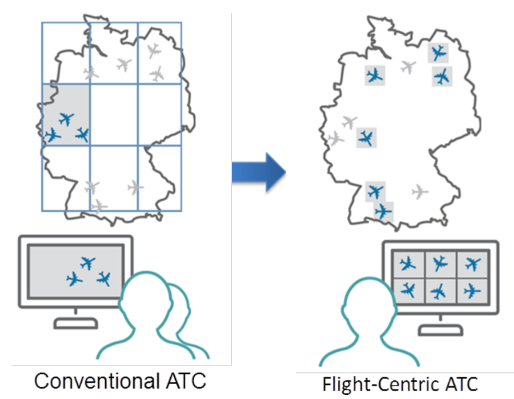

Fig. 1. Current ATM environment vs Sectorless ATM concept

Before introducing teams to the sectorless concept, it is important to understand how the work changes. These changes can be revealed by means of a cognitive work analysis [13], [14]. The cognitive work analysis is an iterative analysis that focuses on the constraints of a certain work environment [14].

In Section II, the sectorless ATM work domain will be analyzed. In Section III, the actions needed to complete the control action within the sectorless ATM domain will be discussed. In Section IV, the information flow within the control tasks is further analyzed. Finally, Section V will start with a discussion and describe the future work to be conducted in this research area.

II. Work Domain Analysis

The first step in the cognitive work analysis is the work domain analysis. The work domain analysis aim to identify the functional structure and constraints of the work domain [14].

The main tools used in the work domain analysis is the abstraction hierarchy. The abstraction hierarchy divides the work domain into five levels of abstraction: functional purpose, abstract function, generalized function, physical function, and physical form. Each of these levels contain information about the work domain and are linked by mean-end or how-why relationships [13], [14].

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Figure 2 show the abstraction hierarchy of the current ATM environment and Figure 3 shows that of the sectorless ATM environment. The most important differences, being either new elements within the abstraction hierarchy or elements that change internally, are highlighted in Figure 3. The numbers between brackets indicate the connections with the higher level.

Functional Purpose	1. Safety; 2. Productivity; 3. Efficiency
Abstract Function	1. Separation (1); 2. Information sharing (1,2,3); 3. Obstruction (1); 4. Utilization (2,3)
Generalized Function	1. Coordination (1,2,3,4); 2. Responsibility (2,4); 3. obstacle avoidance (1,2,3); 4. Flight plan updating (1,2,3); 5. Scheduling demands (2,4)
Physical Function	1. Weather Conditions (3,4,5); 2. Radar data analysis (1,3,4,5); 3. Aircraft (1,2,3,4,5); 4. Other Controllers (1,2); 5. Aircraft performance (1,3,4); 6. Communication (1,2,3,4); 7. Restricted Airspace (1,3,4,5)
Physical Form	1. Prohibited Airspace (2,3,6,7); 2. Data link (3,6); 3. Radio (3); 4. Telephone (4); 5. Terrain (7); 6. Thunderstorms (1); 7. Shear wind (1); 8. Aircraft Position (2,3); 9. Aircraft States (2,5)

Fig. 2. Abstraction hierarchy current ATM environment

Functional Purpose	1. Safety; 2. Productivity; 3. Efficiency
Abstract Function	1. Separation (1); 2. Information sharing (1,2,3); 3. Obstruction (1); 4. Utilization (2,3)
Generalized Function	1. Coordination (1,2,3,4); 2. Responsibility (2,4); 3. obstacle avoidance (1,2,3); 4. Flight plan updating (1,2,3); 5. Scheduling demands (2,4)
Physical Function	1. Weather Conditions (3,4,5); 2. Radar data analysis (1,3,4,5); 3. Assigned Aircraft (1,2,3,4,5); 4. Other Aircraft (2,3,5); 5. Other Controllers (1,2); 6. Aircraft performance (1,3,4); 7. Communication (1,2,3,4); 8. Restricted Airspace (1,3,4,5)
Physical Form	1. Prohibited Airspace (2,3,4,7,8); 2. Data link (3,7); 3. Radio (3); 4. Telephone (5); 5. Terrain (8); 6. Thunderstorms (1); 7. Shear wind (1); 8. Aircraft Position (2,3,4); 9. Aircraft States (2,6)

