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TAPAS

TOWARDS AN AUTOMATED AND EXPLAINABLE ATM SYSTEM

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Abstract

This document provides a description of the Visual Analytics components of the prototype systems that have been implemented in the context of TAPAS, addressing the requirements of the two use cases: Air Traffic Flow and Capacity Management (ATFCM) and Conflict Detection and Resolution (CD&R). The document refers to the descriptions of the use cases provided in D4.1. The illustrations were created using the example data sets that are exploited within the project. The document describes the overall design of the Visual Analytics components of the ATFCM and CD&R prototype systems, the functionality of the VA modules, and their integration within the TAPAS architecture.

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1 Executive Summary

Visualisation and interactive visual interfaces are very important for enabling human understanding of data, computer operations, and computer-generated results. In particular, interactive visual interfaces are necessary for supporting explainability of ML/AI methods by presenting information about how the method works in the form that is easily perceived and understood by humans [[1]]. This document describes the Visual Analytics component of the integrated TAPAS system (prototype) that addresses the ATFCM use case and the CD&R use case. The VA component works in combination with the ML/AI components, which detect or predict problematic situations and develop appropriate solutions. The VA component supports understanding and exploration of the problems and the solutions.

The VA components were developed in accordance with the specification of the ATFCM and CD&R tasks and functional requirements provided in the TAPAS deliverable D2.3 “Consolidated requirements and functional roadmap”. The development process was also guided by the transparency requirements specified in the TAPAS deliverable D3.1 “ATFM transparency requirements” and D3.2 “CD&R transparency requirements”.

The VA techniques are intended to be used for the following purposes:

- Understanding of problematic situations requiring solution, such as demand-capacity imbalances.
- Exploration and understanding of solutions developed by the ML/AI component and the process of the solution development.

For the two use cases of TAPAS, different VA components have been developed. For the ATFCM use case, the VA component includes two modules providing different levels of abstraction and details:

- Solution Explorer: high level of abstraction and low level of detail. It is meant for gaining overviews of scenarios (the term “scenario” refers to the set of flights and evolution of the use of the airspace over a day), identifying major differences between scenarios, and tracking major changes along the process of solution development.
- Sector Explorer: lower level of abstraction and higher level of detail. Unlike Solution Explorer, Sector Explorer shows information about individual flights.

In the CD&R use case, the task of the VA component is to inform the users about imminent conflicts between flights that have been predicted by the XAI component and present the conflict resolution actions proposed by the XAI component. This needs to be done in real time while the current situation constantly changes. The VA component consists of a single module providing several complementary views: a table describing conflicts detected by the XAI component, a graphical view providing a schematic representation of conflict geometry, and a table with conflict resolution actions proposed by the XAI component.

The document describes the functionality of the VA modules, the contents and appearance of the visual displays, and the interactive operations. It also describes examples of the use of the interactive visual interfaces.

1.1 Intended Readership

This document is intended to be used by:

- SJU
- TAPAS project members
- SESAR2020 and international research community addressing automation in Air Traffic Management and Artificial Intelligence / Machine Learning.

1.2 Terminology and Acronyms

Term	Definition
AI	Artificial Intelligence
ATC	Air Traffic Control
ATCo	Air Traffic Controller
ATFCM	Air Traffic Flow and Capacity Management
ATM	Air Traffic Management
CD&R	Conflict Detection and Resolution
DCB	Demand and Capacity Balancing
DL	Deep Learning
EC	European Commission
HEC	Hourly Entry Counts
LTM	Local Traffic Manager
ML	Machine Learning
NM	Network Manager
NOP	Network Operations Plan
MDV	Multivariate Data Visualization
OCC	Occupancy Counts
SESAR	Single European Sky ATM Research
TAPAS	Towards an Automated and Explainable ATM System
VA	Visual Analytics
XAI	Explainable AI

2 Visualisation and Visual Analytics for the ATFCM Use Case

This chapter describes the visual analytics modules developed for the ATFCM use case (Air Traffic Flow and Capacity Management). The VA component works in combination with the ML/AI component in an integrated prototype. The ML/AI component develops solutions for demand-capacity imbalance problems. The VA component supports exploration of the problems and the solutions.

The VA component was developed in accordance with the specification of the ATFCM tasks and functional requirements provided in the TAPAS deliverable D2.2 “Consolidated requirements and functional roadmap” (Sections 4.1, 7.2). The development process was also guided by the transparency requirements specified in the TAPAS deliverable D3.1 “Use cases transparency requirements” (section 4.2). The scientific aspects of the developed VA approach are described in a published paper [[2]].

2.1 General description

In the integrated system, the VA component is intended to be used for the following purposes:

- Understanding of problematic situations requiring solution, such as demand-capacity imbalances and imminent conflicts (losses of separation) between flights.
- Exploration and understanding of solutions developed by the ML/AI component and the process of the solution development.
- Exploration and understanding of the explanations of the decisions taken by the ML/AI component.

In the following, we shall use the term *scenario* to refer to the evolution of the *real or expected* air traffic situation within a certain region (such as the airspace of Spain) over a day. The traffic information comes from the XAI prototype, but, potentially, it can also come from other sources.

A scenario includes all flights taking place over the day and the evolving division of the region into sectors (i.e., sector configuration plan). For each flight, it is known which sectors it enters in which time intervals. This allows to determine the loads of the sectors (i.e., the temporal frequency distribution of the sector entries) and compare the loads with the sector capacities.

At the most general level, the VA component supports the following analytical tasks:

- Gain an **overview** of a single scenario.
- **Compare** two or more scenarios that involve the same set of flights.
- Understand the process of **solution development**, i.e., see how the ML component modifies the flight plans and resolves the hotspots. Each step of the solution development is represented by a scenario based on the modified flight plans.
- **Investigate details** for selected scenarios, sectors, time intervals, and subsets of the flights.

The VA component consists of two modules providing different levels of abstraction and details:

- **Solution Explorer:** high level of abstraction and low level of detail. It is meant for gaining overviews of scenarios, identifying major differences between scenarios, and tracking major changes along the process of solution development.
- **Sector Explorer:** lower level of abstraction and higher level of detail. Unlike Solution Explorer, Sector Explorer shows information about individual flights.

2.1.1 Technical details

The source codes of the VA component are stored at GitHub (<https://github.com/>). Below are the links to the modules of the VA component:

- <https://github.com/gandrienko/Tapas>
- <https://github.com/gandrienko/TapasSolutionExplorer>
- <https://github.com/gandrienko/TapasSectorExplorer>
- <https://github.com/gandrienko/TapasDataReader>

VA component operates with the following data:

- One or multiple scenarios:
 - For each scenario, there is a set of flights. Each flight has a unique identifier and a corresponding set of records specifying the identifiers of the crossed sectors and the time intervals when the sector entry takes place.
 - The scenarios may, in particular, represent results of different runs of the ML/AI component (e.g., obtained using different algorithms or parameter settings) or results of multiple consecutive steps of developing a solution in one run of the ML/AI component.
- Capacities of the sectors.

2.1.2 Extended range of applicability

The VA modules supporting exploration of scenarios can be used not only in combination with the ML/AI component but also separately. Possible applications include:

- Exploration of a set of flight plans (original or modified by demand-capacity measures) or actually flown flights for one day.
- Comparison of different versions of flight plans or flight plans and actually flown flights for the same day.
- Comparison of sets of flight plans for different days. For this way of use, it is necessary to generate additional flight identifiers which will be common for the same flights conducted in different days.

2.2 Solution Explorer

2.2.1 Task: gain an overview of a scenario

To gain an overview of one scenario, Solution Explorer proposes a table view demonstrated in Fig. 1. The columns of the table correspond to sectors and the rows to *hourly time intervals*. The time shift between the intervals (also called “time step”) is 20 minutes.

Please note: The labels of the rows indicate only the beginnings of the time intervals, i.e., 00:00, 00:20, 00:40, 01:00, 01:20, and so on. It should be remembered that the length of each interval is always 1 hour, because the current practice is to measure the demand and capacity of a sector as the number of flights per hour. All aggregates are computed for time intervals of this standard length.

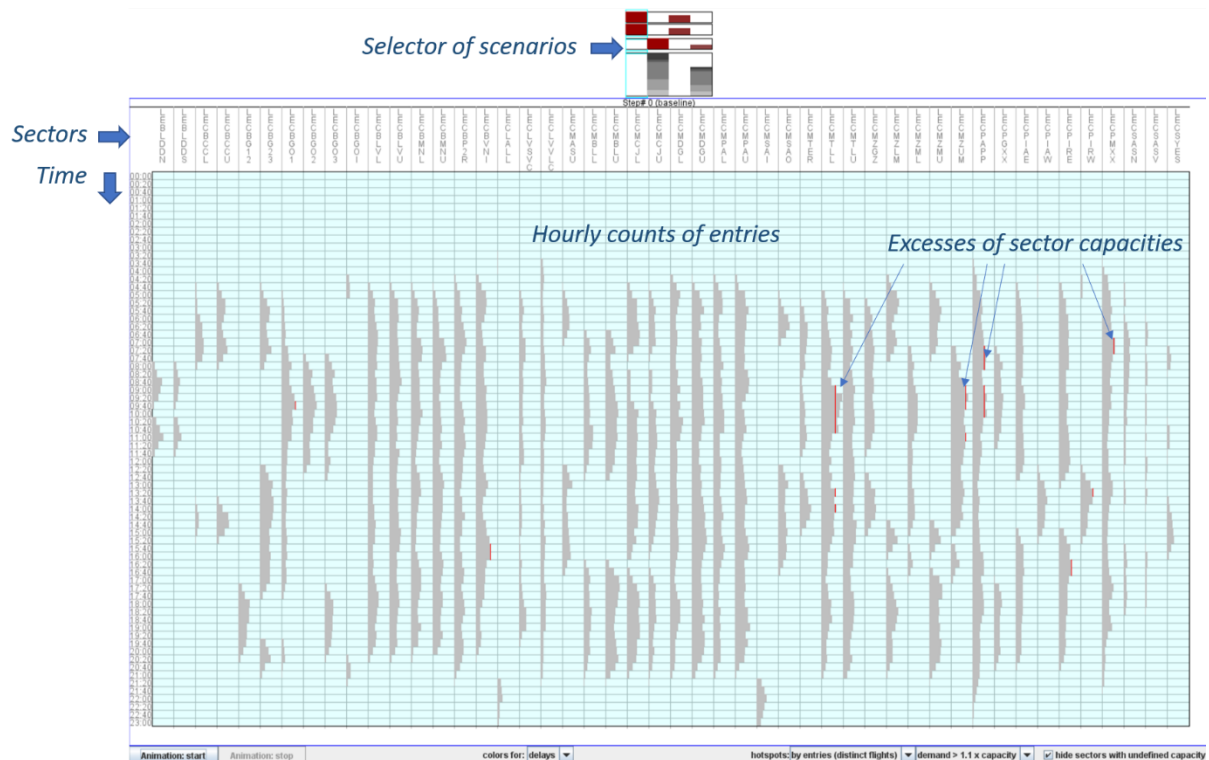


Figure 1. An overview of a scenario. Upper part: selector of scenarios. In this example, there are 4 scenarios. Lower part: a table view with columns corresponding to sectors and rows to time intervals.

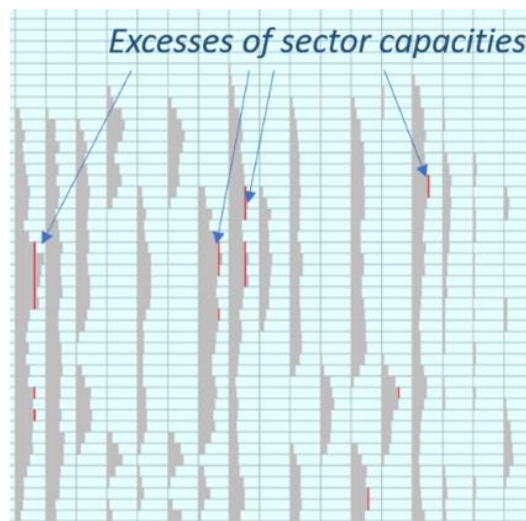


Figure 1a. An overview of a scenario: an extract from the image (Fig.1) in higher details. Red lines indicate demand exceeding capacity.

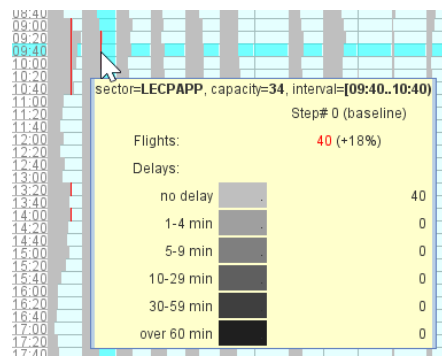


Figure 2. A popup window appearing when the mouse cursor points on a table cell shows aggregated information about the flights entering one sector during one time interval.

The cells contain horizontal bars with the lengths proportional to the counts of the flights that enter the sectors in the 1-hour intervals corresponding to the rows. Where the number of the entries is over 110% of the sector capacity threshold, the cell contains a red vertical line crossing the bar showing the counts of the entries. The horizontal position of the line within the cell corresponds to the sector capacity; hence, it is possible to compare the capacity with the demand and judge the amount of excessive demand. Of course, the visual representation enables only approximate judgements. Precise numbers can be seen when the mouse cursor is positioned on a cell. Detailed information about the corresponding sector and time interval is shown in a popup window, as demonstrated in Fig. 2.

When the scenario represented in the table view involves delayed flights, the bars inside the cells are divided into segments corresponding to different durations of the delays. The segments are painted in different shades of grey, so that darker shades correspond to longer delays. The general appearance of a table view with segmented bars is shown in Fig. 3. The intervals of the delay duration represented by bar segments and the shades corresponding to these intervals can be seen in the popup window in Fig. 2. Pointing with the mouse cursor on the caption of a table column invokes a popup window showing aggregated data about the corresponding sector for the whole day, including the numbers of the flights with different durations of the delays; see Fig. 4.

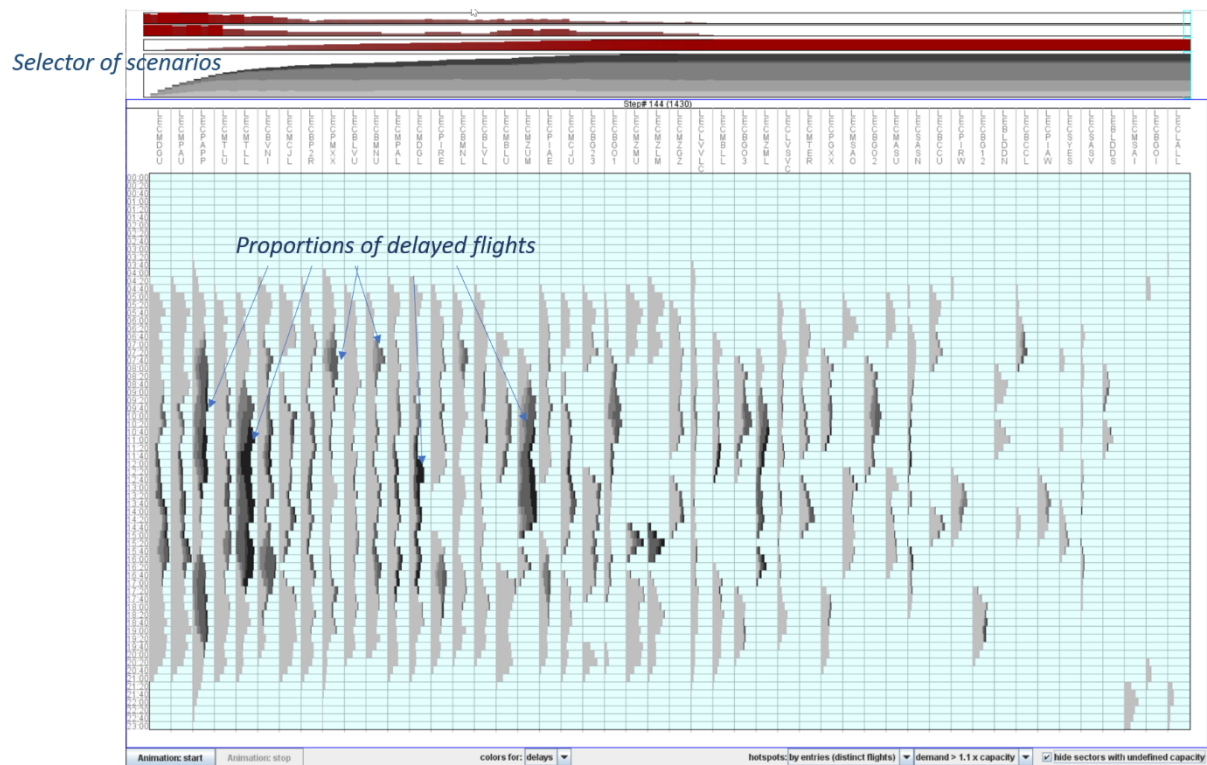


Figure 3. An overview of a scenario involving flight delays. The selector of scenarios includes 145 scenarios corresponding to different steps of the solution development by the ML component.

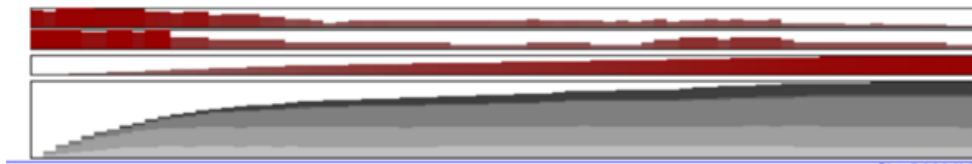


Figure 3a. An extract from Fig.3 shown in higher details. The horizontal dimension corresponds to the sequence of iteration steps of the solution development. Three histograms in red show the counts of hotspots, counts of sectors with hotspots, and accumulated delays in each of the iteration steps. Segmented bars in different shades of grey indicate proportions of delayed flights with different durations of delays.

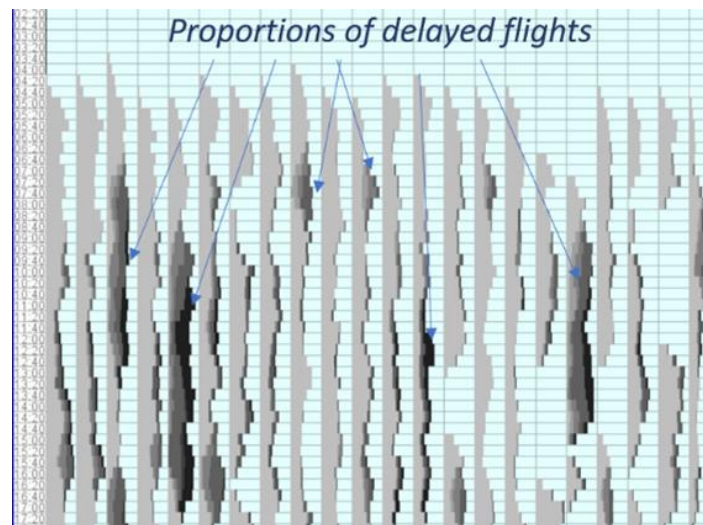


Figure 3b. An overview of a scenario involving flight delays: an extract from the image (Fig.3) in higher details. Segmented bars of different shades of grey indicate proportions of delayed flights with different delay durations. Light grey corresponds to non-delayed flights; the darkness increases proportionally to the delay duration.

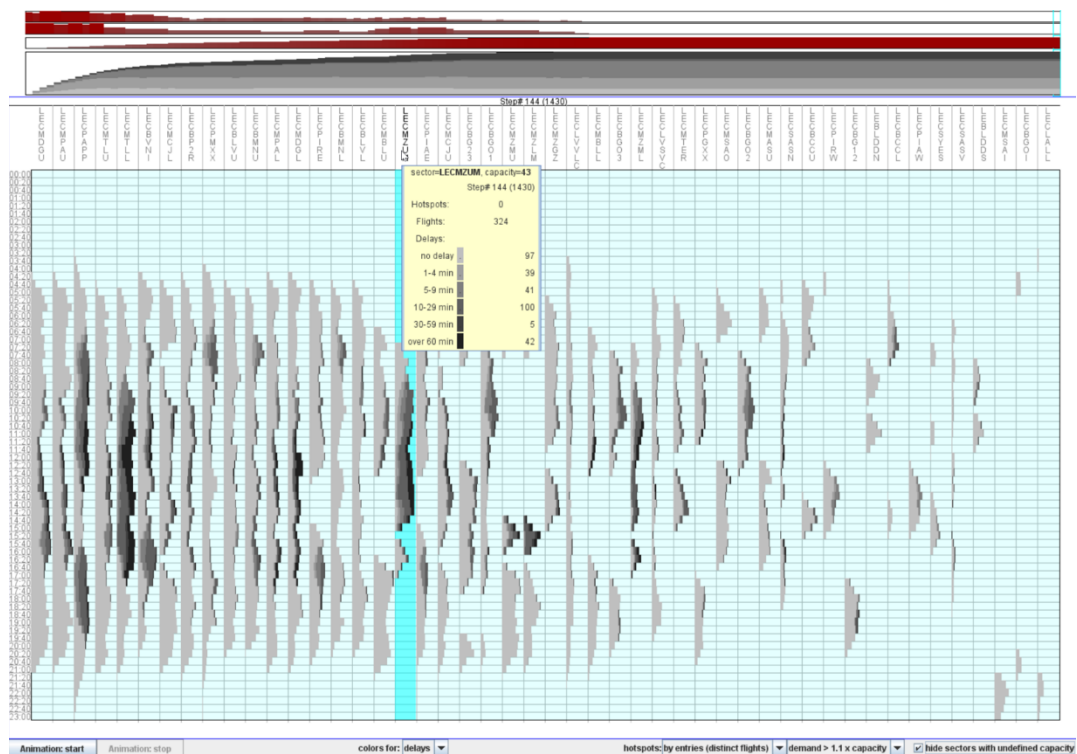


Figure 4. A popup window appearing when the mouse cursor points on a table column caption shows aggregated information about the flights entering one sector during the whole day.

