Abstract

The growing complexity of air traffic flows around major airports requires improvements in decision-making strategies if these flows are to be processed safely, comfortably, and efficiently in the near future. While support tools currently typically focus on minimization of traffic delays, multiple criteria need to be taken into account such as high fuel efficiency, low noise production, and more accurate aircraft spacing. In this paper a method is discussed to enable a computational process based on a genetic algorithm to be used to increase the air traffic controller's awareness with respect to key performance criteria and to support the process of decision making. To optimally tune the underlying decision logic to human information processing and decision making, the principles of satisficing decision theory and naturalistic decision making are integrated into the search algorithms and method of information processing. It is expected that communicating the output of this decision logic in a human-centered format will help controllers to efficiently make decisions that yield higher multi-objective performance under realistic conditions.

Keywords: Air Traffic Planning, Naturalistic Decision Making, Satisficing Decision Making, Situation Awareness, Human-Machine Interaction.
1 Introduction
Along with the growing size of air traffic demand at major airports, the complexity of traffic flows is significantly growing. Besides the expected increase in the number of aircraft movements, other factors contributing to increasing complexity are environmental regulations and more advanced on-board aircraft equipment, which allows the aircraft and the flight crew to safely follow a more efficient but often more complex flight path. Such a flight path may involve for example more turns or a descent profile as preferred by the airline or pilot.

Currently, several automated decision support systems are already in place in Air Traffic Control (ATC) centers, such as for example the Center-TRACON Automation System (CTAS). These systems are particularly useful in arrival and departure management where the traffic situations are most complex. Generally, these decision support systems give advisories to achieve optimal performance with respect to one criterion (e.g., system delay). However, with the growing level of complexity faced it becomes necessary to consider many more performance criteria, yielding a solution search process that will be increasingly difficult to be carried out by humans efficiently and safely. At the same time the growing need for more shared situation awareness between pilots, controllers and other components of the system (Farley et al, 1998) makes more data available and poses additional requirements to solutions.

Increased use of computer-based support promises to be able to help humans in finding good solutions in these difficult circumstances. However, when dealing with such multi-objective problems it becomes important to define the relative importance of meeting the different criteria and complex choices will have to be made. This paper suggests a method to use computer-based decision support for arrival flow managers and controllers in multi-objective decision making, where we aim for increasing the awareness of controllers in the traffic situation instead of suggesting ‘optimal’ courses of action. The paper addresses respectively the different performance factors that need to be considered, the question of how solutions should be generated and how they should be searched for, and some simulation results of an implementation of the suggested methods to demonstrate the difference between classical optimization and an approach based on aspiration levels or satisficing decision theory for this domain.

2 Performance Factors in Short-Term Traffic Planning
Planning and regulating traffic flows requires taking into account multiple and usually competing objectives. These objectives are to be met by distributed control actions, e.g. scheduling and vectoring by air traffic controllers, fleet management by airlines and planning of and complying with reference trajectories by pilots.

Safety and efficiency can be considered as the main objectives of arrival and departure management, albeit that safety is more critical than efficiency. Improvements are necessary though to continue meeting these objectives in the future. The key performance areas on the airside in which improvements are required have been identified to include (Fron, 2001): peak hour capacity, punctuality, cost efficiency, predictability, and environmental sustainability. These objectives are generally conflicting but controllers currently do not have all information available to clearly and intuitively understand all the trade-offs.
The different objectives are here taken into account as follows. By continuously minimizing overall system delay a high level of punctuality can be achieved in the short-term planning through timely arrivals and departures. Therefore, minimizing delays is generally considered as the appropriate strategy to obtain both high capacity and high punctuality. Also, because taking into account user-preferred trajectories better is considered a major requirement in future air traffic management (IATA, 1996) it is already anticipated that future flight plans will incorporate preferred climb/descent airspeeds and climb/descent gradients (Warren, 2000). Trying to implement speed and altitude profiles filed by the flight crew is therefore considered a feasible strategy to achieve higher cost efficiency. Finally, environmental impact is concerned with emission exhausts, external safety and noise exposure levels, where especially the latter has become a significant factor limiting airport capacity. Environmental impact is captured in a new quantity named ‘area load’ which takes into account a penalty factor on solutions where traffic crosses a populated area below a certain altitude.