Fig. 3. Abstraction hierarchy sectorless ATM

In the current ATM environment controllers are responsible for a given geographical area in which they control all aircraft. In the sectorless ATM environment on the other hand, a team of controllers will be responsible for a pool of aircraft, from the moment these aircraft enter the airspace, until they exit it. The result is that in the sectorless ATM environment, the aircraft that are under control by a certain team of air traffic controllers, are surrounded by aircraft that are under control by different teams of air traffic controller. In the abstraction hierarchy this is highlighted by the differentiation between the assigned aircraft and the other aircraft.

In case of a conflict there might be more than one team of controllers involved. This means there is an interaction between the teams of controllers in order to solve a conflict. The interaction between the teams of controllers thus changes dramatically within the sectorless concept.

Communication with respect to both the aircraft as well as the other controllers changes. Controllers will not be able to directly communicate with the aircraft that are not assigned to them. The communication to the other aircraft will flow through the controllers that are responsible for these aircraft.

The changes on the physical function level further influence those on the generalized function level. The main changes on the generalized function level occur within the coordination, responsibility and obstacle avoidance.

Unlike in tranditional ATM concepts, communication with aircraft that are not assigned to the team is accomplished by communicating with the controllers who are responsible for those aircraft. The only direct coordination with aircraft takes place with those that are assigned to the team.

The responsibility of the controllers to the aircraft changes more to an aircraft centered responsibility. This would result in more possibilities for the controller to grant pilot requests for more efficient flight routes.

Changes in obstacle avoidance are seen by the way obstacles are defined in the sectorless ATM environment. Since sectorless ATM is a concept for the upper airspace, possible obstacles are: thunderstorms, shear wind, other aircraft, etc. Since the team of controllers in no longer in control over the aircraft that are not assigned to them, these become moving obstacles that cannot be controlled directly by them.

At the abstract function and functional purpose level, no major changes occur, but the changes on the lower level do influence the way these levels are expressed. For separation does not change directly, but it is influenced by the changes in coordination due to differentiation between assigned aircraft and other aircraft.

III. Control Task Analysis

The second phase of the cognitive work analysis, is the control task analysis. The control task analysis aims to understand the control activities in the work domain.

The main tool for the control task analysis is the decision ladder, shown in Figure 4. The decision ladder helps to capture the information-processing activities and knowledge states of a control task [14].

First the control activities of the sectorless ATM environment should be identified. The following activities will be discussed:

- Accepting a new aircraft.
- Conflict detection and resolution.
- Adherence monitoring and tweaking an aircraft.
- Assign aircraft between the members of the team.

A. Accepting a New Aircraft

Since no tools for accepting new aircraft have been developed, the decision ladder is of the form shown in Figure 4, without any shortcuts implemented.

The accepting a new aircraft task is activated when a new aircraft is assigned to the controller. A decisions should be made whether the extra aircraft can be handled or not.

Activate: A new aircraft is assigned to the team of controllers.

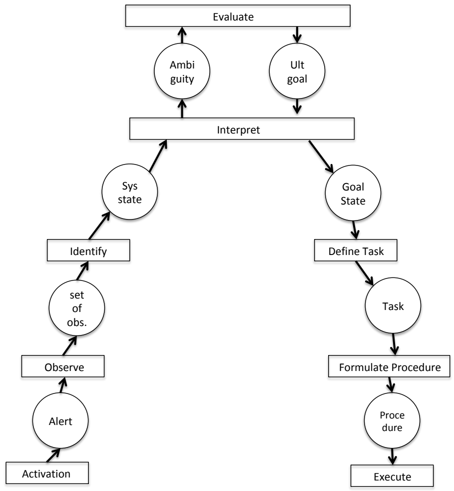

Fig. 4. Decision ladder

Observe: Gather information about the flight (e.g. flight plan, aircraft type, etc.)