Clicking on column captions or cells in the table view makes the respective columns selected or deselected. Selected columns have bright cyan background, as can be seen in Fig. 5.

Pressing the right mouse button inside the table view invokes a popup menu shown in Fig. 5. The menu provides access to the functions for sorting and selecting sectors and, respectively, the table columns.

In particular, when several sectors are selected, it is possible to use the function “show only selected”, which hides the table columns presenting the sectors that are not selected and distributes the whole width of the table among the columns presenting the selected sectors. The menu also allows to select the sectors that are connected to the sector whose column contains the mouse cursor.

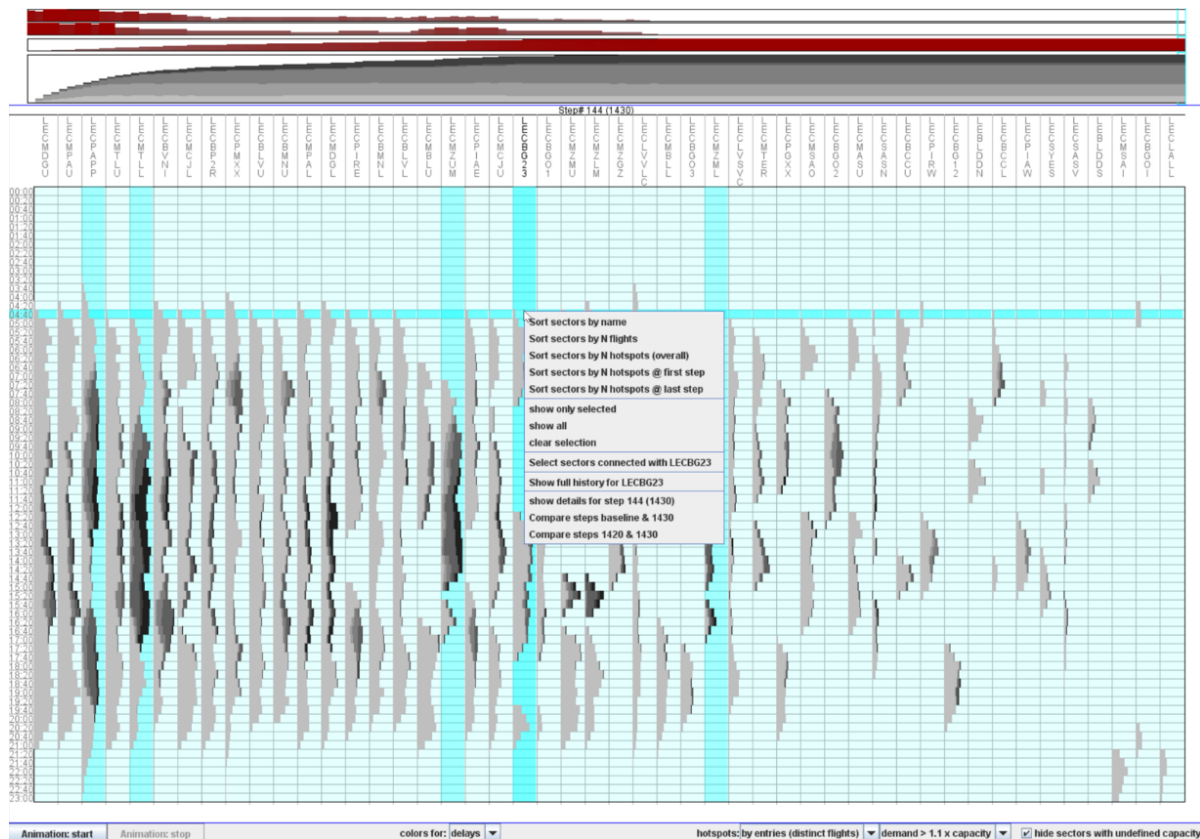


Figure 5. A popup menu appearing upon clicking the right mouse button within the table view provides access to the functions of sorting the table columns, selecting sectors to view, and starting detailed exploration.

Apart from sorting and selecting table columns, the menu also suggests several functions for obtaining more detailed visual representations for selected sectors and/or scenarios. These representations will be introduced in Sections 2.2.3.2 and 2.3.

The section above the table view (see the top parts of Figs. 1-5, except Fig. 2) provides the possibility to select scenarios for viewing and comparison; we shall thus call this part of the display “selector of scenarios” or “scenarios selector”. It contains a highly aggregated representation of several scenarios; each scenario being represented by one column. In the example in Fig. 1, there are four columns. The corresponding four scenarios represent different alternative solutions generated by the ML model. In the example in Figs. 3-5, there are 145 columns. The corresponding scenarios represent 145 consecutive steps of the solution development by the ML component.

The upper part of the scenarios selector contains three rows of red vertical bars whose heights represent for every scenario (1) the counts of the hotspots, (2) the counts of the sectors containing hotspots, and (3) the total amount of all flight delays. The lower part of the selector consists of segmented vertical bars showing the proportions of the flights with different durations of the delay. The duration intervals and the shades in which the segments are painted are the same as in the table view. Precise

numeric information about the hotspots and flight delays of a scenario can be seen in a popup window appearing when the mouse cursor is pointing on a column in the scenarios selector, as shown in Fig. 6.

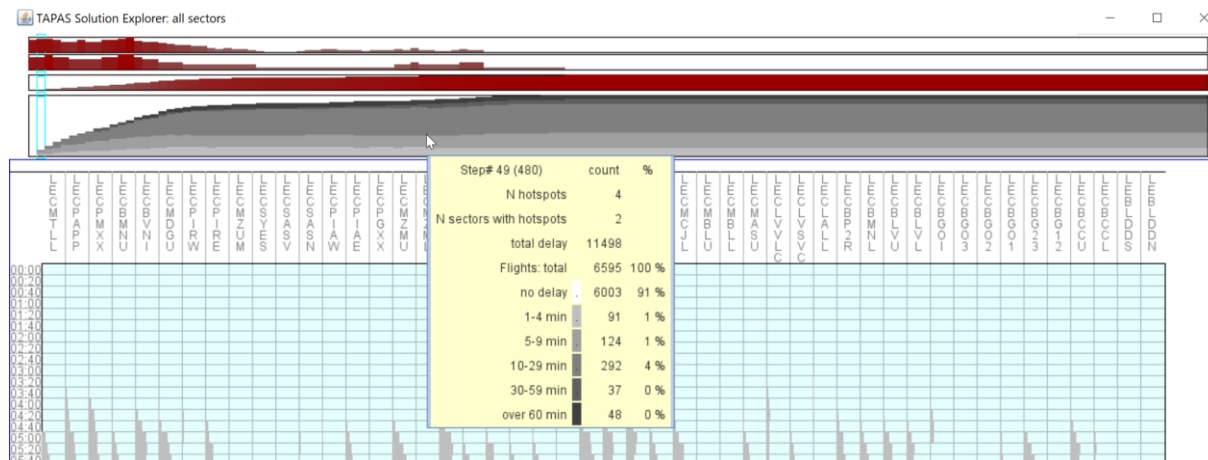


Figure 6. Positioning the mouse cursor on a column in the scenarios selector invokes a popup window showing aggregated information about the hotspots and flight delays of the corresponding scenario.

A scenario can be selected for viewing and comparing with another scenario by mouse-clicking on the corresponding column in the scenarios selector. A user can select as many scenarios as he/she wishes, but it should be taken into account that the width of the display window is divided between the selected scenarios. Hence, each scenario may receive quite a narrow portion of the display space, which can make the view illegible.

The column(s) of the currently selected scenario(s) are marked in the scenarios selector by frames in light cyan, as can be seen in Figs. 1-5 (except Fig. 2). To unselect a selected scenario, it is necessary to click on the corresponding framed column.

2.2.2 Task: compare scenarios at the overall level

High-level comparison of two or more scenarios is supported by juxtaposing the corresponding table views in the display, as shown in Fig. 7. The scenarios to compare are selected through the selector of scenarios as described in the previous section. It may be reasonable to choose subsets of sectors for comparison between scenarios. For example, Figure 8 demonstrates comparison of three scenarios with a focus on a particular sector (LECPiRE) and the sectors connected to it. Two sectors are considered connected when there are flights going from one of them directly to the other.

When two or more scenarios are compared, all popup windows appearing in the table view upon mouse cursor pointing show information about all these scenarios, as demonstrated in Fig. 8.

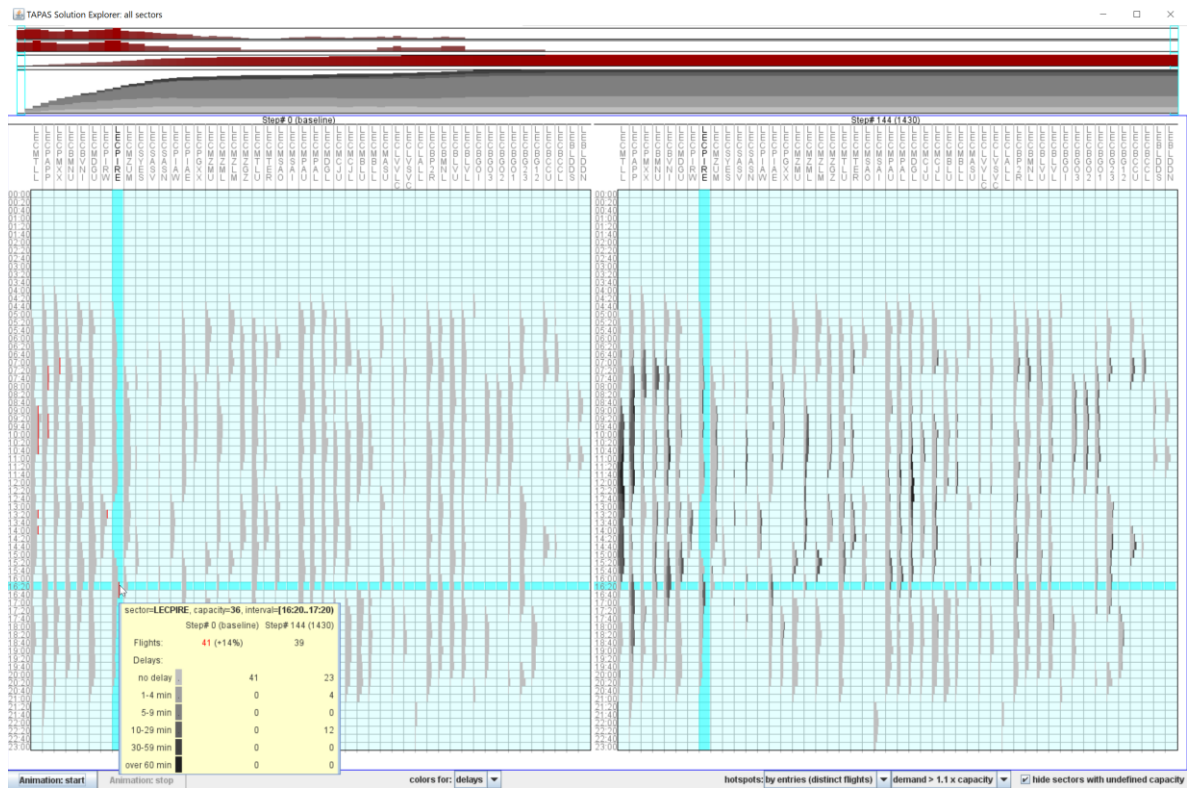


Figure 7. Table views presenting two or more scenarios are put side by side for enabling high-level comparisons.

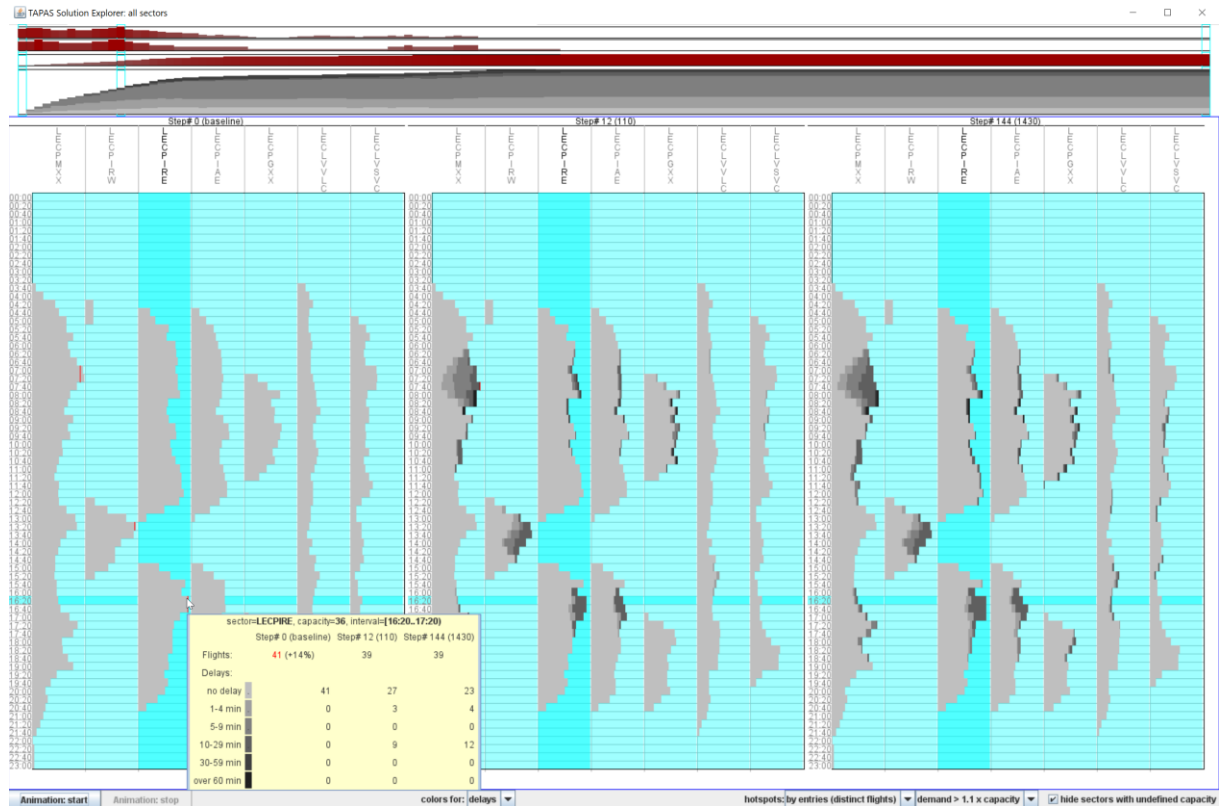


Figure 8. Comparison of three scenarios with a focus on a selected sector and the sectors connected to it.

Founding Members

2.2.3 Task: explore and understand solution development

There are two possibilities for exploring the solution development. One possibility is animation within the overall view of scenarios. In this way, the sequence of changes in multiple sectors can be viewed consecutively. It may be quite hard to investigate the changes thoroughly since each step of the solution development is presented for only a short time. However, the animation allows the viewer to grasp the overall pattern of the development, such as spreading of demands further in time and gradually increasing proportions of delayed flights. The other possibility is to select a single sector and see for this sector the whole sequence of steps at once, i.e., the whole history of changes in this sector. Such a history view can be opened for two or more sectors thus enabling comparisons.

2.2.3.1 Subtask: grasp development patterns in multiple sectors

As mentioned above, this subtask is supported by animation, which is started by pressing a special button in the lower left corner of the window of the Solution Explorer. Next to this button is a button for stopping the animation.

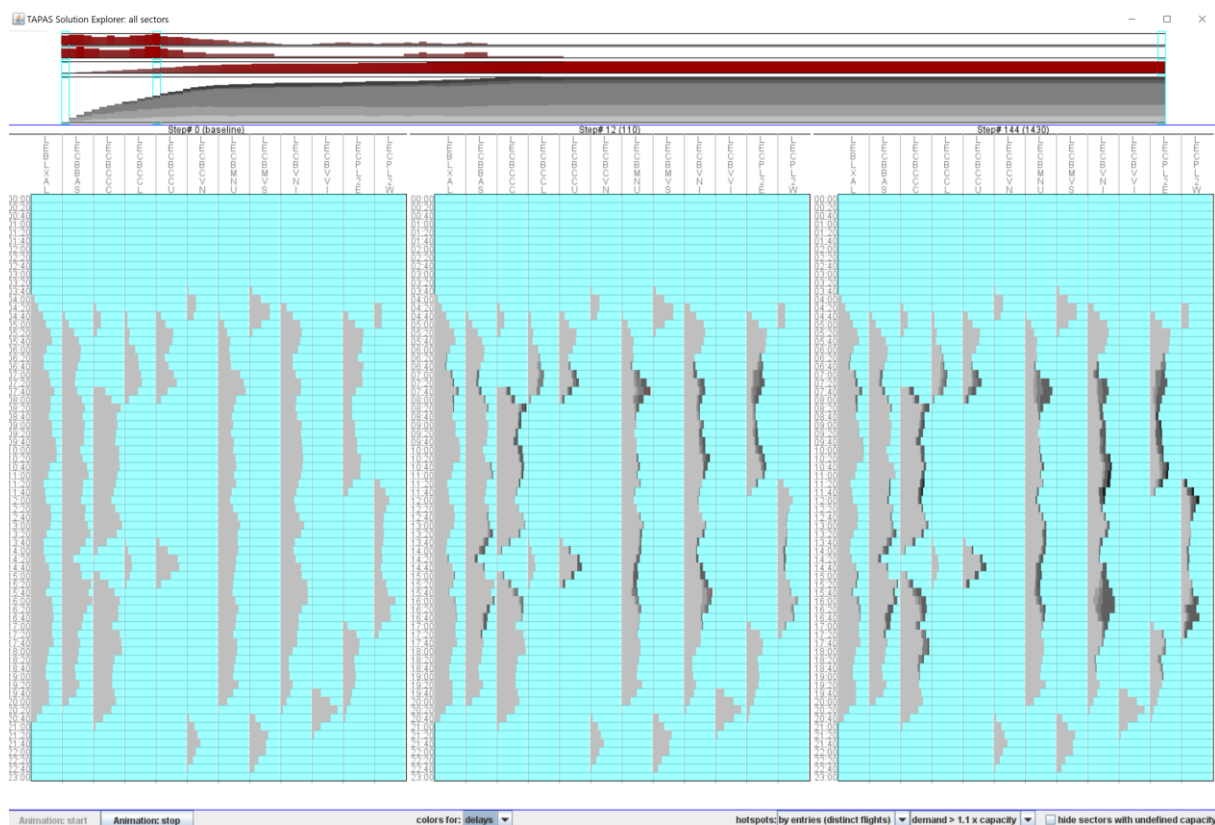


Figure 9. A snapshot from an animated view of solution development. The animation is shown in the central panel while the left and right panels represent the initial scenario and the final solution, respectively. The steps that are currently shown are indicated by frames in light cyan in the selector of scenarios above the table views. The animated and fixed views include a subset of sectors connected to one selected sector.

When the animation is started, a new panel with a table view is inserted in the Solution Explorer window in addition to the panel(s) that existed before starting the animation. This allows to see the progression of the changes in comparison to one or more selected scenarios, which are shown statically. The panels, including the animation panel, are arranged in the window from left to right in the order

of the steps in the solution development. For example, if there are two panels representing the initial scenario (step #0) and the final scenario (i.e., the last step of the solution development), the animation panel will be positioned between them, as shown in Fig. 9. If there is a panel representing step #N ($0 < N < \text{last}$), the animation panel will be initially positioned on the left of this panel until the animation step reaches N. After this, the two panels swap their positions, i.e., the animation panel is put on the right and shows the following steps starting from N+1. The step N is not included in the animation since it is already shown in the fixed panel.

It is recommended not to have multiple fixed panels in the Solution Explorer window before starting the animation; otherwise, the display space allocated to each panel may be too small. It is also reasonable to select a subset of sectors, for example, sectors connected to one selected sector, as demonstrated in Fig. 9. Such a selection can be good for seeing how demands and flight delays are propagated across the set of connected sectors.

Please note: although the contents of the panels representing fixed steps (i.e., the data that are shown) do not change during the animation, the panels may be redrawn from time to time because the scale of the bars in the table cells depends on the maximal value that needs to be encoded by the bar length in the whole window. Since the contents of the animation panel constantly change, the maximal value may differ from step to step, which may require re-scaling of the bars in all panels. Hence, the “fixed” panels are redrawn, which creates an impression of changing contents. This impression should be ignored. The misleading impression could be precluded by scaling the bars in each step according to the overall maximum taken from the whole sequence. However, there may be a single step or a few steps in which the maximal values are much higher than in all other steps. If a very high overall maximum is used for visualizing these other steps, the bars in the visualization will be too small to be visible. Therefore, using the maximum of each step is a better strategy.

2.2.3.2 Subtask: explore the history of changes in a single sector

A display of the whole solution history for a selected sector can be opened using the popup menu shown in Fig. 5. Figure 10 demonstrates the appearance of the history view. It is a table with the rows corresponding to the time intervals along the day and the columns corresponding to the steps of the solution development. The table cells contain *vertical* bars representing flight counts. This is different from the overall view, where the bars are horizontal. The reason for choosing vertical bars to use in the history display is that such bars put in a row enable a better perception of the continuous sequence of changes as the solution develops. Like in the overall view, the bars are divided into differently shaded segments proportionally to counts of flights with different durations of delays. The shades and the duration intervals are the same as in the overall view.