3 Designing for Human-Centered Automation

3.1 Multi-Objective Optimal Control and Satisficing Decision Theory
The concept of multi-objective optimal control and the concept of satisficing decision theory, as discussed for example by Goodrich et al (2000), are closely interrelated and can both be used in automation tools to find solutions to complex problems. However, there are important differences between these two concepts as well.

In traditional decision support methods the approach has usually been to generate a range of options, identify evaluation criteria, calculate the results, and select the option with the highest score. This approach can easily be linked to either single-objective or multi-objective optimal control. In this approach the separate contributions from different performance factors are usually combined using weight factors into an aggregate performance index. This approach was explored earlier (Vormer et al, 2002).

However, it is in most operator-controlled domains difficult to determine true ‘optimal’ solutions, because it is difficult to define what optimality really means and to identify all factors influencing a controller’s decision. Because the automated system does not have all the necessary information it is not possible to decide what is truly optimal: the system is constrained because of its bounded rationality. Furthermore, a generated solution may qualify as an optimal solution using an aggregate performance index but may give such a poor performance on an individual performance factor that this solution is highly undesirable. Closely related to this is that in presenting the information resulting from the solution search process it is crucial to show how acceptable a solution or a situation is because this is used in priority scheduling by human operators.

In most decision-making processes in real life human operators are primarily interested in solutions that meet the demands and that do not violate the constraints. For ATC, these constraints are determined by separation minima, weather, standard procedures, expected level of efficiency, etc. Finding an ‘optimal’ solution is a secondary task. This is exactly the main difference between optimal control and satisficing decision theory: the satisficing approach gives a set of acceptable solutions whereas the optimal approach does not necessarily. To fully exploit this approach,
3.2 Supporting Naturalistic Decision Making

The recently emerged principles of Naturalistic Decision Making (NDM) have provided new approaches to the way it is believed experts make decisions in real-life situations (Klein, 1997). The theory of NDM advocates providing more situation awareness and generating better recognition cues for utilizing previous experience. Controllers have encountered many similar situations before and will indeed have an extensive source of experience to draw from. Even so, better support tools will be necessary in the increasingly complex solution space since so many parameters are involved that it is hard or even impossible to determine truly efficient solutions without these tools. This is especially important when new approach paths or different restrictions are introduced.

Under the NDM paradigm, the strategy of presenting different courses of action of different quality randomly, usually the case in looking for solutions to multi-objective problems, is no longer supported. Instead, observations of human decision makers suggest considering improvements to a single solution sequentially. Also, the design of decision support tools should be guided by the formulation of decision requirements based on the specific tasks to be carried out and not on the information available. This is essentially the same as the main guideline of designing ecological interfaces, which dictates manipulation of information at a meaningful abstraction level.

For the problem studied here, the first implication of this theory is that emphasis should be put onto manipulating a single solution, although alternative solutions may be shown in the background so that the controller is aware that other solutions can be switched to if necessary. The second implication is that it is no longer desirable to search for better solutions in a format that is most suitable for the optimization algorithms and the type of information considered. Instead, this process should be carried out in a way similar to how controllers cognitively carry out their tasks and the decision support logic should include controller cognitive and knowledge factors. The third implication is that using an aggregate index in an optimization process is not a suitable method since it does not increase the controller’s awareness and is not consistent with the way controllers are thought to make decisions, since their approach to solution finding certainly does not include aggregation of many factors for large numbers of solutions and then selecting the best alternative. Instead, human operators generally search until criteria are satisfied using NDM to quickly find the most relevant attribute or to learn acceptable composite states.

4 Decision Support by Gradually Improving Solutions

4.1 Starting with Constraints

According to NDM theory, cognitive analysis in the ATC domain is necessary to define what decision requirements exist in the controller’s task. For example, it is well known that controllers continuously read aircraft positions, directions, and speeds and mentally
project aircraft positions. However, the roles of controllers are required to change (Graham et al., 2000) and new decision requirements will emerge when new approaches to solution finding are used. The approaches discussed above emphasize the need for increasing the operator's awareness on meeting performance constraints, which forms one of the potential new decision requirements.