Identify: Determine whether the additional workload of the aircraft can be handled.

Interpret: Determine the effects of accepting this aircraft for the other aircraft under control.

Evaluate: Choose to accept or decline the aircraft .

Task Definition: Define the procedure for accepting or declining the aircraft.

Procedure Evaluation: Determine the procedure for accepting or declining the aircraft.

Execution: Decline or accept the aircraft.

B. Distributing the Aircraft within the Team of Controllers

Since there are no tools developed yet for the task of distributing the aircraft within the controller team, the decision ladder is as depicted in Figure 4. This task involves the distribution of the aircraft between the members of the team. This division will be dependent on the responsibilities of the team members in the sectorless ATM environment.

This task is activated when an aircraft that is controlled by a team of controllers requires an action to be completed. The team should then decide who will be responsible for this aircraft and then make sure the action is completed.

Activate: An aircraft under control requires actions.

Observe: Observe what actions should be conducted.

Identify: Identify which controller is responsible for these tasks.

Interpret: Determine the workload of the controller that is responsible for handling the task.

Evaluate: Chose to transfer aircraft to this controller or to conduct the action.

Task Definition: Define the procedure of handling the task.

Procedure Evaluation: Define the steps to be taken to complete the task or transfer.

Execution: Complete task or transfer.

C. Conflict Detection and Resolution

Since tools have been developed to support the controller in the conflict detection and resolution activity, shortcuts between different elements of the decision ladders have been developed, as can be seen in Figure 5. The controller does not need to process the information, but the tool provides the knowledge needed to go from the one state to the other state in the decision ladder.

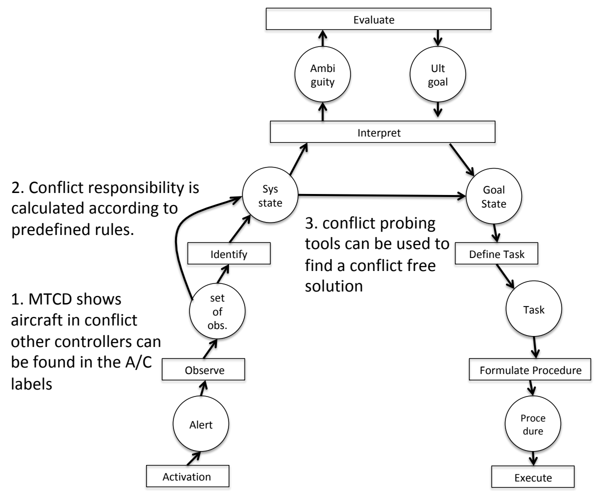

Fig. 5. Decision ladder for conflict detection and resolution

The conflict detection and resolution task gets activated when two aircraft are on a conflicting path. However, the medium term conflict detection tool is made to highlight these situations to the controller, as shown by Shortcut 1. Further the conflict responsibility is automatically calculated with the rules that are applicable in the sectorless ATM environment [15]. The controller has the option to use a conflict probing tool to search for a conflict free solution to the conflict, as indicated with Shortcut 3 in Figure 5.

Activate: An aircraft under control is on a conflicting path with one ore more other aircraft.

Observe: Gather information about the aircraft involved in the conflict and the other controllers involved in the conflict.

Identify: Identify the conflict parameters (closest point of approach, conflict geometry, etc.), conflict responsibility.

Interpret: If responsible for solving the conflict, determine how rerouting the aircraft will affect the other aircraft around it. If not responsible for solving the aircraft determine if the controller responsible for the conflict recognized the conflict.

Evaluate: If responsible for the conflict chose the best available option for solving the conflict. If not responsible for the conflict set a priority to the conflict to monitor it.

Task Definition: If responsible, define the rerouting procedure for the aircraft. If not responsible, define a monitoring strategy.