Since the height of the table rows and, hence, the height of the bars is quite small, there is an opportunity to allocate a larger amount of the vertical space to the time intervals when there were hotspots, as shown in Fig. 11. This effect is achieved by checking the check box in the lower right corner of the display window.

When the mouse cursor points on a table cell, a popup window with corresponding data appears, as shown in Fig. 12. The window contents include the demand (i.e., the total count of the flight entries), the flight counts for the different intervals of delay durations, and the numbers of the flights coming from and going to the connected sectors.

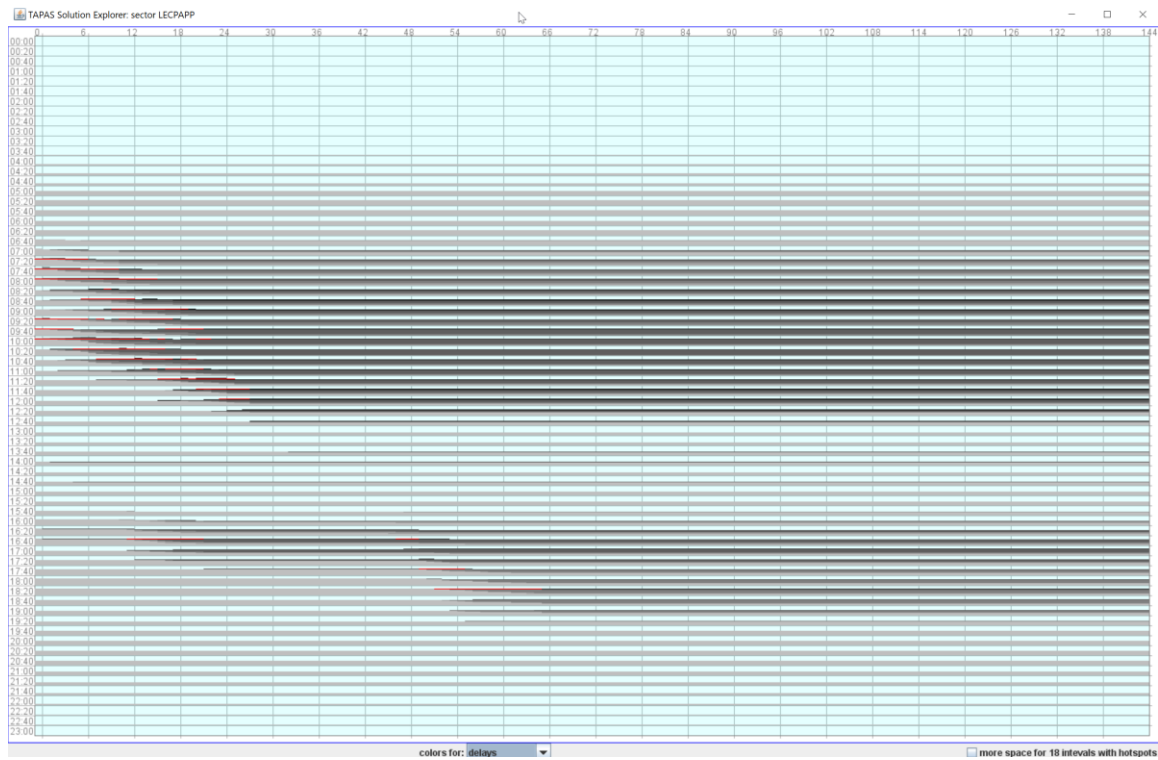


Figure 10. Solution history view for a single selected sector. Rows: time intervals; columns: steps of the solution development; cells: segmented vertical bars encoding flight counts by intervals of delay duration.

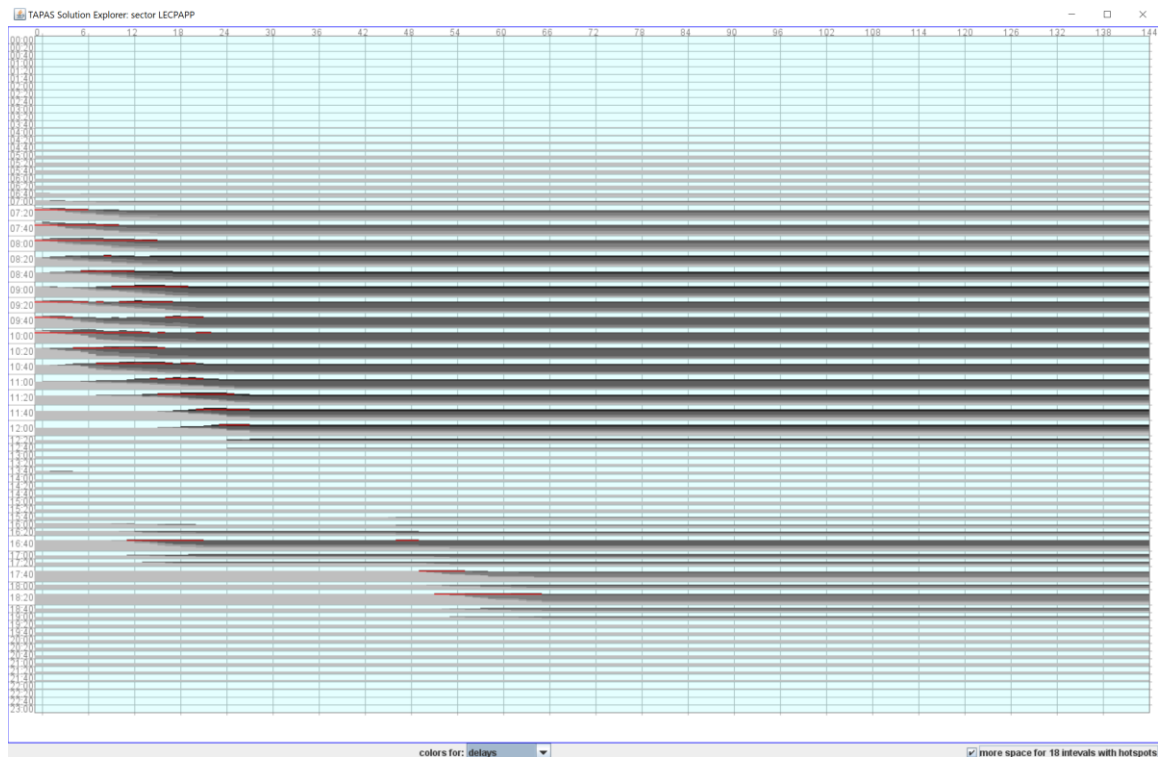


Figure 11. The same view as in Fig. 11 with more vertical space in the display allocated to the time intervals with hotspots.

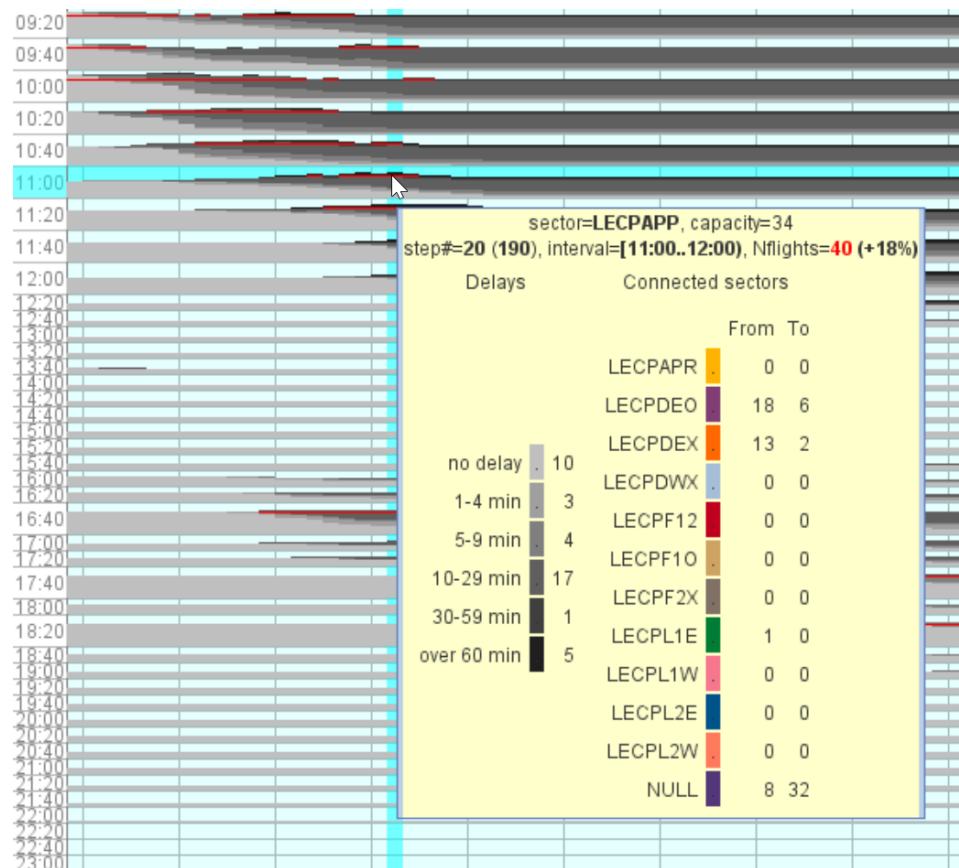


Figure 12. A popup window shows information for the combination of the solution development step and time interval corresponding to the mouse cursor position.



Figure 13. A popup menu appearing upon pressing the right mouse button can be used to open a detailed view of the scenario corresponding to the table column or a detailed comparative view for this scenario together with another one.

Pressing the right button on the mouse when the cursor is pointing on a table column or cell activates a popup menu, as shown in Fig. 13. The menu commands are similar to the commands in the lower part of the menu appearing in the overall view (see Fig. 5). All these commands are used to open a detailed view of a single scenario or a comparative detailed view of two scenarios. Thus, a scenario corresponding to one step of the solution development can be compared to the initial scenario (base-line), the final scenario, and the scenarios of the previous and next steps of the solution development. The detailed view, called Sector Explorer, is described in the following section.

2.3 Sector Explorer

Sector Explorer can present a single scenario or provide a comparative view of two scenarios. Sector Explorer can be started from Solution Explorer using popup menus shown in Figs. 5 and 13. The main components and contents of Sector Explorer can be seen in Fig. 14.

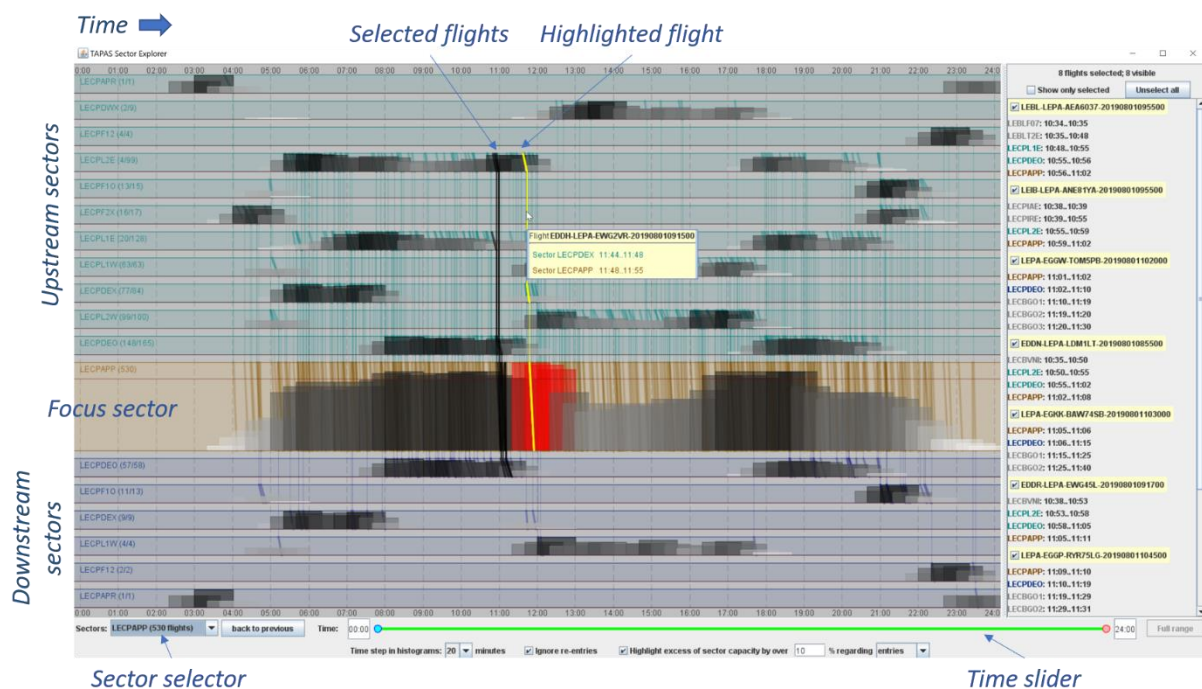


Figure 14. Components and contents of Sector Explorer in the mode of showing a single scenario.

A major part of the display is given to the main view where the horizontal dimension represents time. The time slider below the main view is used for choosing a time interval to be shown with the highest possible resolution, i.e., the whole width of the panel is used for representing this interval, as shown in Fig. 15.

The vertical dimension of the main view accommodates several sectors one of which is considered as the **focus sector**. When Sector Explorer is activated using a popup menu in the main view of Solution Explorer (Fig. 5), the sector in whose column the mouse cursor was at the moment of pressing the right button of the mouse becomes the focus sector. When Sector Explorer is activated from the solution history view (Fig. 13), the sector represented in the history display becomes the focus sector.

The focus sector receives a larger portion of the vertical space of the display than the other sectors. Above the band of the focus sector are the bands corresponding to the upstream sectors, i.e., the

sectors from which flights come directly to the focus sector. The bands below the band of the focus sector correspond to the downstream sectors, i.e., the sectors to which flights go directly from the focus sector. It is often the case that the same sector S is both upstream and downstream with respect to the focus sector F , which means that there are flights going from S to F as well as flights going from F to S . In this case, the display will contain two bands for sector S , one above the band of sector F and another below the band of F . In the example in Fig. 14, all downstream sectors are simultaneously upstream sectors. Therefore, there are bands for these sectors both above and below the focus sector band. However, some of the shown sectors only hand over some flights to the focus sector but do not receive any flights from it. Each such sector is represented by a single band positioned above the focus sector band.

Double-clicking on a sector band puts the corresponding sector in focus. It is also possible to choose another focus sector through the sector selector in the lower left corner of the window. Pressing the right mouse button when the cursor points on the sector selector activates a popup menu with functions for sorting the list of sectors in the sector selector.

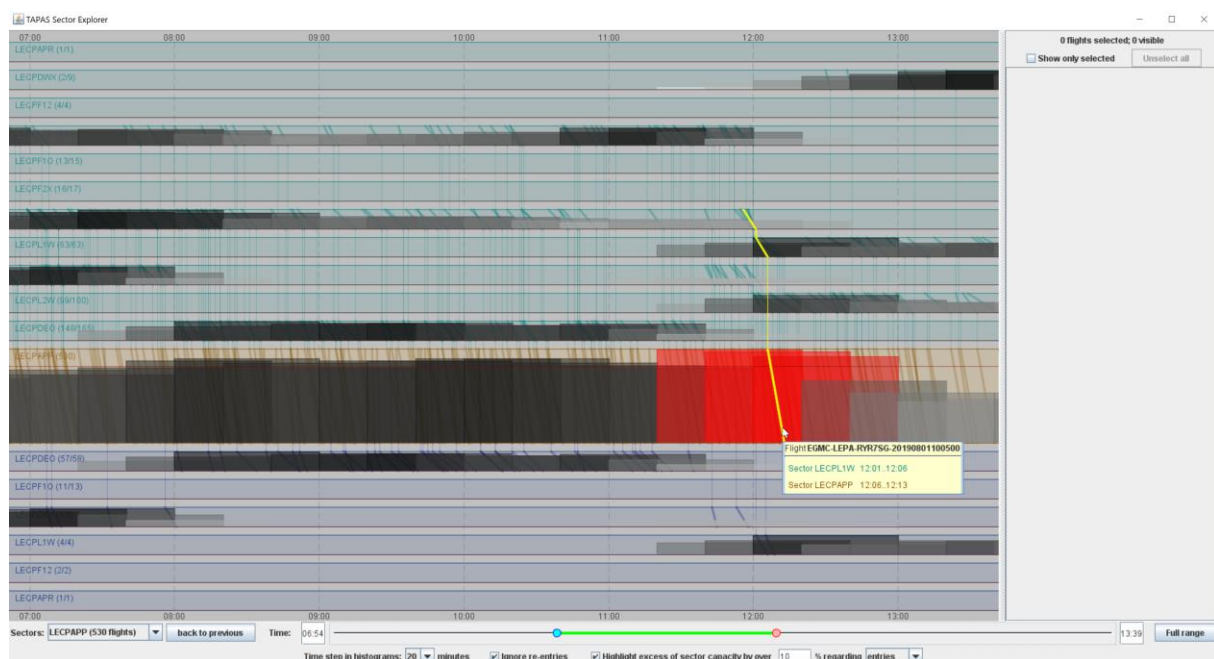


Figure 15. The full width of the main view represents the time interval selected by means of the time slider.

The flights are represented by lines drawn across the sector bands according to the times when the flights cross the sectors. The lines corresponding to the same flight that crosses two or more sectors are connected by thin vertical lines. When the mouse cursor points on a line representing a flight, this line is highlighted, as shown in Figs. 14 and 15.

Please note that, as a rule, only the entries of the focus sector and its immediate predecessor and successor are shown for each flight. Earlier and later crossed sectors can be shown only when two conditions are fulfilled: (1) the sector crossed earlier or later is also present in the display and (2) the vertical arrangement of the sector bands allows drawing the lines in the downward direction, without any upward-oriented segments. An example is the highlighted line in Fig. 15. The flight represented by this line enters the sector LECPL1W immediately before entering the focus sector LECPAPP. The entry of LECPL1W is represented by a line segment drawn across the band of this sector. Immediately before

entering LECPL1W, the flight enters the sector LECPL1E, whose band is shown above the band of the sector LECPL1W. This gives an opportunity to represent also the entry of LECPL1E. The sectors crossed by this flight before entering LECPL1E are not present in the display. Those entries are thus not shown.

One or more flights may be interactively selected. The corresponding lines are drawn in black, as can be seen in Fig. 14. For the selected flights, the sequences of the sector entries and the times of the entries are shown in the flight information panel on the right of the main view. Flights can be selected by clicking on their lines, by dragging the mouse while keeping the left button pressed, or by using popup menus appearing when the right mouse button is pressed while the cursor is located in one of the sector bands (see Fig. 16). Following clicking or dragging operations unselect affected flights that were previously selected and select those that were not. In the upper part of the flight information panel there is a button for unselecting all flights. The same can be done using the command “Unselect all flights” from the popup menu (Fig. 16). Individual flights can be unselected using the corresponding check boxes in the flight information panel (Fig. 14, right).

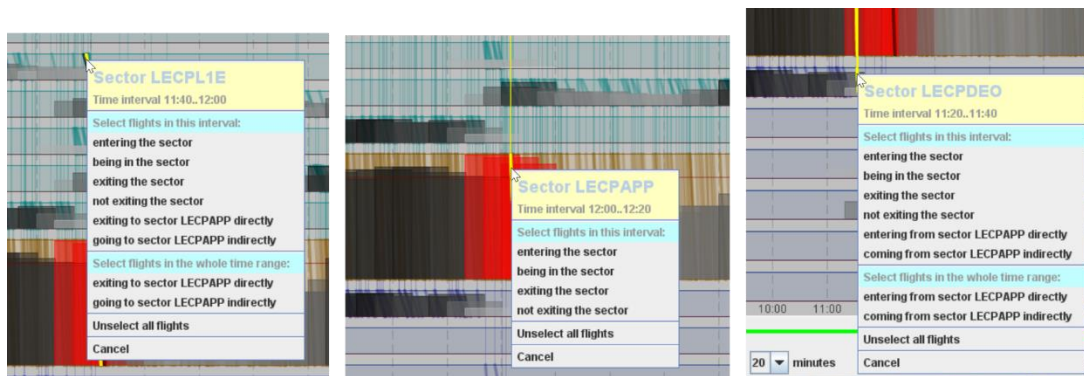


Figure 16. Popup menus with flight selection commands. The combination of the commands depends on whether the mouse cursor is located in the focus sector (in the centre of the figure), in one of the upstream sectors (left), or in one of the downstream sectors (right).

Using the check box “Show only selected” in the flight information panel, it is possible to hide the lines of all flights except those of the selected ones (if any). This possibility is demonstrated in Fig. 17. In the mode of showing only selected flights, some of the flights can be **marked**, i.e., drawn in black, as shown in Fig. 18. A flight can be marked by clicking on its line in the main view, by dragging a mouse while keeping the left button pressed (this operation can be applied to a group of flight lines), or through the flight information panel using a popup menu, as described below.

When the mouse cursor points on a flight description in the flight information panel, the line of this flight is highlighted in the main view. Pressing the right mouse button activates a popup menu enabling two operations: marking a flight, i.e., showing its line in black, when the mode is “Show only selected flights” (see Fig. 18) and showing all sectors visited by a flight (Fig. 19). The latter operation changes the set of sectors shown in the main view but the focus sector remains the same.

The flight information panel provides an additional opportunity to change the focus sector by clicking on any of the sector identifiers in any flight description. A text at the top of the flight information panel shows how many flights are currently selected and how many of them are visible. In the mode of showing only selected flights, when some flights are marked, also the number of marked flights is shown. When some flights are selected, pointing on the text with the mouse cursor and pressing the right button of the mouse activates a popup menu (Fig. 20). The menu allows putting the identifiers or

the paths of the selected flights to the clipboard. In the mode of showing only selected flights, when some of the flights are marked, three additional menu commands are enabled (see the lower right image in Fig. 20): deselect marked flights, deselect NOT marked flights, and clear marking.