This approach of starting with constraints offers the possibility to let required performance values be established by the parties who are in the best position to formulate the constraints. This follows the line of decision making that has been proposed under the concept of Collaborative Decision Making (CDM), where decisions are made by those in the best position for that decision. It has now become possible to establish a satisficing solution by defining acceptable levels of performance and to determine if the strategies currently used can yield sets of acceptable solutions. This notion of looking for sets of solutions lies at the foundation of satisficing decision theory. Once solutions are found, this method can be used to investigate if it is possible to tighten the aspiration levels and which modifications can yield higher levels of performance.

4.2 The Computational Logic
The solution search algorithm studied here was implemented based on a genetic algorithm, which is a type of algorithm that has been applied widely in complex optimization problems. The developed genetic algorithm generates arrival trajectories and tries to improve the quality of the solutions in a set. This is done by using a solution from the strategic flow planning process (e.g., generated by Eurocontrol) as an initial solution and making modifications in a way similar to biological evolution. In this way strategic flow planning assures that an initial solution can be found. This solution search process is similar to the sequential improvement process advocated by the theory of NDM and thus expected to be compatible with an operator's approach to selecting and improving solutions. For more information about the implemented logic, see (Vormer et al., 2002). Which information about these solutions should be communicated with the operator and in what format is beyond the scope of this paper and part of further research.

4.3 Fast-Time Simulation
A fast-time simulation was carried out to demonstrate the benefits of using the approach based on satisficing decision making for this particular domain versus classical optimization approaches based on aggregate performance metrics. In the simulation the computational logic makes arrival flow plannings into a two-runway airport for a period of 10 minutes ahead. The performance factors considered are those identified earlier: delay, deviation from altitude and speed profiles as filed by the flight crews, and area load (all calculated for an entire planning, which corresponds to one solution). An example is given in Figure 1 where it can be seen how the fitness of the solutions changes as the solutions are modified from generation to generation. The fitness is calculated based on an aggregate performance index, which is in turn based on directly combining the separate performance scores. While the level of convergence of the best score seems to be high, other solutions were found with a lower fitness that did exhibit higher scores on individual performance factors than the optimal solution.
Selecting solutions based on required performance values on the other hand would filter out acceptable solutions, leaving the controller to continue looking for better solutions only if it is possible to allocate the additional efforts involved. For the same numerical example the separate performance scores are plotted in Figure 2 for all generated solutions (the genetic algorithm evaluates all solutions in the set continuously, making its way from left to right in the figures as the process continues). All individual scores were normalized with respect to the scores observed in one particular solution found so that values below 1 indicate that the performance on that particular factor of the recorded solution is met. It can be observed that the objectives are indeed highly competitive, that there is significant trade-off present, and that high fitness scores not necessarily correspond with good performance on individual factors.

![Figure 1. Development of the fitness function based on aggregate performance.](image1)

![Figure 2. Scores on individual performance factors.](image2)
5 Conclusions
A framework was discussed to allow computational support algorithms to be used in air traffic planning taking into account multiple objectives. Several disadvantages of using an aggregate performance index for obtaining solutions were identified and it was emphasized that for the type of tasks considered it is more important to meet aspiration levels for performance indices than optimizing the performance. Simulation results were used to demonstrate the disadvantages of using aggregate performance optimization and to stress that using satisficing decision theory would be much more appropriate in this domain. Using this approach the solution search process should start with the constraints, generate solution sets, and then have the operator select the one that is most appropriate for the situation. This allows controller knowledge to be taken into account, bringing factors into the decision that may not be known or used by the automation logic. By increasing awareness on the performance related to different factors the process of NDM is supported and controllers can be assisted in determining the most important attribute in a particular situation or to learn acceptable states of the performance distribution. The framework of the decision support tool based on a genetic algorithm can be used to identify acceptable solutions and to further explore and improve a solution where the controller works iteratively with the decision support tool to mutually evolve towards an acceptable solution.

6 References