Procedure Evaluation: If responsible, define the commands to be given to the aircraft. If not responsible, evaluate if a solution has been implemented by the other controller.

Execution: If responsible, communicate the commands to the aircraft. If not responsible, monitor the evolution of the conflict.

D. Adherence Monitoring and Tweaking an Aircraft

Figure 6 shows the decision ladder for the adherence monitoring and tweaking an aircraft task, with the existing shortcuts provided by the existing tools.

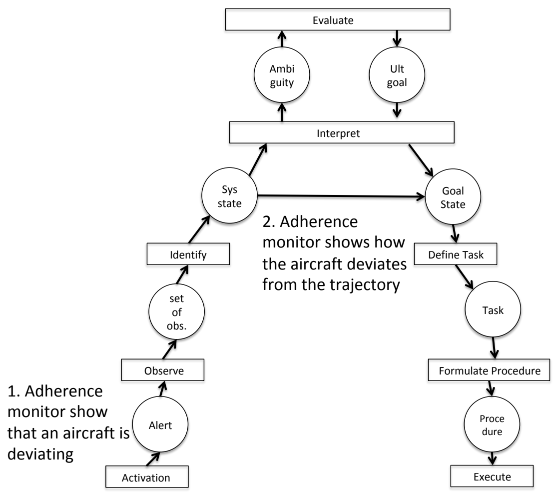

Fig. 6. Decision ladder for adherence monitoring and tweaking an aircraft

This task is activated when an aircraft under control is deviating from its flight path. The first shortcut takes place at the alert state, where the adherence monitor indicates an aircraft that is deviating from its trajectory. The second shortcut can be seen from the system state to the goal state, where the adherence monitor shows how the aircraft is deviating from the trajectory.

Activate: An aircraft under control is not adhering to it's flight path.
Observe: Observe how the aircraft is deviating from its trajectory.
Identify: Identify which aircraft are impacted by this aircraft, identify the constraints for the deviating aircraft.
Interpret: Determine how changing the aircraft's path affects the other aircraft in the airspace.
Evaluate: Chose the best option to redirect the aircraft back on the path.
Task Definition: Define tweaking strategy for the aircraft.
Procedure Evaluation: Define the commands to be given to the aircraft.
Execution: Communicate the commands to the aircraft.

IV. Strategies Analysis

The third step in the cognitive work analysis is the strategies analysis. This analysis focuses on how the tasks identified in the decision ladder may be performed [14]. In the strategies analysis, strategies for performing the control tasks identified in the control tasks analysis are formed.

The main tool used in the strategies analysis is the information flow map. The information flow map is a graphical representation of the information processing activities and knowledge states of a particular strategy [14]. In the figures that follow, the knowledge states are represented by the circles and the information processing activities by the rectangles.

A. Accepting a New Aircraft

The first step in accepting a new aircraft, is to determine the extra workload that can be handled and the workload that the assigned aircraft would require in order to guide it safely through the airspace.

To determine spare capacity of a controller, the aircraft under control and their respective flight plans must be know, as these impose a certain workload on the air traffic controllers. The spare capacity of the controllers can be determined by comparing the maximum workload with the current workload of the controllers.

To determine the extra workload the newly assigned aircraft creates, the flight plan of the aircraft, the aircraft type and the point of entry and exit to the airspace have to be known.

As a final step the extra workload that can be handled and the extra workload the assigned aircraft would impose can be compared to check if the aircraft can be accepted. Depending on the outcome of this comparison, the aircraft gets accepted or declined.

The information flow map is visualized in Figure 7.