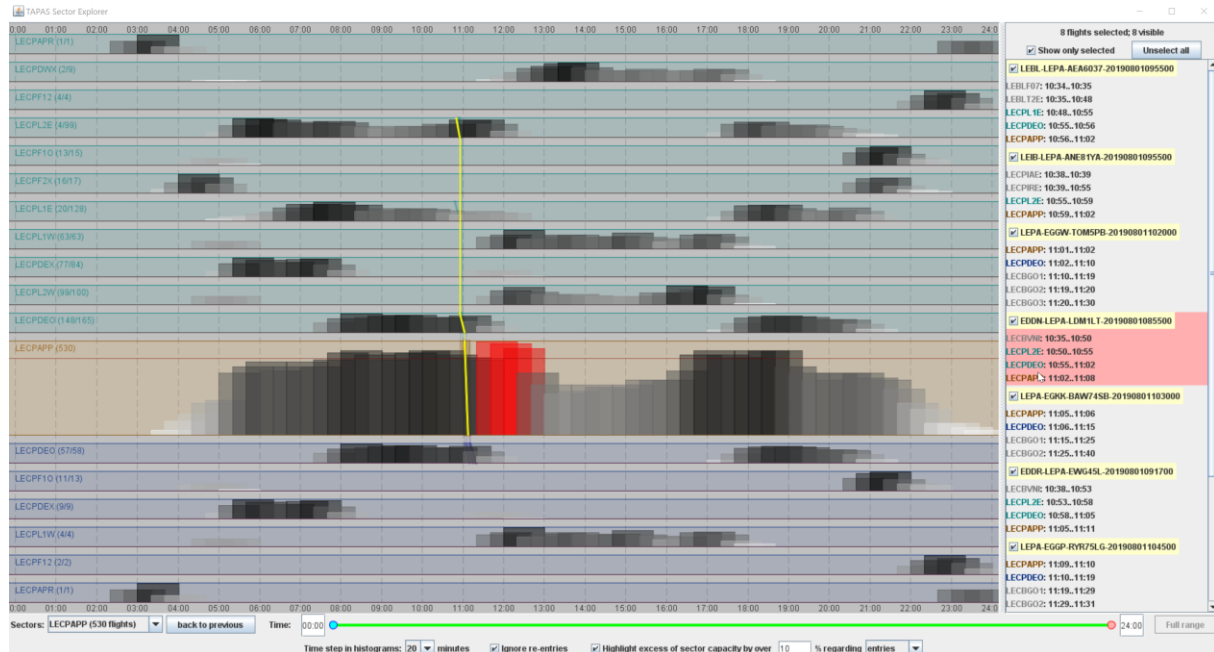


Figure 17. Appearance of Sector Explorer in the mode “Show only selected flights”.

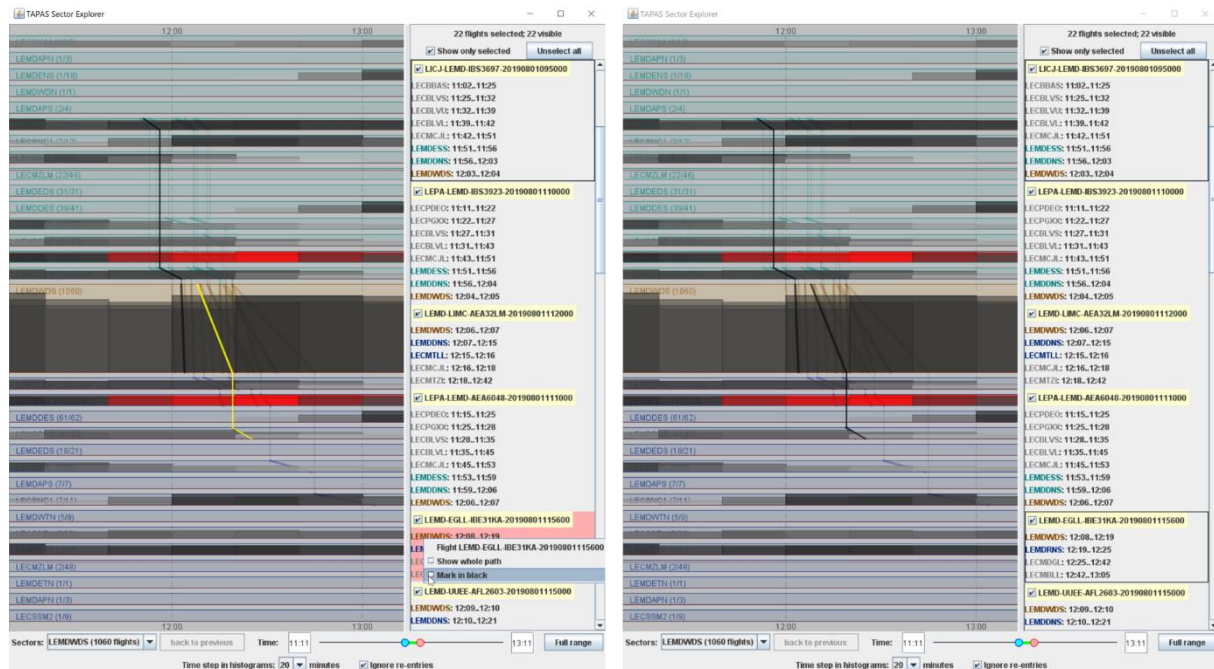


Figure 18. Left: In the mode of showing only selected flights, a popup menu appearing in the flight information panel when the right mouse button is pressed can be used to mark one of the selected flights. The line of this flight is then shown in black (right). The descriptions of the marked flights are enclosed in black frames. The same popup menu can be used to unmark an earlier marked flight.

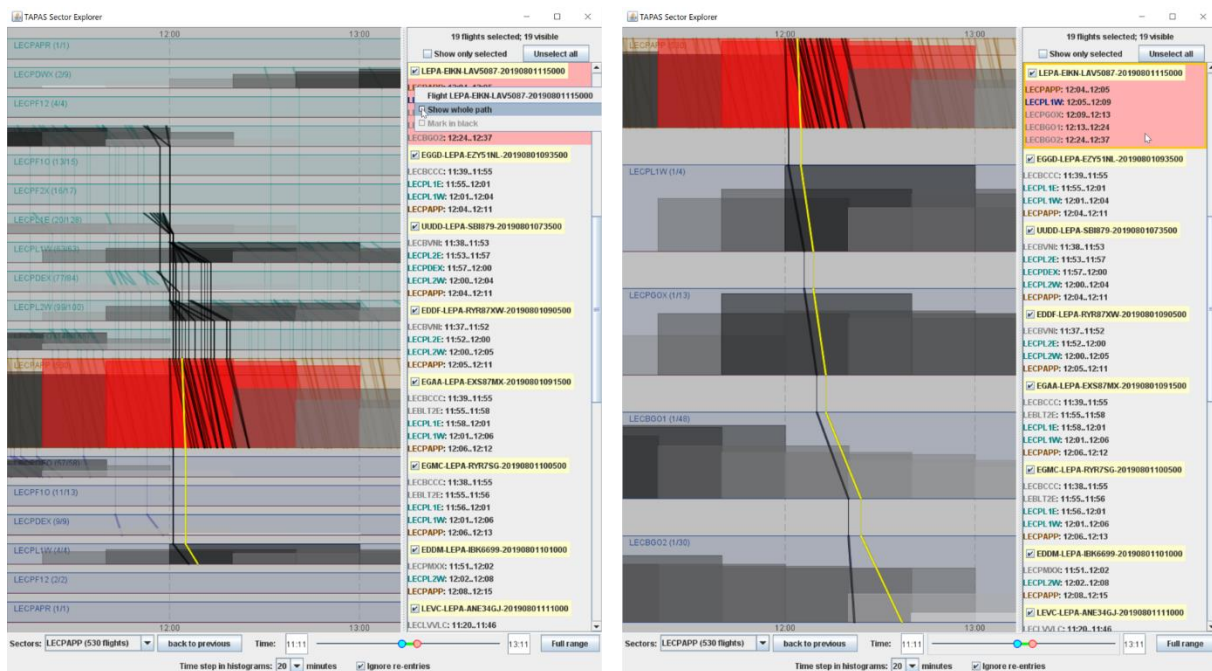


Figure 19. A popup menu appearing in the flight information panel upon pressing the right mouse button includes a command “Show whole path”, which turns the main view to presenting all sectors visited by this flight. The description of the flight whose whole path is currently shown is enclosed in an orange frame. The mode of showing the whole path can be cancelled through the same popup menu.

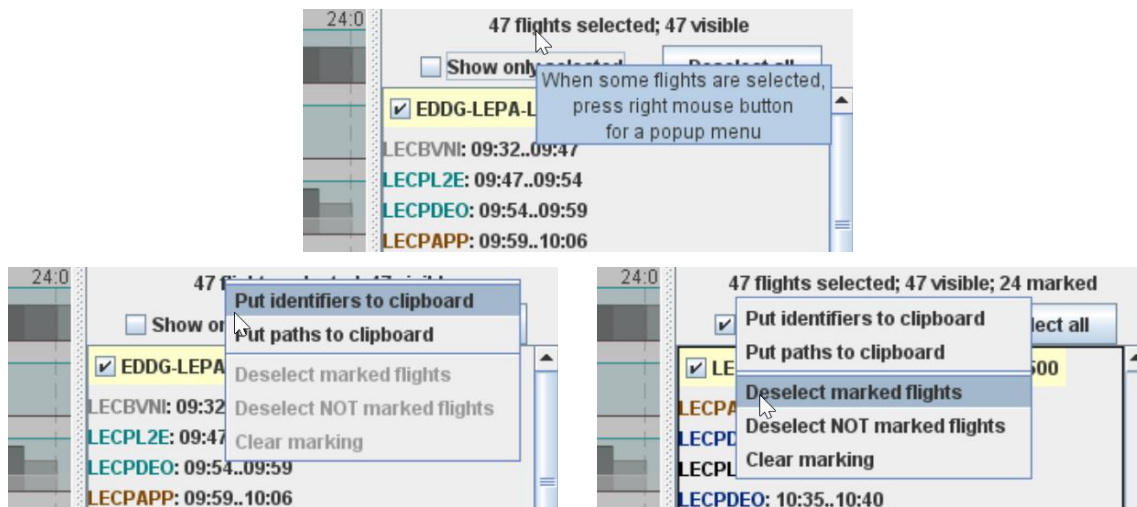


Figure 20. When the mouse cursor points on the text at the top of the flight information panel, pressing the right mouse button activates a popup menu. It can be used to put identifiers or paths of selected flights to the clipboard, to deselect marked or unmarked flights, or to clear marking.

2.3.1 Task: investigate details of a single scenario

Apart from the flights, the main panel of Sector Explorer shows sector loads (i.e., demands) by time intervals of 1-hour length. The demands are represented by time-based histograms with overlapping bars, as shown in Fig. 21.

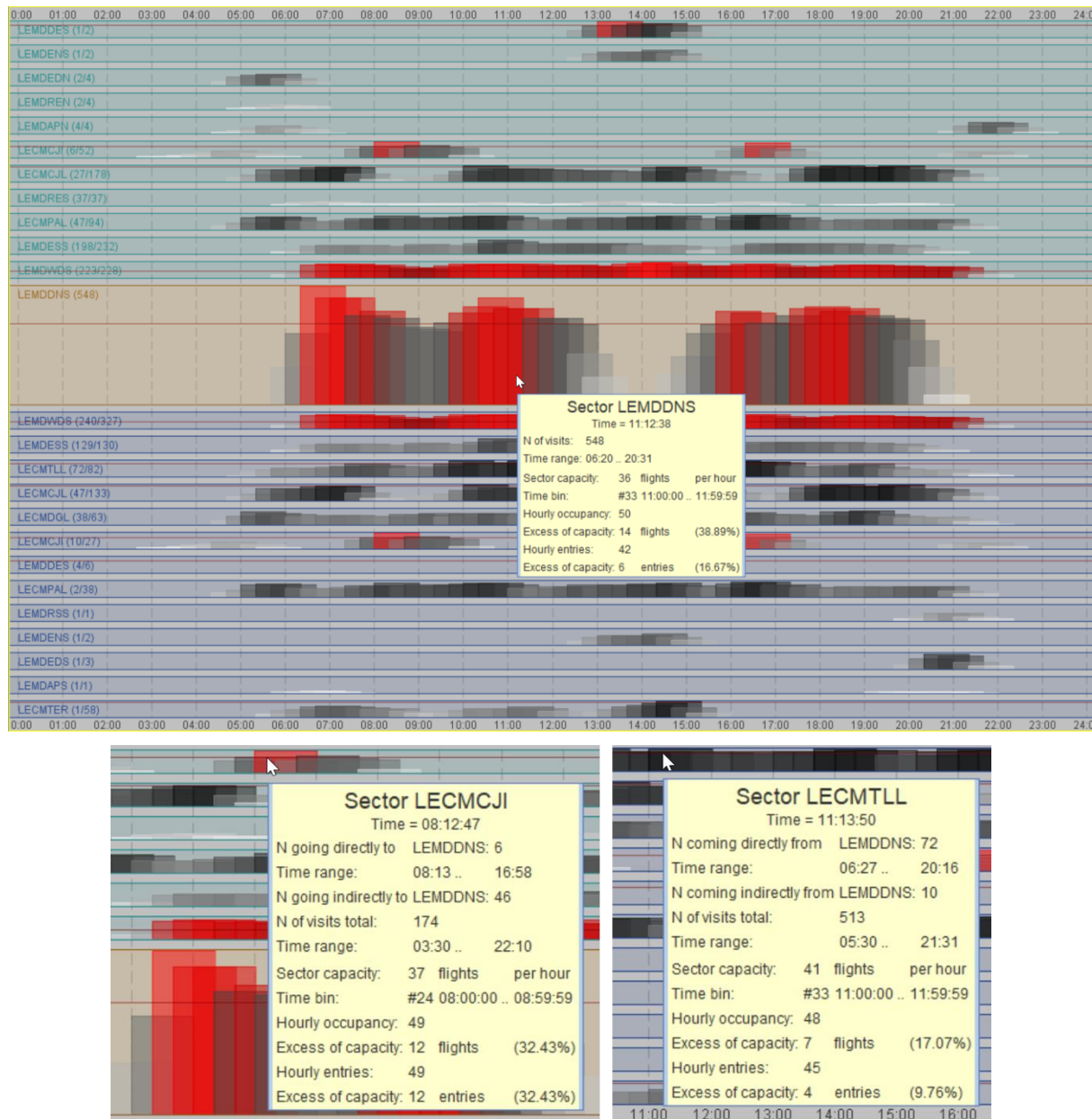


Figure 21. Hourly demands for sectors are represented by time-based histograms with overlapping bars. A popup window with information about a sector, time interval, and the corresponding flights appears when the mouse cursor is within the band corresponding to the sector. For upstream and downstream sectors (lower left and right images, respectively), with respect to the focus sector, the popup windows show the numbers of the flights going to or coming from the focus sector directly and indirectly.

The bar heights are proportional to the demand values. For each sector, the vertical scale of the bars is determined independently from the other sectors, based on the maximal demand value in this sector. All bars have equal widths corresponding to 1 hour according to the horizontal scale of the display. The position of the left margin of each bar corresponds to the beginning of the hourly interval for which the demand is computed; hence, the right margin marks the end of the interval. In the example shown in Fig. 21, the temporal shift (step) between the consecutive bars is 20 minutes. A different step can be chosen using an interactive control below the display, as shown in Fig. 22 (A).

Besides, it is possible to choose whether the sector demands are defined in terms of sector entries or in terms of sector occupancy (presence), i.e., the flights that have been present in the sectors at any times within hourly intervals (Fig. 22 B). For counting the occupancy, the duration of the time window is the same as for counting the entries, i.e., one hour.

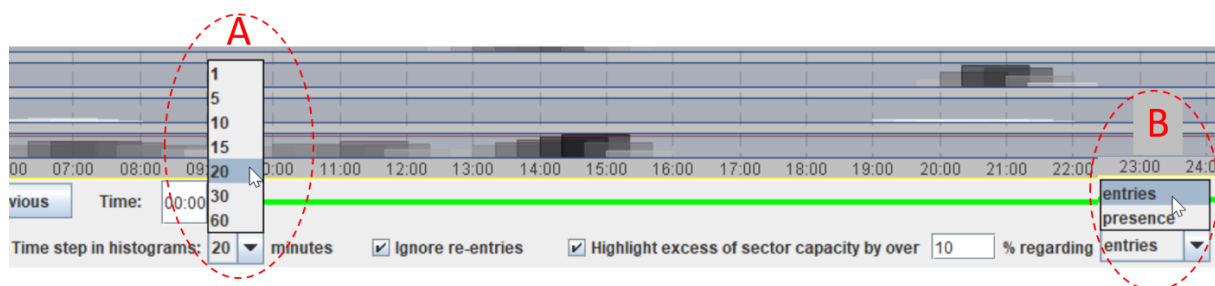


Figure 22. A: An interactive tool used for choosing the length of the temporal shift (step) between consecutive histogram bars. **B:** An interactive tool used for choosing what to count: flight entries to the sectors or sector occupancies, i.e., flights that have been present in the sectors at any times within hourly intervals.

The painting of the histogram bars depends on the values they represent. Shades of grey (darker for higher values) are used to represent the demands that do not exceed the sector capacities by more than the specified threshold, which can be regulated using a text field below the display; it is visible in the lower right part of Fig. 22. The default threshold is 10%. To change this, a different number needs to be put in the text field, followed by pressing the “Enter” key on the keyboard. Shades of red (brighter for higher values) are used for demands exceeding the capacities by more than the threshold. The capacity of a sector, if defined in the input data, is represented by a horizontal line drawn inside the band of this sector.

It may be useful to explore how the choice of the time step between the hourly intervals for which the demand is computed affects the appearance or disappearance of hotspot. Possible effects are demonstrated in Fig. 23, which shows the appearance of the demand histogram in one and the same sector for different time shifts from 30 minutes at the top to 1 minute at the bottom.

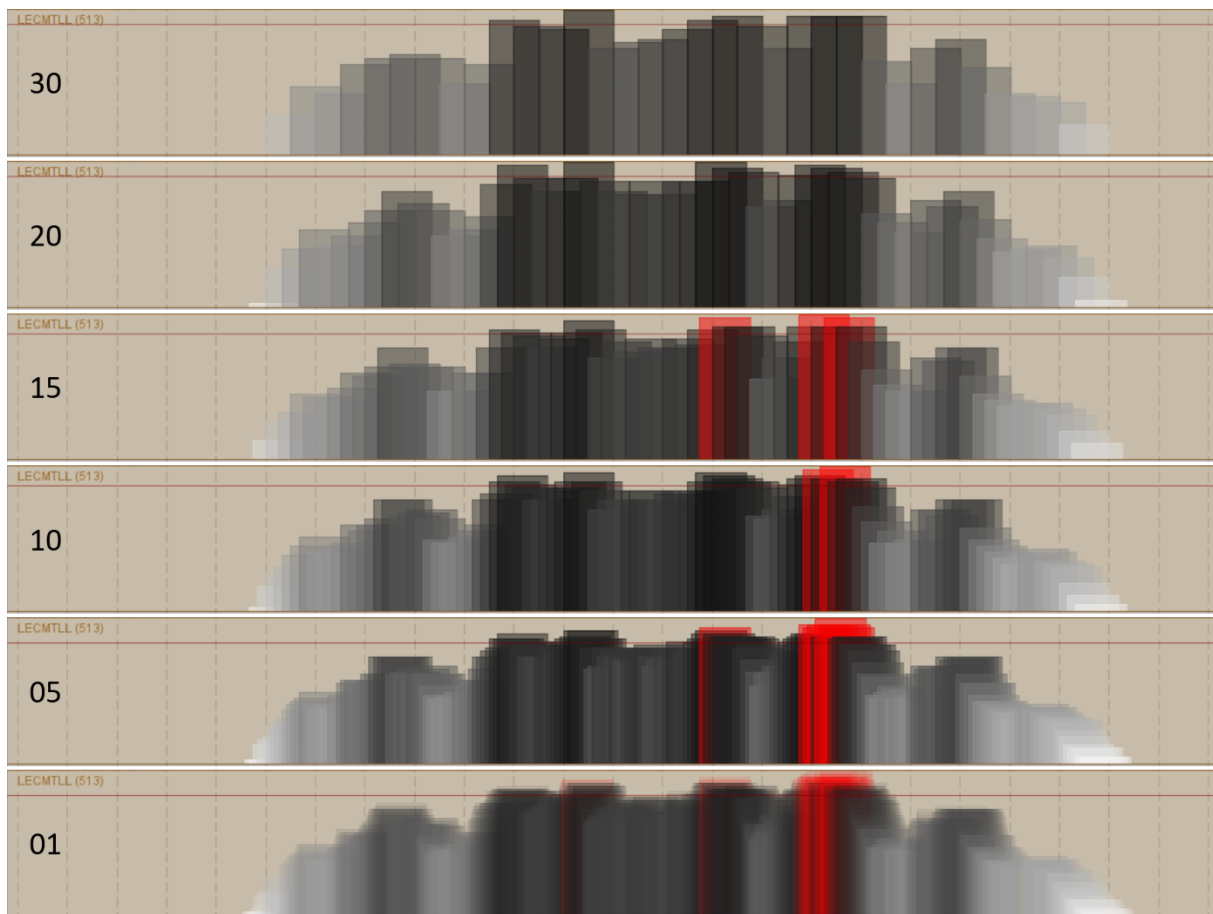


Figure 23. The appearance of hotspots, i.e., demands exceeding the sector capacity by more than the adopted threshold, may depend on the choice of the time shift (step) between the time intervals for which the demands are computed. Here, all six histograms represent the temporal distribution of the demands for the same sector, but the demands are computed using different temporal shifts. From top to bottom: 30, 20, 15, 10, 5 minutes and 1 minute. The bars painted in red indicate hotspots.

The histograms in the sector bands not only show the temporal variation of the demands but also indicate approximately the time intervals when the sectors are active. More precise indication is given by the flight-representing lines crossing a sector band. The exact times of entering sectors can be seen in popup windows appearing upon pointing on flight lines with the mouse cursor. Thus, in Fig. 24, we have determined that the focus sector have been active in the intervals 05:20-12:00 and 17:50-21:00.

Another useful analytical operation is to select and explore flights contributing to hotspots in a focus sector. This can be done using the popup menu shown in the centre of Fig. 16. Please note that the menu supports selecting flights by time intervals with the length equal to the length of the time step between the histogram bars. For example, when the time step is 20 minutes, the menu proposes to select the flights entering the sector (or being in it, or exiting it, or not exiting; see Fig. 16) during an interval of 20 minutes length, such as 05:20-05:40. The meanings of the available flight selection options are explained below:

- **“entering the sector”:** flights entering the sector within the given interval regardless of the time when they exit the sector;

- **“being in the sector”**: flights that are present in the sector *at some moment* within the given interval, including flights that have entered the sector earlier but still present in it at the beginning of the interval, as well as flights that exit the sector after the beginning of the interval;
- **“exiting the sector”**: flights that exit the sector within the given interval regardless of the time when they entered;
- **“not exiting the sector”**: flights that remain in the sector by the end of the given interval regardless of the time when they entered.

To select the flights entering (being, exiting, etc.) during an interval of 1 hour, it will be necessary to perform three consecutive selections for adjacent 20-minutes intervals. Another possibility is to drag the mouse across the time interval. For a more precise selection, it is recommended to reduce the length of the time span represented in the display, as shown in Fig. 25.

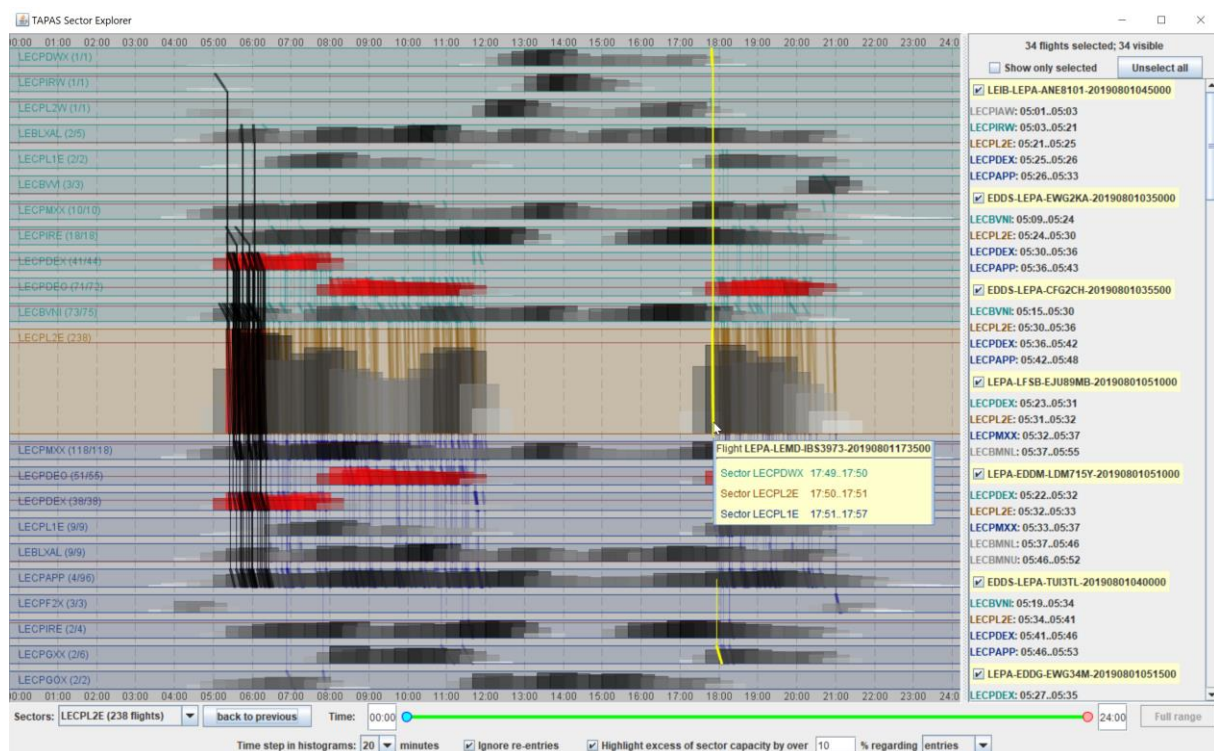


Figure 24. The horizontal positions of the histogram bars in the sector bands indicate in what time intervals the sectors are active. For the focus sector, the lines representing the flights show where the flights come from and go to. Using a popup menu (Fig. 16, centre), it is possible, in particular, to select the flights contributing to a hotspot, see where they come from, and whether they are also involved in hotspots in other sectors.

After selecting flights, you will see from which sectors these flights come to the focus sector and to which sectors they go next; see the selection (lines in black) in Figs. 24 and 25. It will be visible which of the selected flights, if any, are also involved in hotspots in other sectors.

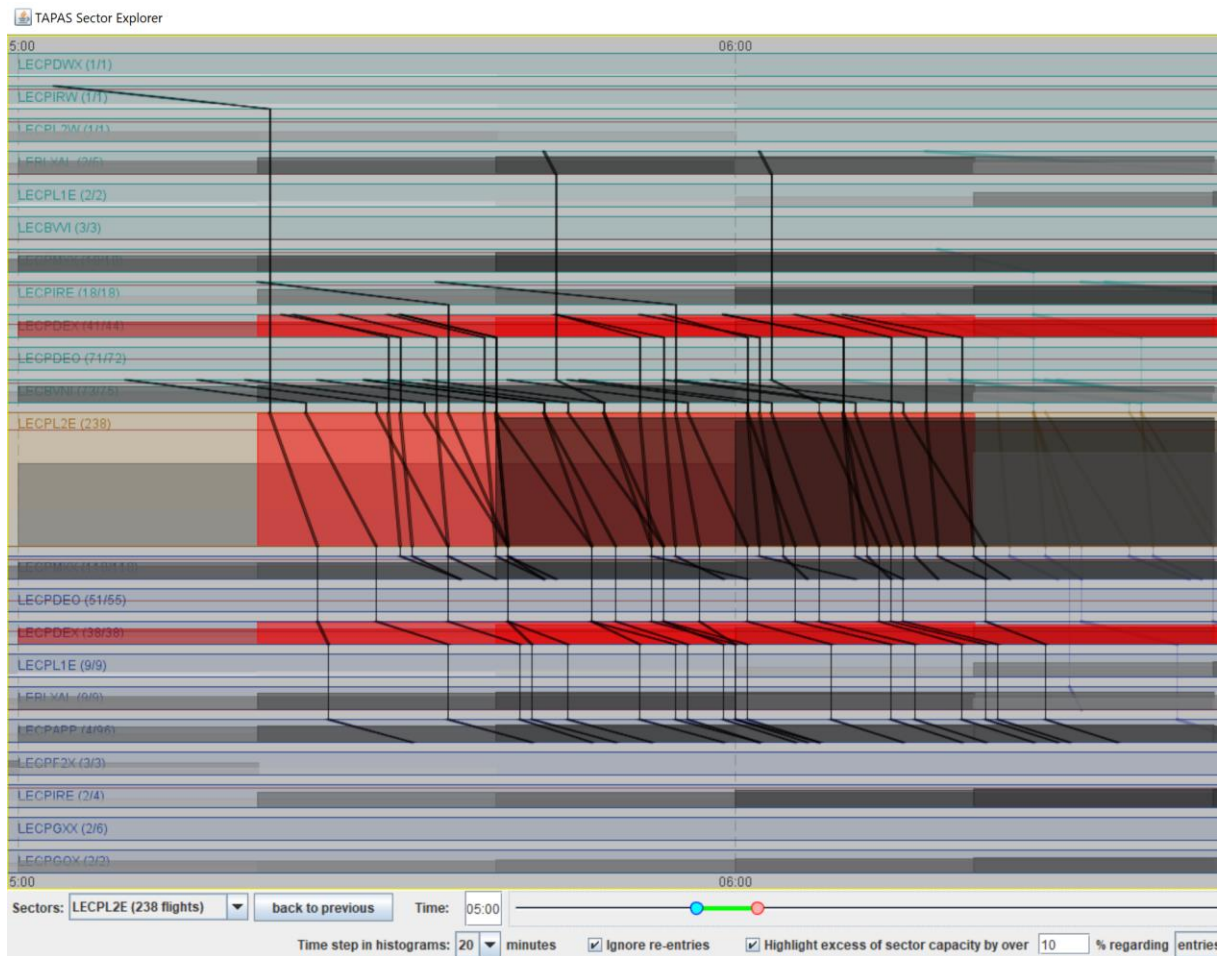


Figure 25. The time span represented in the display can be reduced for a more convenient selection and exploration of flights involved in a hotspot.

2.3.2 Task: compare two scenarios in detail

Apart from visualising details of a single scenario, Sector Explorer supports detailed comparison of two selected scenarios. Sector Explorer can be started in the comparative mode using commands beginning with “Compare ...” in the popup menus appearing in the main view of Solution Explorer (Figs. 5 and 26) or in the solution history view (Fig. 13).

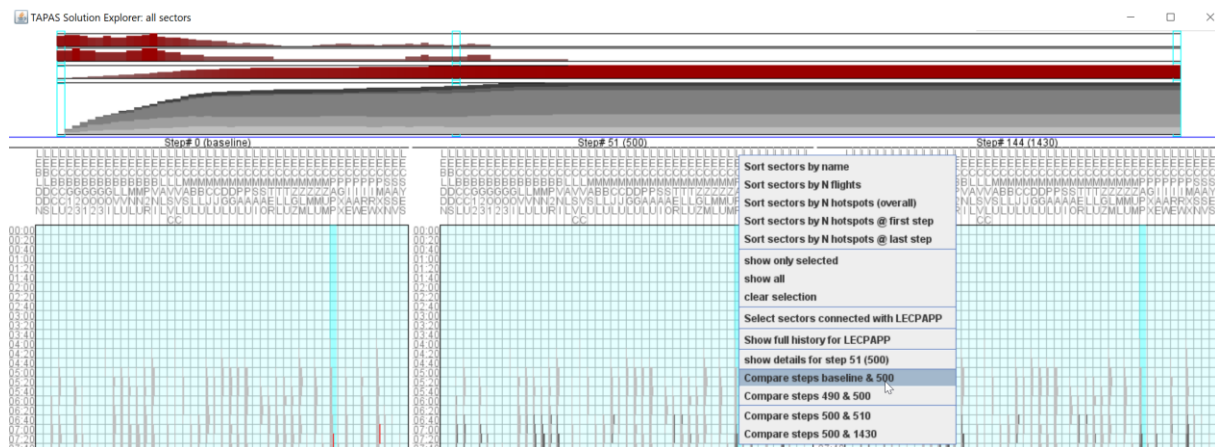


Figure 26. Using a popup menu in Solution Explorer to run Sector Explorer in comparative mode. See also Fig. 5.

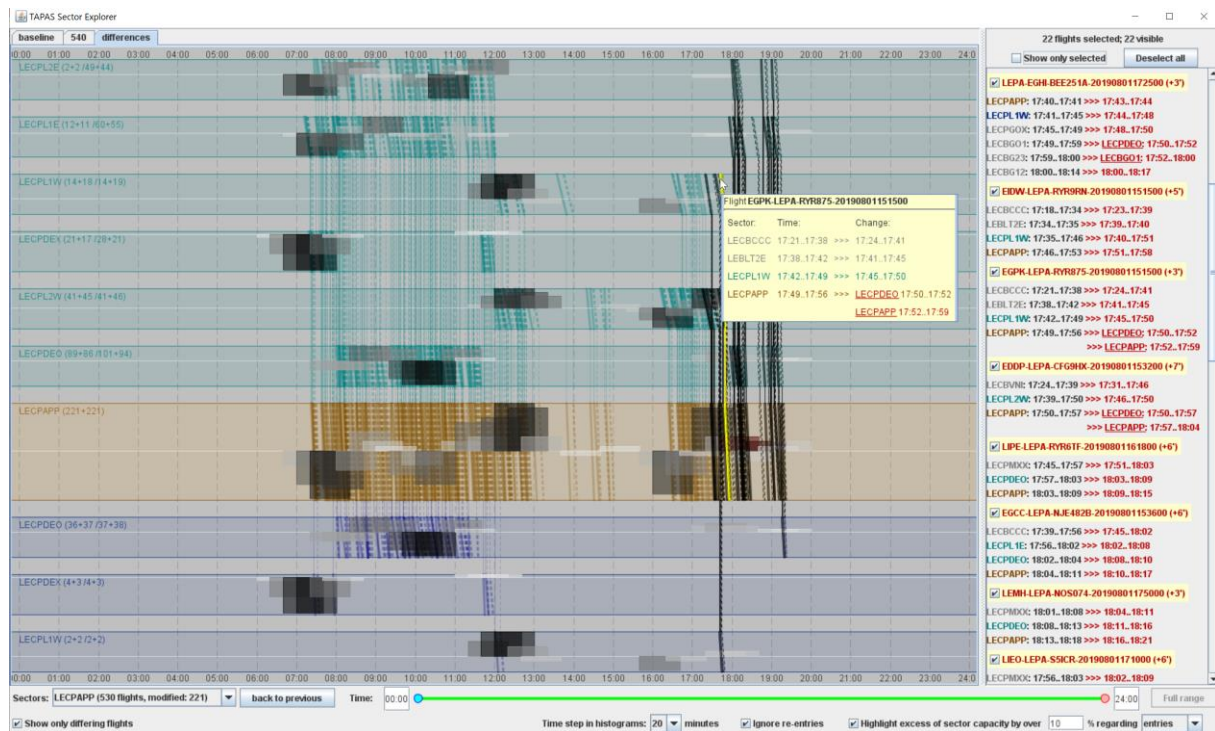


Figure 27. The comparative mode of Sector Explorer. The visualisation is presented in a tabbed panel with three tabs. The first two tabs show two scenarios and the third tab shows their differences. A tab to be showing is selected by clicking on its label in the upper left corner of the panel. The difference view, which is visible in this figure, represents differences between sector demands by upward and downward oriented histogram bars. It also shows differences between the flight versions from the two scenarios. Versions from the first scenario are represented by solid lines and versions from the second scenario by dashed lines. Detailed information about the differences between the flight version can be seen in a popup window appearing upon mouse-pointing or in the flight information panel (on the right) showing information for selected flights (marked in black).

The appearance of the comparative mode of Sector Explorer is demonstrated in Fig. 27. It contains a tabbed panel with three tabs. The first two tabs show two scenarios and the third tab shows their differences. A tab for viewing is selected by clicking on its label in the upper left corner of the panel.

When Sector Explorer is started in the comparative mode, the difference tab is visible originally, and the displays of the two scenarios are hidden beneath.

Each of the two scenarios is represented as described in the previous section and can be explored using all tools described earlier. An additional interactive control is the checkbox “Show only differing flights” in the lower left corner, which allows to hide the lines of the flights that do not differ between the scenarios.

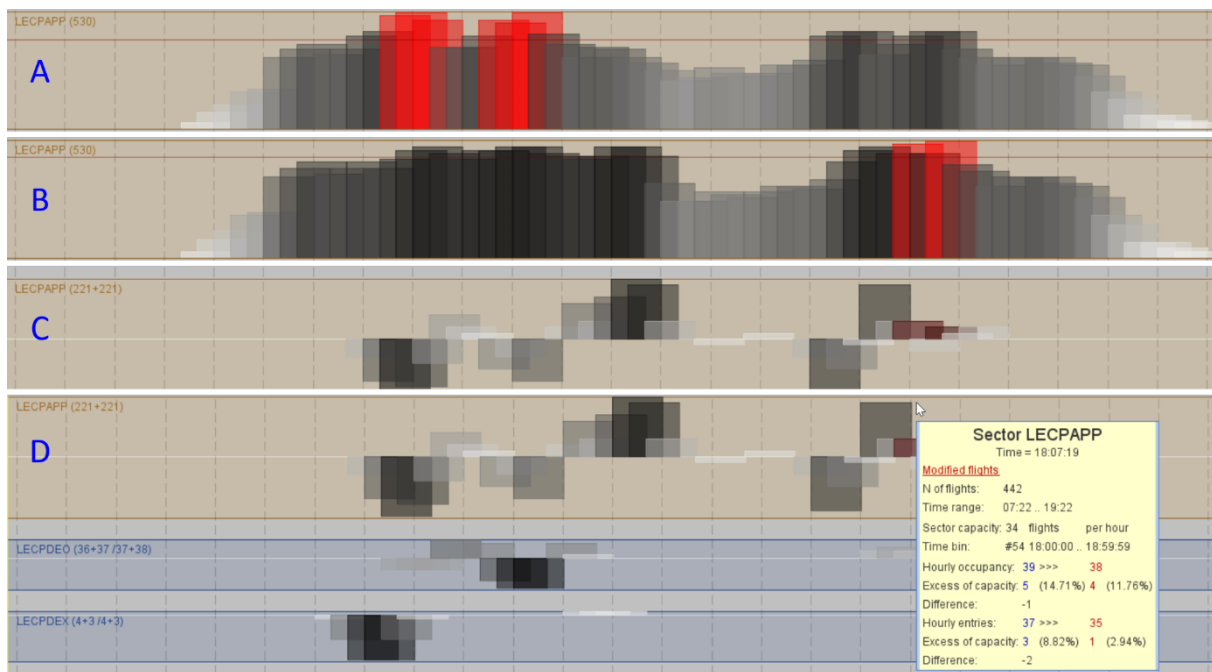


Figure 28. Comparison of sector demands in two scenarios. A: A histogram of sector demands in scenario 1 (shown in the first tab). B: The corresponding histogram of the sector demands in scenario 2 (shown in the second tab). C: Representation of the differences between the demands in the difference view (shown in the third tab). D: Pointing with a mouse cursor on a time interval activates a popup window with detailed information about the differences.

The difference view (i.e., the content of the difference tab) represents differences between sector demands by upward and downward oriented histogram bars. An upward oriented bar means that the second scenario has a higher demand in the corresponding hourly interval than the first scenario. A downward oriented bar means the opposite. An absence of a bar indicates equal demands in both scenarios. When the mouse cursor is located in a sector band in the difference view, detailed information about the differences for the corresponding time interval is shown in a popup window (Fig. 28 D).

The difference view also shows both versions of the flights that differ between the two scenarios (this view does not include the flights that do not differ). The versions from the first scenario are represented by solid lines and the versions from the second scenario by dashed lines (see Fig. 27). Detailed information about the differences is shown in a popup window when the mouse cursor is pointing on the line representing a flight. When some flights are selected, the information about the differences for these flights is shown in the flight information panel (see Fig. 27). Two versions of a flight may have the same sequence of crossed sectors but different entry times, or the sector sequences may also differ.

As an example, let us describe a potentially useful sequence of exploratory operations. We compare the baseline scenario (i.e., based on the original flight plans without any changes) with the scenario from one of the steps of the solution development (#540). When we open the comparative view, we see the picture presented in Fig. 29.

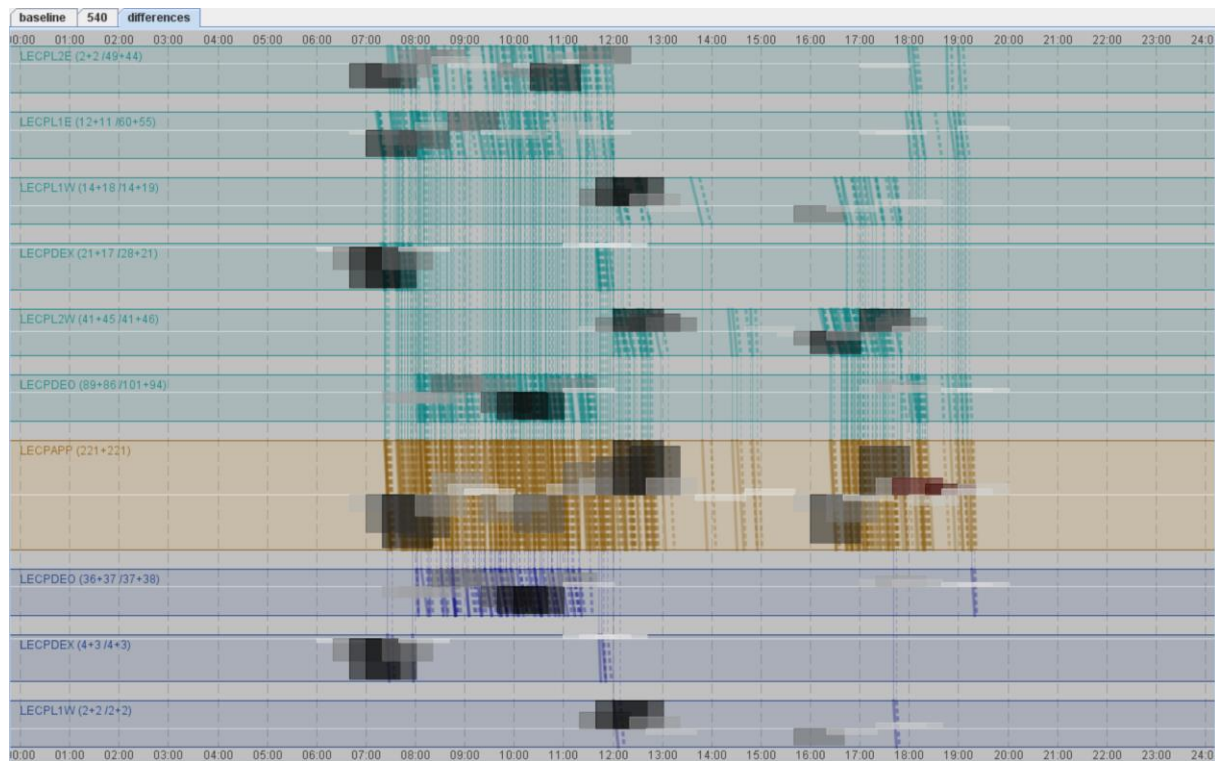


Figure 29. An initial appearance of the comparative view with the focus sector LECPAPP.