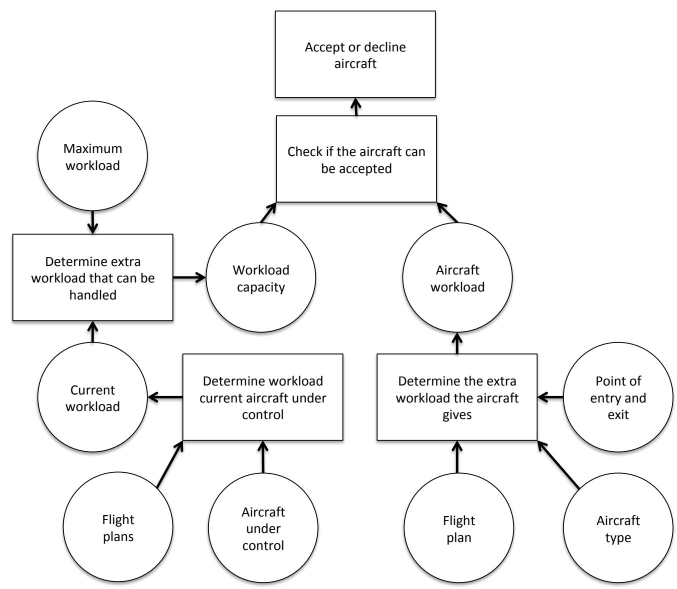

Fig. 7. Information flow map for accepting a new aircraft

B. Distributing the Aircraft within the Team of Controllers

In Figure 8 the information flow map of the distributing aircraft within the team task can be seen.

This task start of with identifying the actions that are to be completed for a given aircraft. Then the controller who is responsible for these given actions has to be determined and

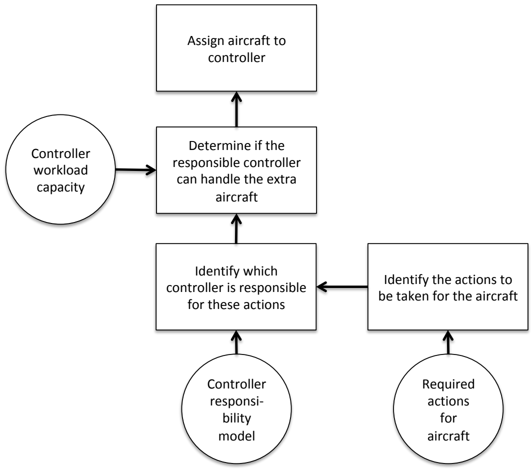

Fig. 8. Information flow map for distributing the aircraft within the team of controllers

if this controller has the capacity to handle more tasks. If the responsible controller can handle the additional aircraft, the aircraft is transferred to him.

C. Conflict Detection and Resolution

As can be seen in the conflict detection and resolution decision ladder, there are two different possibilities: the controllers are either responsible to solve the conflict themselves or they monitor other controllers resolving the conflict. This means there are two information flow maps, one for solving the conflict and one for monitoring the conflict.

Figure 9 shows the information flow map for the case where the team of controllers is responsible for the conflict resolution.

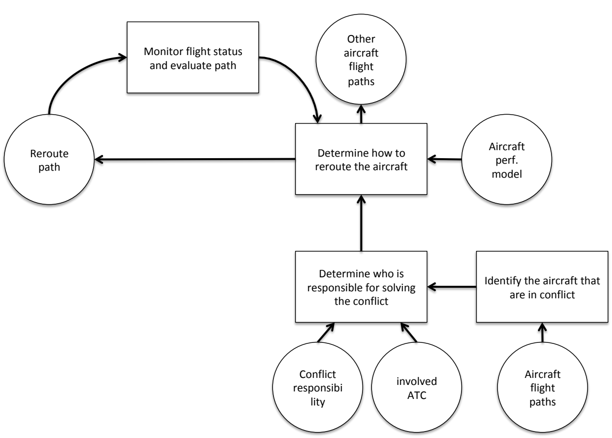

Fig. 9. Information flow map for conflict detection and resolution - team responsible

First the controllers identify the aircraft that are in conflict. The information that is required to do this are the flight plans of all aircraft in the airspace. When they identified the aircraft that are involved in the conflict, they have to identify the controller team that is responsible for solving the conflict.