In the focus sector band, we notice several reddish histogram bars oriented upward (in the time range 17:40-19.20). They mean that in these sector and time range there are more flights in the second scenario than in the first one and that the capacity of the sector is exceeded by more than the chosen threshold (10%). We want to know whether the hotspot existed in the baseline scenario or appeared in the second scenario due to delaying some flights. We use the time slider to focus the view on the time range of interest (Fig. 30 A, B) and look in the tabs of the baseline scenario (Fig. 30 C) and the scenario of the step #540 (Fig. 30 D). We see that there is no hotspot in the baseline but it appears in the solution step #540.

By means of mouse dragging (keeping the left button pressed), as shown in Fig. 30 E, we select the flights that enter the focus sector during the existence of the hotspot. The result of the selection is shown in Fig. 31. The text above the flight information panel shows us that 62 flights are selected. We switch to the baseline tab (Fig. 32) and see that some flights entered the focus sector before 17:40. When we switch to the comparative tab (Fig. 33), the text above the flight information panel tells us that only 22 flights out of the selected 62 are now visible. This means that the remaining 40 flights are the same in both scenarios.

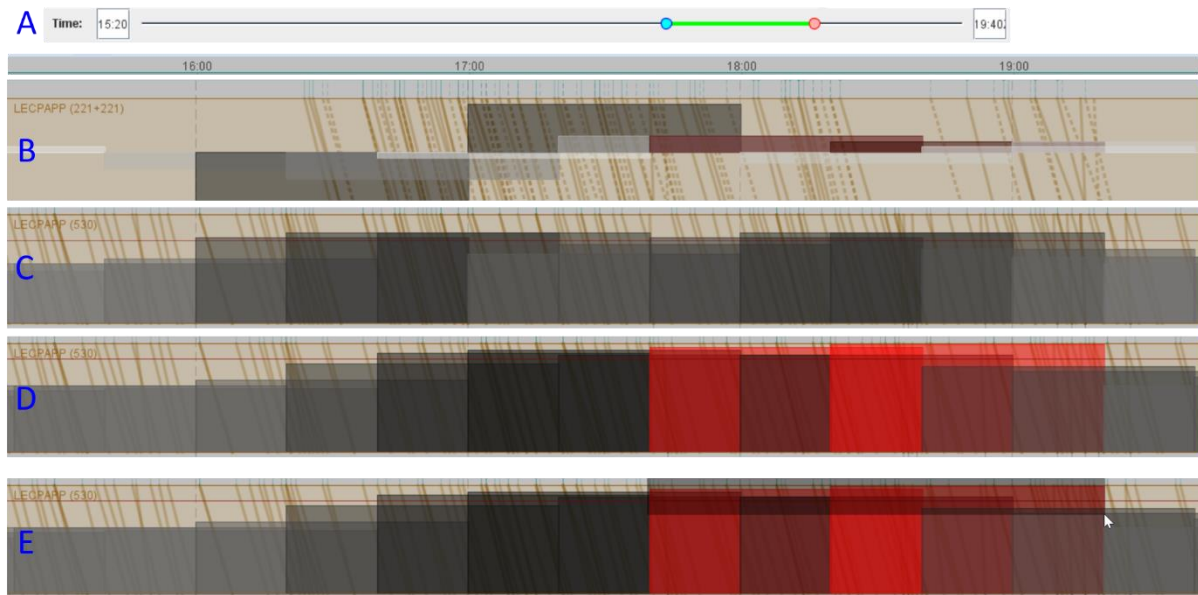


Figure 30. A sequence of interactive operations. A: Select the time range of interest to be shown with higher resolution. B: The appearance of the focus sector band in the comparison tab after selecting the time range. C: The focus sector band in the first tab (baseline scenario) has no hotspot in this time range. D: The focus sector band in the second tab shows an existence of a hotspot in the scenario of the solution step #540. E: Mouse dragging is used to select the flights involved in the hotspot.

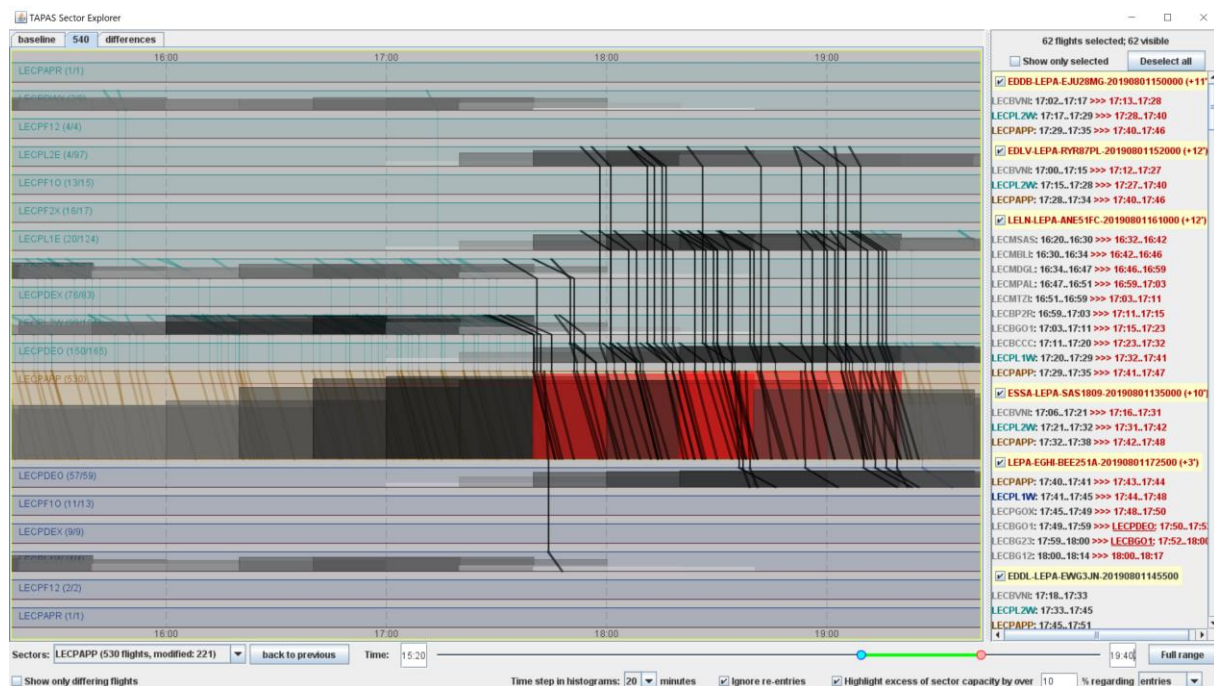


Figure 31. The result of selecting flights by the mouse dragging operation shown in Fig. 30 E.

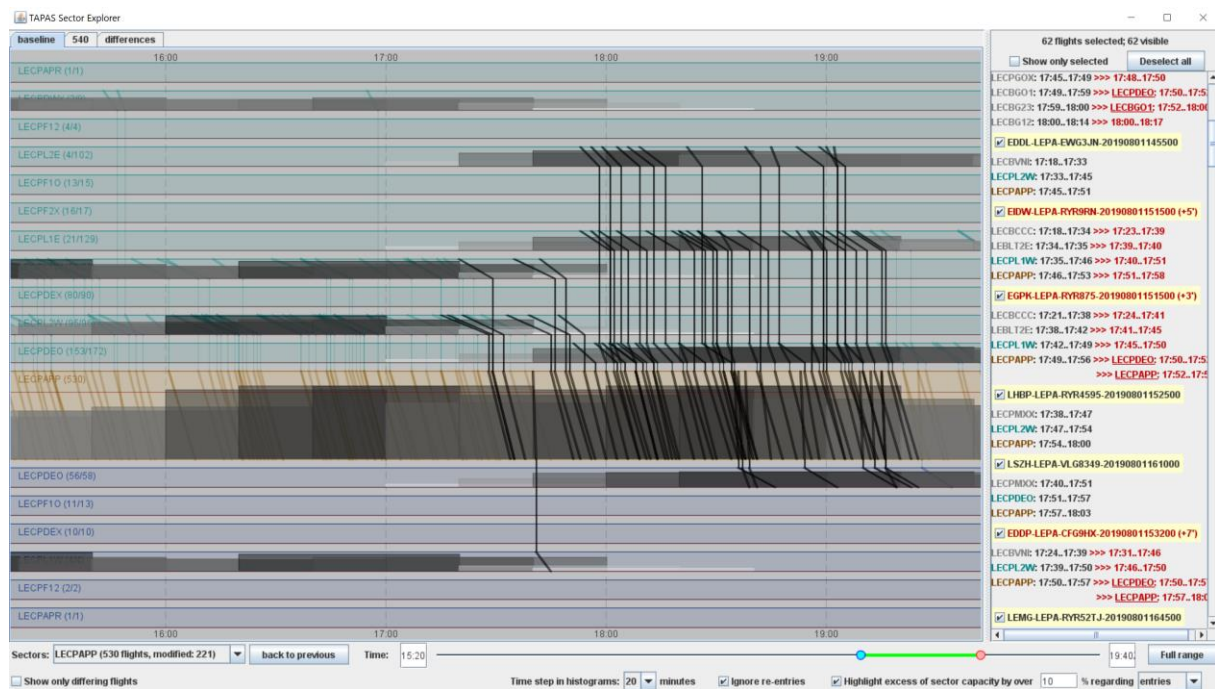


Figure 32. The distribution of the selected flights over time in the baseline scenario.

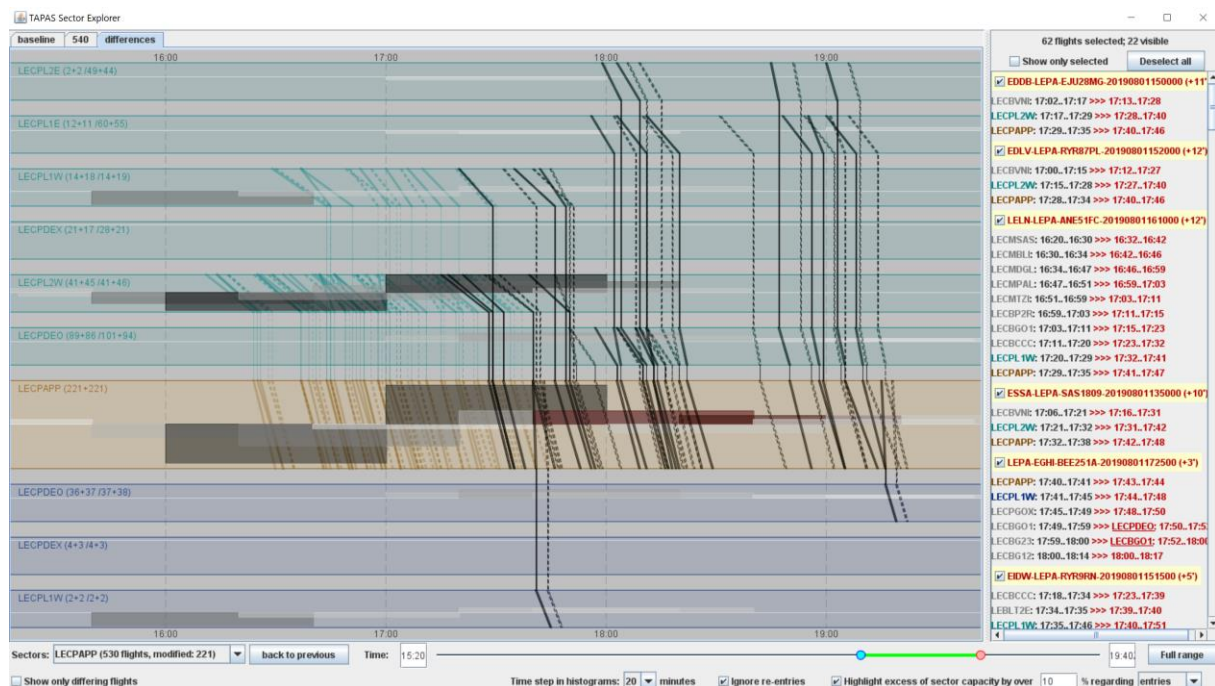


Figure 33. The comparative tab shows the flights that have been modified in the solution with respect to the baseline.

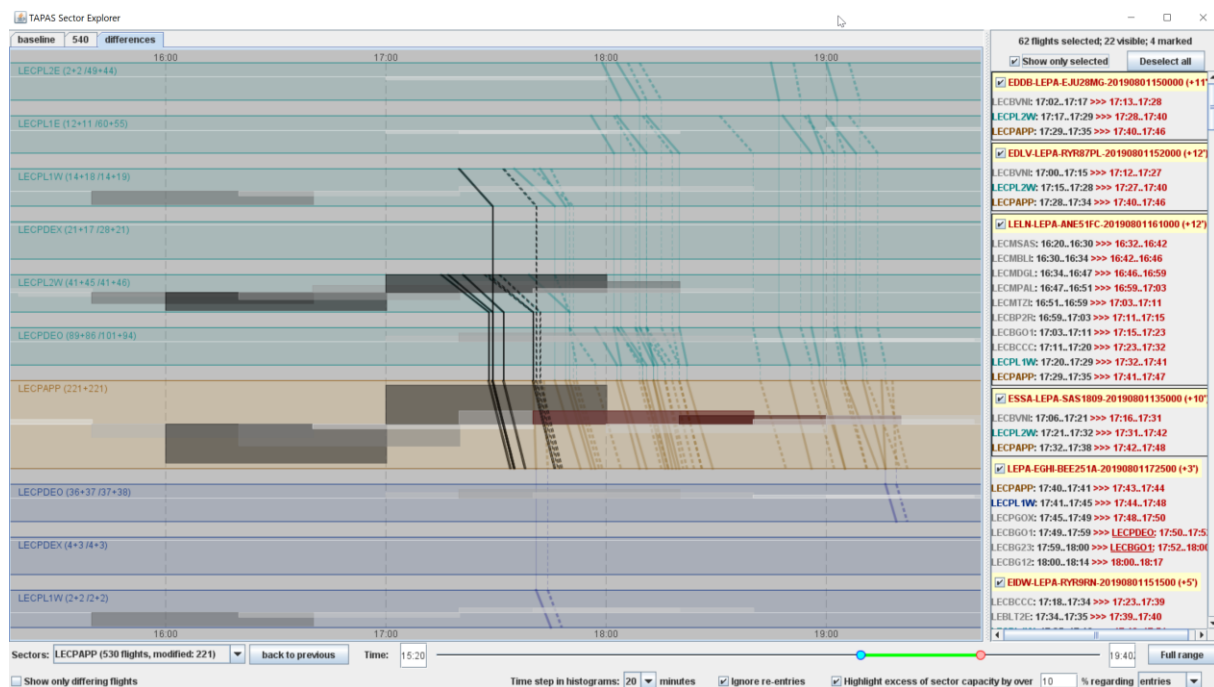


Figure 34. After switching to the mode of showing only selected flights, we have marked the flights whose baseline versions entered the focus sector before 17:40.

When we switch to the mode of showing only selected flights, we can conveniently mark the flights whose baseline versions enter the focus sector before 17:40, i.e., before the time when the hotspot appears in the second scenario (Figure 34). We see that there are 4 such flights. The excess of the sector capacity is thus caused by shifting these four flights forward in time. The flight information panel shows us the time shifts of these flights, which range from 10 to 12 minutes. We see that the routes of these flights (i.e., the sequences of the visited sectors) are the same in both scenarios.

As we see in the flight information panel, there are flights whose routes differ between the scenario. We clear the previous marking using the popup menu shown in Fig. 20. Then we mark the flights whose routes differ. For this purpose, we use popup menus appearing after mouse-pointing on the flight descriptions in the flight information panel and pressing the right button of the mouse. The result of marking is shown in Fig. 35. We see that, for two of the three marked flights, both versions of the routes end in the focus sector, whereas the third flight begins in the focus sector and goes further. To see whether this flight is involved in any hotspots in other sectors, we select the mode of showing the whole path of this flight (using the same popup menu as for marking) and see the original and modified versions of this flight (Fig. 36). When we switch to the first and second tab, we can see the original and modified versions separately. We see that neither version is involved in any other hotspots.

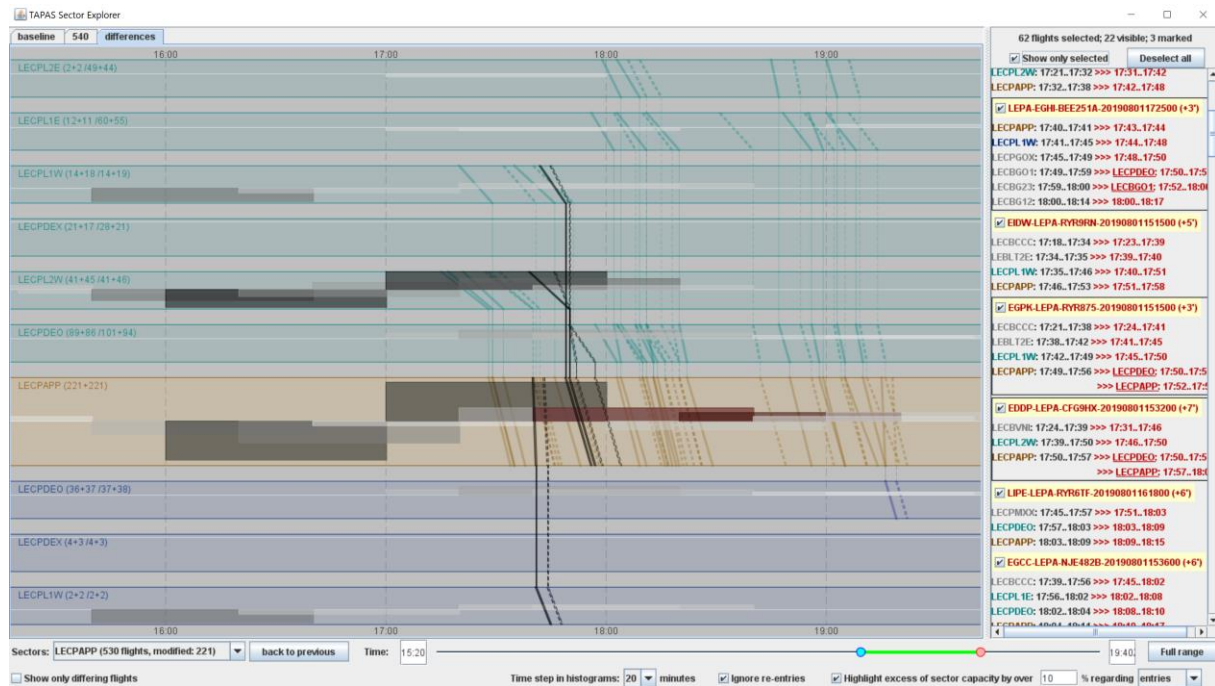


Figure 35. Marking of the flights whose routes differ between the scenarios.

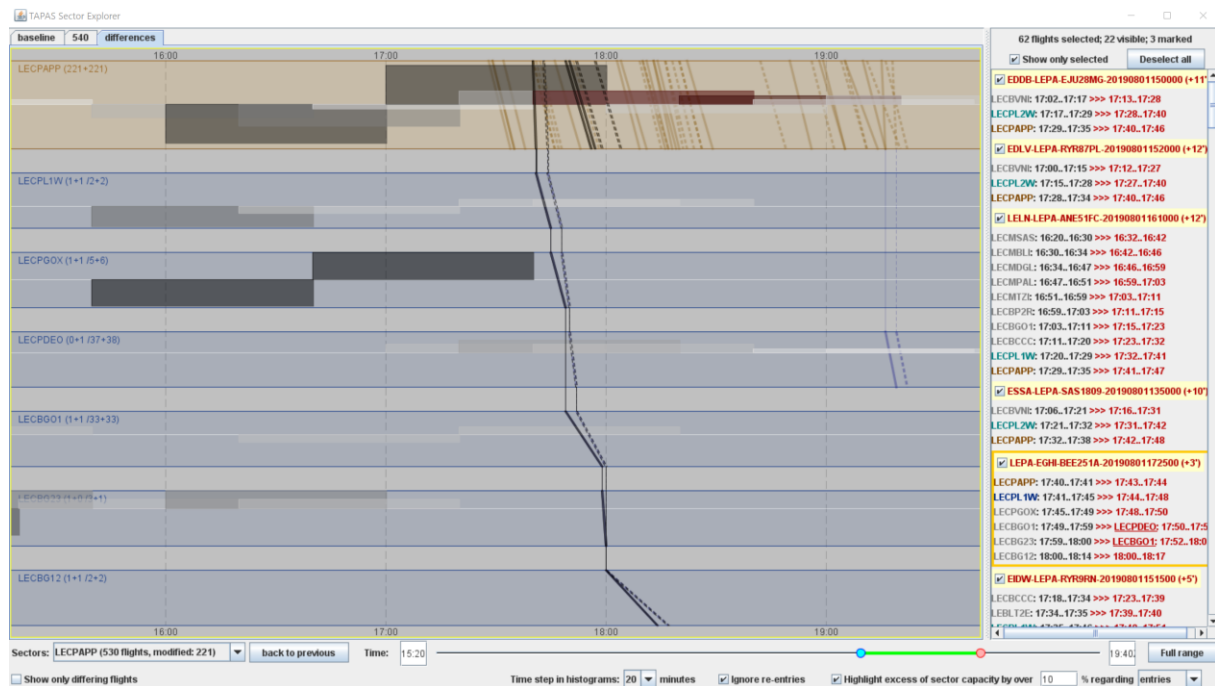


Figure 36. The mode of showing the path of a selected flight.

2.4 Visual Analytics within the Overall ATFCM Prototype

Figure 37 provides the overall architecture of the TAPAS ATFCM prototype. The Visual Analytics component provides interface to outputs of AI/ML solutions, enabling investigation of a single solution and comparison of multiple solutions.

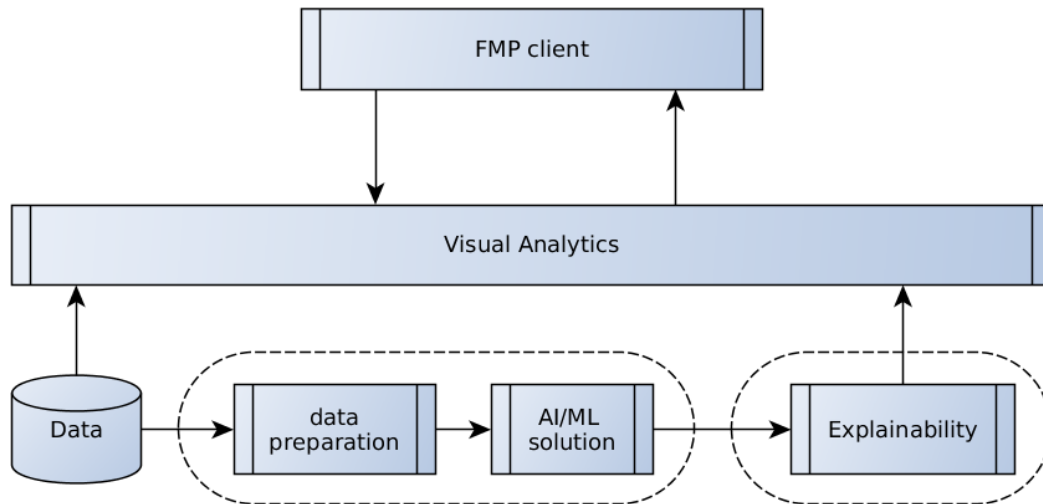


Figure 37. Overall System and Interaction with FMP

VA module takes outputs of the AI/ML module as inputs, specifically: capacities of sectors, variants of flight plans, and decisions files combined with computed explanations.

VA module enables exploration of the data, providing

- visual summaries for the variants of solutions;
- the evolution of the solutions over iteration steps of the simulation process;
- details for each hotspot, sector, and time interval, including aggregated information about the flight delays;
- on demand: features that explain/justify delay decisions for selected flights, sectors, and time periods;
- further relevant information, to be selected in collaboration with project partners.

VA component communicates with other parts of the TAPAS prototype via messages. Upon start, it connects to the last considered output of the AI/ML module and proposes 3 major scenarios of exploration (Figure 38):

1. Exploration of outputs in scenario 0 (delays only).
2. Exploration of outputs in scenario 2 (level capping combined with delays).
3. Comparison of multiple solutions: baseline, scenarios 0 (delays only), 1 (flight capping only), and 2 (level capping combined with delays).

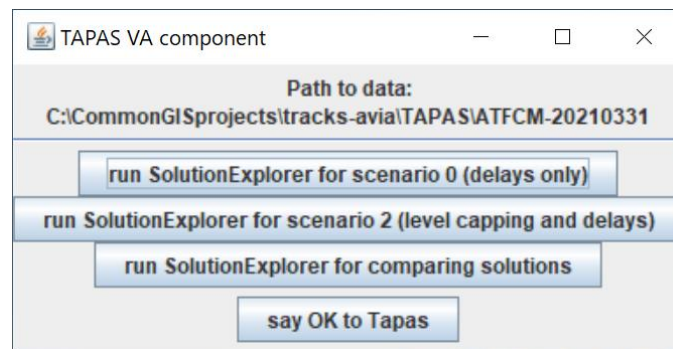


Figure 38. User interface of the integrated VA component

Upon receiving a message that a new solution is computed, the VA component re-connects to the newly produced results, checks data consistency, and informs the user.

Currently, no outputs of the VA component are foreseen. At later stages of the project, the VA module may output specifications of constraints (e.g., no delays allowed for flights passing sector X in interval T, delays less than 15min for flights departing from airport A, etc.) to be considered by the AI/ML module. Potentially useful and feasible to support constraints are to be defined later.

In the current version, the user indicates approval of the solution by pressing the OK button in the bottom of the window, thus instructing the TAPAS system to pass the current outputs to the FMP Client.

3 Visualisation and Visual Analytics for the CD&R Use Case

In this use case, the task of the VA component is to inform the users about imminent conflicts between flights that have been predicted by the XAI component and present the conflict resolution actions proposed by the XAI component. This needs to be done in real time while the current situation constantly changes, which means that the visual displays need to be frequently updated to reflect the changes. The necessity for the users to react quickly to the changes has the following implications for the visualisation design:

- The users should receive minimal information that is sufficient for understanding a problem and the corresponding suggested solutions.
- The information should be represented in a very simple, intuitively understandable form.

Taking this into account, we have developed a visual interface in which the information is presented predominantly in the form of tables. In addition, the interface includes schematic graphical representations of the conflict geometry.

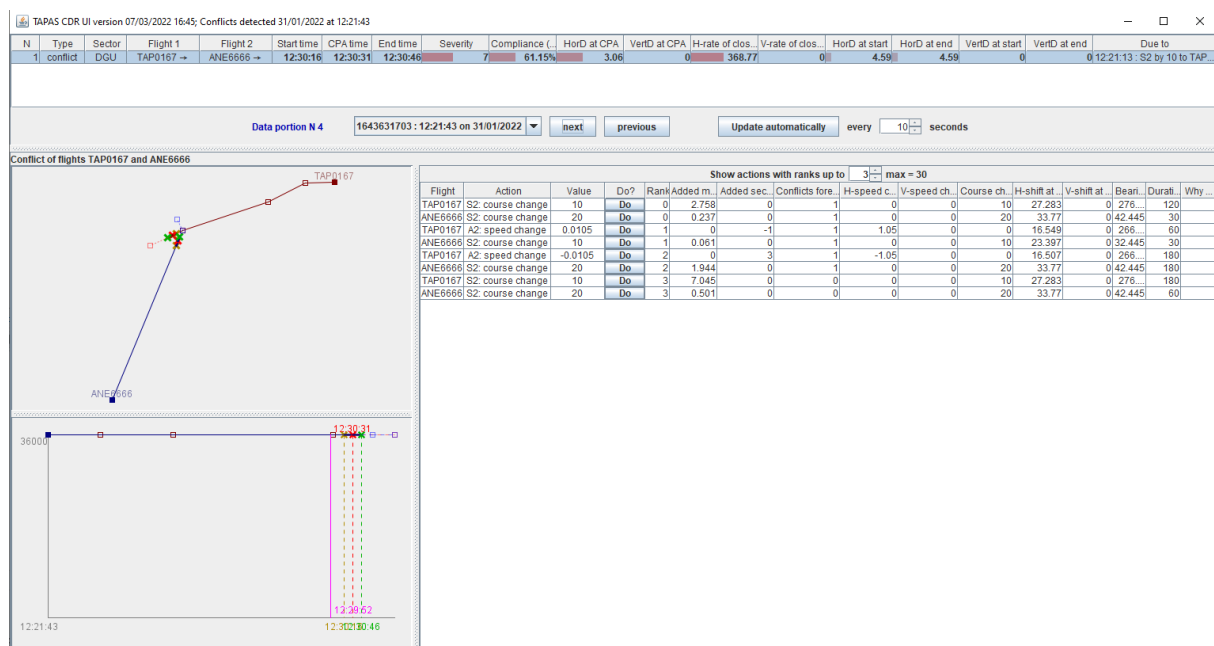


Figure 39. User interface of the VA component for the CD&R use case.

The UI of the VA component, henceforth referred to as TAPAS CDR UI, is illustrated in Fig. 39. This is the main window of the TAPAS CDR UI. Additional windows can appear upon a user's request or when it is necessary to inform the user about non-conformance events, as will be described later. The main window consists of four sub-windows separated by movable dividers. The sizes of the sub-windows can be adjusted by moving the dividers through mouse dragging.

3.1 Conflict description table

In the upper part of the main window there is a table describing the imminent conflicts detected recently (i.e., within the last 30 seconds) by the XAI component. Each row of the table describes one conflict. When no conflicts have been detected, the table is empty, and a message about the absence of conflicts is displayed below the table.

The output of the conflict detection component provides information about the following events: conflicts, alerts and losses of separation. A **loss of separation** is a violation of the separation minima between a pair of aircraft. A **conflict** is a predicted loss of separation. An **alert** is a conflict where the loss of separation is predicted to occur in under 2 minutes.

For a detected event, the following data are shown in the table columns:

- Event type: conflict, alert, or loss (i.e., loss of separation; see the definition above)
- Sector in which the conflict is expected to happen
- Callsigns of the two flights involved in the event followed by one of the symbols ↗, →, or ↘ indicating, respectively, the climbing, cruising, and descending flight phases.
- Start time of the conflict, i.e., when the separation minima will start to be violated.
- Time of the CPA (Closest Point of Approach), i.e., when the separation between the flights is predicted to be the smallest.
- End time of the conflict, i.e., when the separation between the flights will again become sufficient.
- *Severity* score, a value from 0 (not critical) to 15 (most critical); the meaning and way of computing are described below.
- *Compliance* measure, i.e., the extent (expressed in %) to which the situation complies with the separation requirement. Here, 100% means full compliance, i.e., a safe situation, and 0 indicates the most critical situation. The derivation of the compliance measure is described below.
- Horizontal and vertical distances between the flights at the CPA. The horizontal distance is measured in nautical miles (NM) and the vertical distance in feet.
- Horizontal rate of closure, i.e., the relative speed with which the horizontal distance between the flights decreases. This rate is measured in knots, i.e., nautical miles per hour.
- Vertical rate of closure, i.e., the relative speed with which the vertical distance between the flights decreases. This rate is measured in feet per minute.
- Horizontal and vertical distances (in nautical miles and feet, respectively) at the start and end time moments of the conflict event.
- The column “Due to” indicates whether the conflict is going to emerge because of non-conformance of one of the flights to a resolution action that they were required to fulfil according to an earlier taken decision of the air traffic controller. In this case, the column contains information about the action that has been violated.

3.1.1 Calculation of the compliance measure and severity score

The measures of the event criticality were introduced according to requests and instructions of domain experts. The **compliance measure** (a.k.a. Measure of Compliance, abbreviated as MoC) is derived as the maximum of the degrees of the horizontal and vertical separation. The degree of the horizontal separation is 100% when the horizontal distance between two flights is 5 nautical miles or more; otherwise, it is obtained by dividing the horizontal distance by 5 and multiplying by 100%. The degree of the vertical separation is 100% when the vertical distance between two flights is 1000 feet or more; otherwise, the value is obtained by dividing the vertical distance by 1000 and multiplying by 100%. From the two degrees, the higher value is taken.

For example, when two flights that have 0 NM lateral separation but 950 ft vertical are separated by 950 ft, which is 95% of the required vertical separation. The MoC in this case would be 95%. Similarly, two flights that are only 3NM apart (lateral) with 5 NM required and 300 ft vertical with 1000 ft required have 60% MoC in the lateral and only 30% in vertical. However, the actual MoC is 60% and not 30%, based on the furthest distance apart.

The **severity score** is derived as a sum of two scores, one of which is based on the MOC and the other on the horizontal or vertical rate of closure. The score based on the MOC is obtained according to the following schema:

- **0**: $100\% \leq \text{MoC}$
- **1**: $75\% < \text{MoC} < 100\%$
- **3**: $50\% < \text{MoC} \leq 75\%$
- **7**: $25\% < \text{MoC} \leq 50\%$
- **10**: $\text{MoC} \leq 25\%$

The score based on the horizontal closure rate (denoted as *relSpeedH* below) is derived as follows:

- **0** (NONE) : $\text{relSpeedH} \leq 0$
- **1** (LOW) : $0 < \text{relSpeedH} \leq 85$
- **2** (MEDIUM): $85 < \text{relSpeedH} \leq 205$
- **4** (HIGH) : $205 < \text{relSpeedH} \leq 700$
- **5** (VERY HIGH) : $\text{relSpeedH} > 700$

Similarly, the score based on the vertical closure rate (denoted as *relSpeedV* below) is derived in the following way:

- **0** (NONE) : $\text{relSpeedV} \leq 0$
- **1** (LOW) : $0 < \text{relSpeedV} \leq 1000$
- **2** (MEDIUM): $1000 < \text{relSpeedV} \leq 2000$
- **4** (HIGH) : $2000 < \text{relSpeedV} \leq 4000$
- **5** (VERY HIGH) : $\text{relSpeedV} > 4000$

From the two scores based on the horizontal and vertical closure rates the higher one is taken. It is summed with the MoC-based score to make the overall severity score. The severity score thus ranges from 0 to 15, where 15 is the sum of the maximal values for the MoC-based score (10) and the closure rate-based score (5).

3.1.2 Visual representation of the measures of criticality

The cells of the table showing data that are relevant to determining the degree of conflict severity contain horizontal bars whose length and colouring signify the degrees of value criticality, which is

- **directly proportional to** the values of the **severity score** and horizontal and vertical **rates of closure** (higher values are more critical)
- and
- **inversely proportional to** the value of the **compliance measure** and to the horizontal and vertical distances (smaller values are more critical).

To attract user's attention to more critical values, they are represented by longer bars coloured in shades with higher proportions of red, as illustrated in Fig. 40.

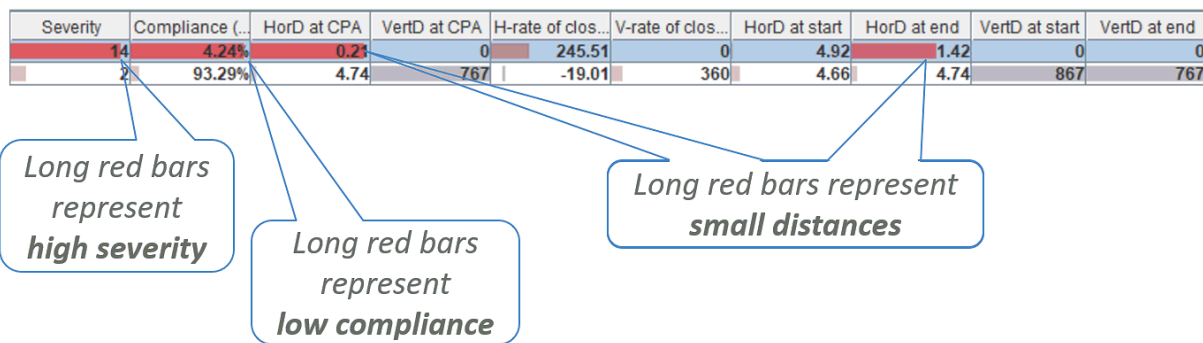


Figure 40. Representation of values relevant to determining conflict severity by horizontal bars in table cells. The bar length and degree of redness represent the degree of criticality, which is directly proportional to the values of the severity score and horizontal and vertical rates of closure (higher values are more critical) and inversely proportional to the value of the compliance measure and to the horizontal and vertical distances (smaller values are more critical).

For example, in the upper row of the table fragment shown in Fig. 40, the severity score is very high, 14 out of 15. It has high criticality; so, the bar in the corresponding cell stretches almost to the full width of the cell and has quite bright reddish colouring. In the next cell, there is the compliance measure. Here, the value is very low, close to zero, which is very critical. Therefore, it is also represented by a long red bar. The value of the compliance measure is low due to small horizontal distance, i.e., the conflict emerges due to insufficient horizontal (lateral) separation. Therefore, the cells showing the horizontal distances at the CPA, start, and end of the conflict event contain reddish-shaded bars with the lengths and the proportion of red being inversely proportional to the distances.

The purpose of this method of visual representation is to attract users' attention to more critical information that is important for making appropriate and timely decisions.

3.1.3 Popup windows with additional information

Upon pointing on particular cells of the conflict description table, users can get additional information relevant to a conflict. The information is shown in popup windows.

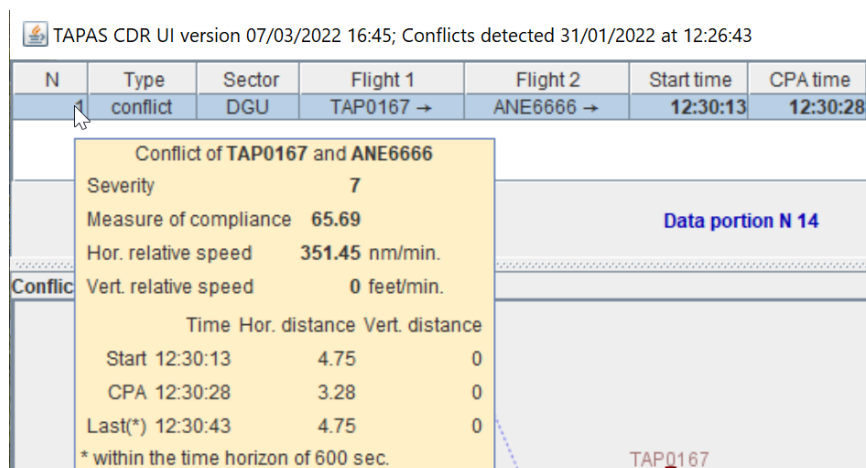


Figure 41. A popup window with information about a conflict re-arranged in a more compact layout.

Figure 41 demonstrates a popup window appearing when the cursor points at a cell containing the sequential number of a conflict. It shows the same information as can be seen in the table, but the information is arranged in a different way, which may be convenient when the table is wide and requires substantial gaze movement for reading values from a long row of the table.

TAPAS CDR UI version 07/03/2022 16:45; Conflicts detected 31/01/2022 at 12:26:43

N	Type	Sector	Flight 1	Flight 2	Start time	CPA time
1	conflict	DGU	TAP0167 →	ANE6666 →	12:30:13	12:30:28

Conflict of flights TAP0167 and ANE6666

Flight TAP0167

Destination LPPT

Phase cruising

Course 251.7 degrees

Horizontal speed 441.662 knots 0.6624 Mach

Vertical speed 0 feet/min.

Altitude 36000 feet

Figure 42. A popup window with additional information about a flight.

Figure 42 demonstrates a popup window appearing when the cursor is pointing on a cell with a callsign of a flight. The window contains additional information about the flights, specifically, its course, horizontal and vertical speed, and altitude.

VertD at start	VertD at end	Due to
0	0	12:26:13 S2 by -10 to TAP0...

12:26:13 issued:

S2 (course change) by -10 applied to TAP0167 and

S2 (course change) by 20 applied to ANE6666

Figure 43. A popup window with additional information about the cause of the conflict that is expected to emerge due to non-conformance of one or two flights to an earlier issued ATCo instruction to fulfil certain conflict resolution actions.

Figure 43 shows a popup window that can be seen when a conflict results from non-conformance of one or two flights to an earlier issued ATCo instruction to fulfil certain conflict resolution actions. In such a case, there is a text in the column “Due to” referring to the cause of the conflict. The popup window appears when the cursor is pointing on the cell containing the text. The window shows the time when the ATCo instruction was issued and the action(s) that the flight(s) was/were required to fulfil.

3.2 Graphical view of the conflict geometry

A sub-window with a graphical illustration of a conflict is positioned on the left below the table with conflict descriptions. The graphical view represents the conflict corresponding to the “active” row of the conflict description table, i.e., the row that is currently highlighted, i.e., the cells have light blue background. A table row becomes “active” after a mouse-click on it.

The graphical view (Fig. 44) consists of two parts separated by a horizontal movable divider. The upper part represents a lateral view, in which the display dimensions correspond to the geographic longitude

and latitude. The positions of the flights at the moment of conflict detection are represented by filled small squares and their expected paths are represented by lines. Solid lines correspond to the paths preceding the conflict and dashed lines to the path continuations after the conflict. The path segments corresponding to the time interval of the conflict existence are represented by thicker lines. Hollow squares correspond to points of projection, i.e., predicted positions of the flights. Dark red and dark blue colours of the squares and lines are used to distinguish two flights.

Cross marks represent the positions of the flights at the moments of conflict start (these crosses are coloured in dark yellow, or brownish), CPA (red), and conflict end (green). It may happen that two or even three of these time moments coincide. The reason is that the XAI uses a limited time horizon, namely, 600 second forward, within which it tries to detect conflicts. When a conflict is expected to start at the end of the detection time horizon, the XAI will report all three times as the same. When a conflict will begin shortly before the end of the time horizon, the times of the reported CPA and last point of the conflict will be the same. When points coincide, the cross representing the CPA may cover the first point of the conflict, and the last point of the conflict may cover the CPA.

Clicking on the left button of the mouse when the cursor is inside the lateral view enlarges the drawing and clicking on the right button makes the drawing smaller. Dragging the mouse inside the view shifts the drawing with respect to the view port.