Since the team of controllers is responsible for solving the conflict, they find the best possible solution to reroute the aircraft. For this they require the flight plans of the aircraft in the airspace as well as the aircraft's performance model.

Finally, the controllers need to monitor the flight status and evaluate the path. If needed, they should change the rerouting procedure to a better solution.

Figure 10 show the situation where the other team of controllers is responsible for solving the conflict.

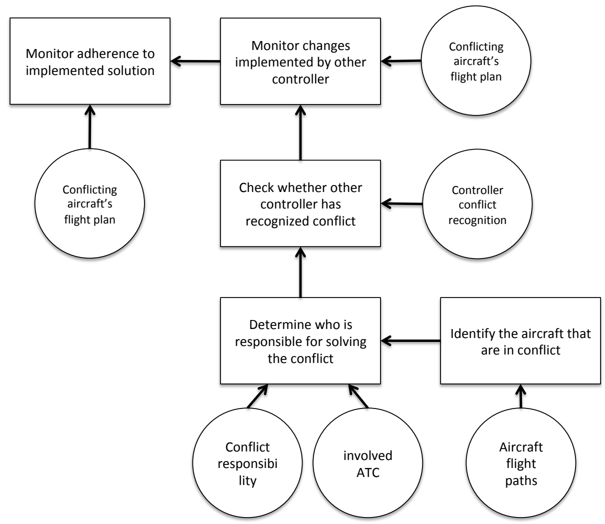

Fig. 10. Information flow map for conflict detection and resolution - other team responsible

After the responsibility has been identified, the controllers should check if the other controllers have recognized the conflict. They then should monitor if the controllers implement a solution and if the aircraft adheres to it.

If the other controllers do not implement a solution to resolve the conflict or the aircraft does not adhere to the implemented solution, the controllers should make the other controllers aware of this situation.

D. Adherence Monitoring and Tweaking an Aircraft

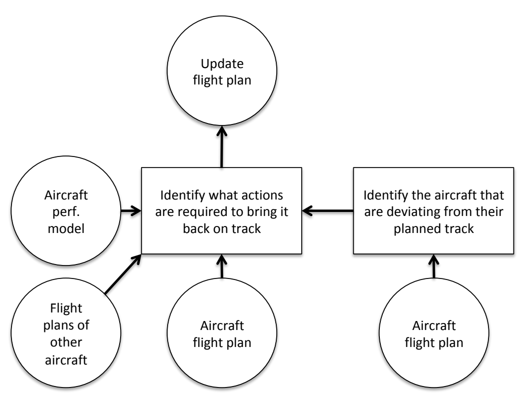

Fig. 11. Information flow map for adherence monitoring and tweaking an aircraft

In Figure 11 the information flow map for the adherence monitoring and tweaking an aircraft task can be found.

The first step is to identify the aircraft that are not adhering to their flight path. Then the actions required to bring the aircraft back on its track have to be determined, after which the flight plan will be updated.

V. Discussion and Future Work

From the cognitive work analysis of the sectorless ATM environment, it can be concluded that changes do occur with respect to the current ATM environment. The main changes are that there is a differentiation between the aircraft that are controlled by the team of controllers and those that are controlled by the other controller teams. These changes affect other elements in the work domain, like the communication between the controllers, the ways obstacles are defined, etc.

The control tasks that are important within the sectorless ATM environment have been defined and analyzed with the help of the decision ladder. From this it could be see that tools currently exist to assist the air traffic controller in both conflict detection and resolution and adherence monitoring and tweaking an aircraft's flight path. However, support is lacking on the tasks of accepting a new aircraft and the distribution of the aircraft within the team of controllers.

Finally, the information flow that is needed to complete the tasks defined in the control task analysis was defined with the help of the information flow maps.

Future work on the implementation of teams to the sectorless concept will focus on providing the tools and displays necessary to support the controller in all the tasks that have been identified in this cognitive work analysis. Theses tools will be based on the shortcomings identified in the control task analysis and will provide the information identified in the strategies analysis.

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