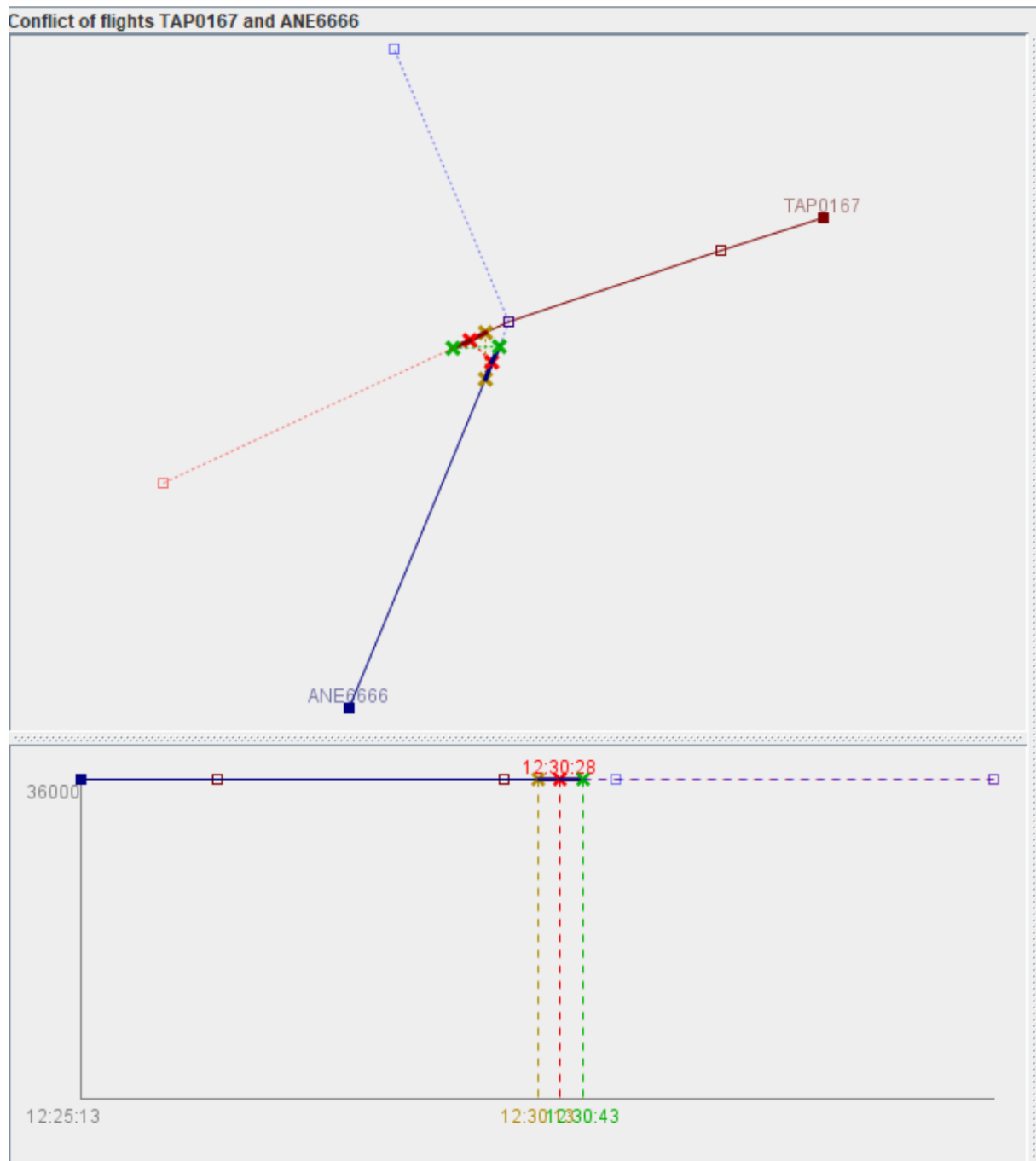


Figure 44. Schematic representation of conflict geometry. The upper sub-window represents the lateral view. The horizontal and vertical dimensions correspond to the longitude and latitude, respectively. The lower sub-window contains a plot of the flight altitudes (vertical dimension) over time (horizontal dimension). In this example, two flights have the same altitude that does not change over time.

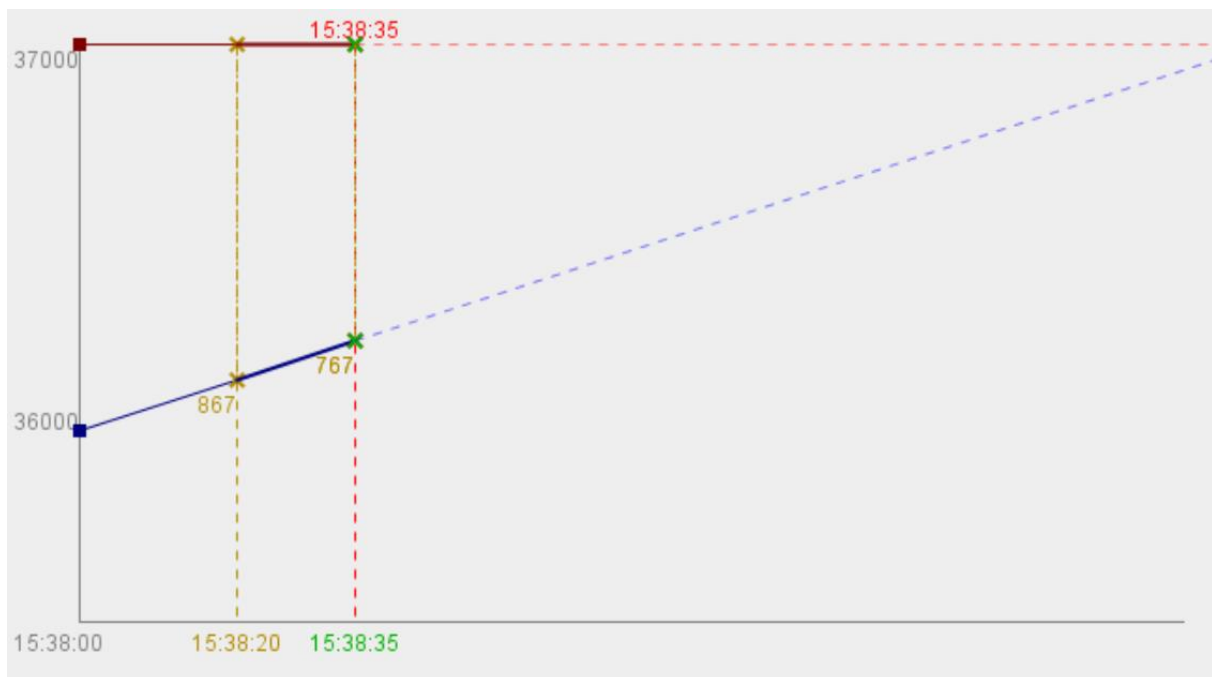


Figure 45. An example of a flight altitude plot for a conflict where the altitude of one of the flights changes over time.

The lower part of the graphical view contains an altitude plot, where the horizontal axis represents time and the vertical axis the flight altitude. The changes of the flight altitudes over time are represented by lines. When the flight altitude does not change, the corresponding line is horizontal. The graphical encoding is consistent with the encoding in the lateral view. When two flights have the same constant altitude, the two lines are drawn one on top of the other, as can be seen in Fig. 44. Figure 45 demonstrates a different example, where one flight has a constant altitude (37000 feet) and the other goes from the altitude 36000 feet upward. If the vertical distance between the flights changes over time, as in Fig. 45, the plot includes numbers showing the vertical distances at the conflict start, CPA, and conflict end. In Fig. 45, the times of the CPA and the last point of the conflict (as reported by the XAI) coincide; therefore, the green crosses cover the red ones, and, obviously, the vertical distance is common for both points. At the top and at the bottom of the plot, the times of the conflict detection (corresponding to the origin of the horizontal axis), conflict start, CPA, and conflict end are shown as text labels.

The lateral view and the altitude plot are linked by an interactive operation working as follows. When the mouse cursor is inside the altitude plot, a vertical line in bright pink colour is drawn through the position of the cursor (Fig. 46, lower part). It marks the time corresponding to the cursor position. The time is shown as a text below the horizontal axis. Simultaneously, a bright pink line is drawn in the lateral view (Fig. 46, upper part). It connects the points of the flight paths corresponding to their positions at the time that is marked in the altitude view. When the mouse cursor moves horizontally across the altitude plot, the corresponding lines in both views also move. At the top of the lateral view a text in bright pink shows the horizontal and vertical distances between the flights at the time corresponding to the mouse position.

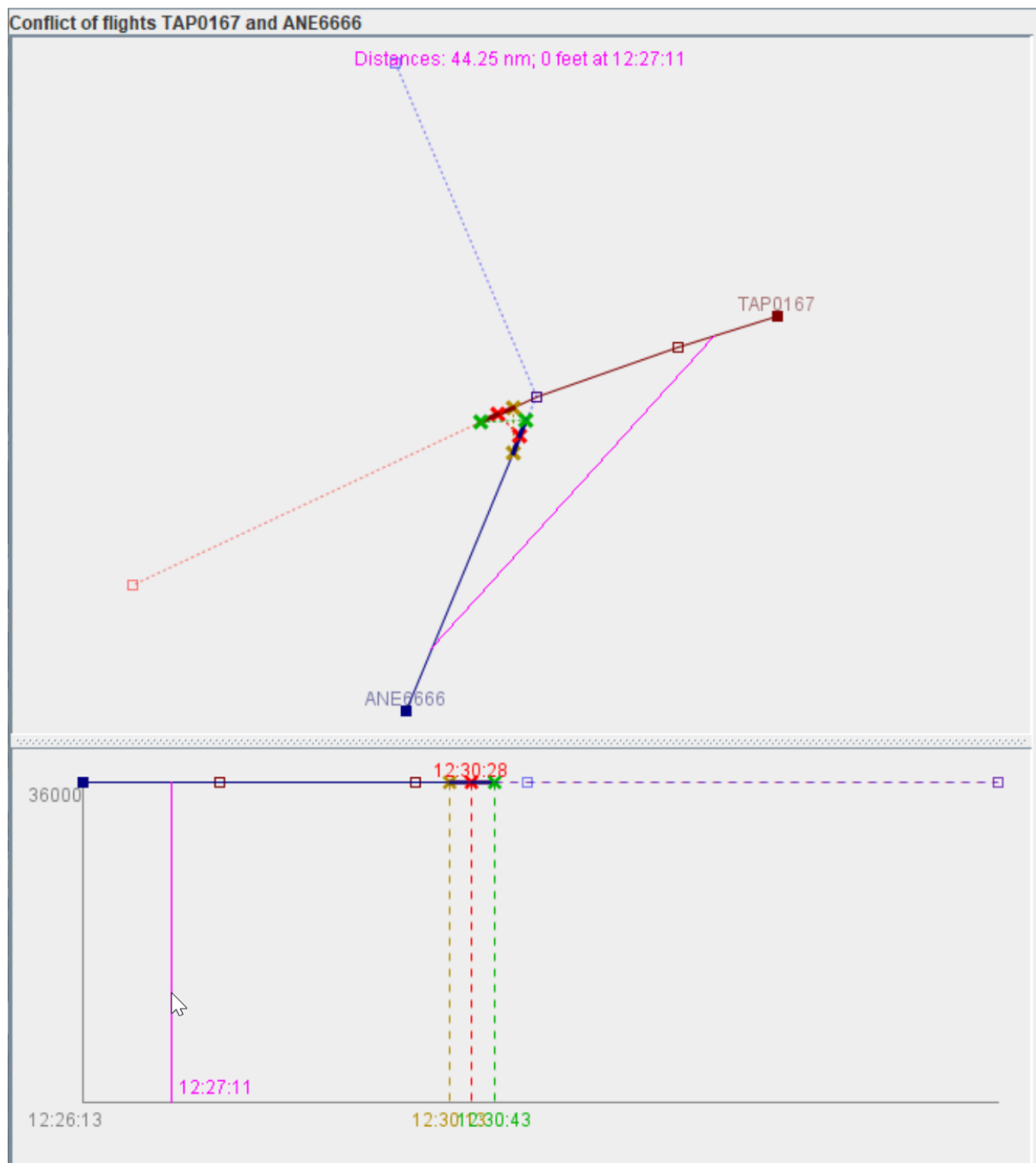


Figure 46. Tracing aircraft positions over time by moving the mouse horizontally across the altitude plot.

3.3 Table with resolution actions

The sub-window on the right below the conflict description table contains a table describing the conflict resolution actions proposed by the XAI component. The appearance of the table is demonstrated in Fig. 47. The figure includes two examples of the table, to demonstrate different types of resolution actions.

Show actions with ranks up to <div><div>3</div><div>max = 30</div></div>															
Flight	Action	Value	Do?	Rank	Added miles	Added seco.	Conflicts fore.	H-speed ch.	V-speed cha.	Course cha.	H-shift at ...	V-shift at ...	Bearing	Duration	Why not
TAP0167	S2: course chan...	10	Do	0	1.479	0	1	0	0	10	14.7	0	264.662	120	
ANE6666	S2: course chan...	20	Do	0	0.24	0	1	0	0	20	35.084	0	42.504	30	
TAP0167	A2: speed change	0.0105	Do	1	0	0	1	1.05	0	0	3.741	0	254.662	30	
ANE6666	S2: course chan...	10	Do	1	0.062	0	1	0	0	10	24.682	0	32.504	30	
TAP0167	A2: speed change	0.0105	Do	2	0	-1	1	1.05	0	0	3.741	0	254.662	60	
ANE6666	S2: course chan...	20	Do	2	2.063	0	1	0	0	20	35.084	0	42.504	180	
TAP0167	S2: course chan...	-10	Do	3	0.503	0	0	0	0	350	-7.242	0	244.662	120	
ANE6666	S2: course chan...	20	Do	3	0.511	0	0	0	0	20	35.084	0	42.504	60	

Flight	Action	Value	Do?	Rank	Added mi.	Added seco.	Conflicts fore.	H-speed ch.	V-speed cha.	Course c.	H-shift at ...	V-shift a	Bearing	Duration	Why not
TAP0167	S2: course change	10	Do	0	0.399	0	1	0	0	10	12.37	0	261.984	120	
ANE6666	S2: course change	20	Do	0	0.244	0	1	0	0	20	36.646	0	42.562	30	
TAP0167	A3: direct to waypoint	MIRPO (N 1)	Do	1	0	0	1	0	0	0.812	0.25	0	251.172	0	
ANE6666	S2: course change	10	Do	1	0.063	0	1	0	0	10	26.211	0	32.562	30	
TAP0167	S2: course change	-10	Do	2	0.267	0	1	0	0	350	-10.054	0	241.984	120	
ANE6666	S2: course change	20	Do	2	2.229	0	0	0	0	20	36.646	0	42.562	180	
TAP0167	A1: flight level chan...	1	Do	3	0	0	0	0	1.020	0	1.161	510	251.984	0	
ANE6666	S2: course change	-10	Do	3	0.123	0	0	0	0	350	5.23	0	12.562	60	

Figure 47. Two examples of the tables with proposed actions for conflict resolution.

The XAI component usually proposes multiple possible actions, which are ranked by preference, so that rank 0 indicates the most preferable action while higher values correspond to less preferable actions. Each action refers to one of the two flights involved in the conflict. The actions are ranked separately for each flight; therefore, there are pairs of actions having the same rank. A text field above the table can be used to set the desired maximal rank of the shown actions, which means that actions with larger ranks, if any, will be hidden. The value in the field can be edited through the keyboard or by pushing on the “up” and “down” buttons on the right of the text field. In Fig. 47, the maximal rank for showing actions is set to 3. As a result, each table shows actions with ranks from 0 to 4, i.e., 4 actions for each flight, 8 actions in total.

The columns of the action table present the following information:

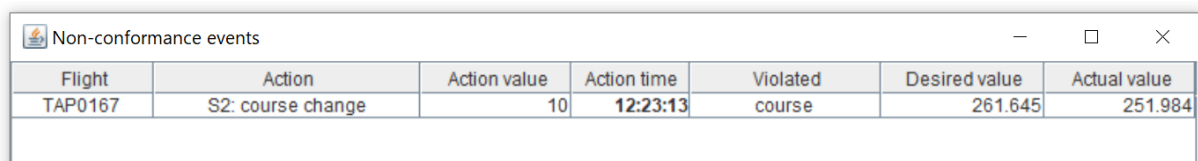
- Callsign of the flight that will need to fulfil the action.
- Action type, which is one of the following:
 - A1 - flight level change,
 - A2 - speed change,
 - A3 - direct to waypoint,
 - A4 - no action,
 - S2 - course change,
 - CA - continue action,
 - RFP - resume to flight plan
- Action value, the meaning of which depends on the action type:
 - A1 - flight level change: either -1 or 1, which means moving to the nearest lower or upper flight level,
 - A2 - speed change: a positive or negative value indicating speed increase or decrease, represented as a Mach number (i.e., as a ratio to the speed of the sound),
 - A3 - direct to waypoint: the name and ordinal number of the waypoint to which the flight is directed,
 - A4 - no action: zero,
 - S2 - course change: angle with respect to the current course, in degrees,
 - CA - continue action: zero,
 - RFP - resume to flight plan: zero.

- Rank: 0, 1, 2, and so on.
- Added miles: change of the flown distance due to the action.
- Added seconds: change of the flight duration due to the action.
- Conflicts foreseen: number of conflicts that will remain or emerge after applying the action.
- H-speed change and V-speed change: changes of the horizontal and vertical speeds, the former represented as Mach number and the latter in feet per minute.
- Course change: angle with respect to the current course, in degrees.
- H-shift at exit and V-shift at exit: the relative position of the point of exit from the sector with respect to the previously planned point of exit. The horizontal shift is measured in metres and the vertical shift in feet.
- Bearing: the bearing of the flight after fulfilling the action.
- Duration: duration of the resolution action, in seconds.
- Why not: when some action is theoretically possible (according to the AI model, which has been derived from historical data) but cannot be performed in the current situation, this field contains a description of the reason, for example, “Vertical speed cannot be increased because it will exceed 60.0 feet/s”.

Apart from the information columns, there is a special column containing buttons with the text “Do”. Pressing on such a button means selecting of the corresponding action to be fulfilled. In response, the VA component displays a dialog window asking for a confirmation that the chosen action is going to be applied to the corresponding flight. If the user confirms the decision, a message about the chosen action is sent to the XAI component.

3.4 Additional windows

When the field “Conflicts foreseen” in a row of the table with the resolution actions contains a value greater than zero, clicking on this row creates an additional window showing information about the secondary conflict(s) that will remain or appear after the action is fulfilled. Like the main window, the secondary conflict window contains a table with conflict descriptions (see Section 3.1). Clicking on a table row opens a graphical view of the conflict geometry, as described in Section 3.2. However, the secondary conflict window does not include a table with resolution actions.



Flight	Action	Action value	Action time	Violated	Desired value	Actual value
TAP0167	S2: course change	10	12:23:13	course	261.645	251.984

Figure 48. An example of a window with information about non-conformance events.

A window containing a table with non-conformance events (Fig. 48) appears when such events are detected by the XAI component. A non-conformance event means that a flight does not fulfil some conflict resolution action that the air traffic controller has chosen earlier. In this case, the table shows the flight that does not conform to the controller’s decision, the action that is not fulfilled, the time when it was supposed to be done, what parameter is violated, i.e., the value differs from the required

(e.g., "horizontal speed", "vertical speed", "course"), the desired value of this parameter, and the actual value. The window disappears when no non-conformance events are detected in the next step of the monitoring process.

3.5 Communication between the XAI and VA components

The XAI and VA components communicate by exchanging messages, which are transmitted via two channels, one directed from XAI to VA and the other in the opposite direction. In each iteration step of its work, the XAI tries to detect conflicts that will emerge within a certain time horizon (currently 600 seconds) from the current moment. The results of the calculation are put in files, and the XAI sends a message to the VAI component notifying about the appearance of the new data. In response, the VA component takes the data from the files and immediately updates the views to show the most recent information. When no conflicts are expected, the views will be empty.

A message from the VA component to the XAI is sent when the user selects a resolution action (i.e., presses the button "Do" in the corresponding row of the actions table) and confirms the decision. The message contains the description of the action.

4 Conclusion

The research field of XAI emerged in response to the pressing need to explain untransparent ML models (“black boxes”) to users. The work in this field was boosted by the European Parliament’s adoption of the General Data Protection Regulation (GDPR), which introduces the right of individuals to receive explanations of automatically made decisions relevant to them. However, some ML researchers argue that the current XAI approaches fail to provide satisfactory explanations that can be well understood by humans, i.e., linked to their mental models. A promising approach to solving this problem is to combine XAI with Visual Analytics [[1]]. Visualisation and interactive visual interfaces are recognised as effective means enabling human understanding of data, computer operations, and computer-generated results. Therefore, interactive visual interfaces are deemed necessary for supporting explainability of ML/AI methods and models by presenting information about their work and underlying logic in the form that is easily perceived and understood by humans.

In this document, we have described the interactive visual interfaces developed in the context of the TAPAS project with the aim to address the requirements towards explainable Artificial Intelligence methods for the ATFCM use case (Chapter 2) and the CD&R use case (Chapter 3). The VA components were developed in accordance with the specification of the ATFCM and CD&R tasks and functional requirements provided in the TAPAS deliverable D2.3 “Consolidated requirements and functional roadmap”. The development process was also guided by the transparency requirements specified in the TAPAS deliverable D3.1 “ATFM transparency requirements” and D3.2 “CD&R transparency requirements”.

The VA techniques have proved to be useful in supporting understanding of problematic situations and solutions suggested by the ML/AI components. The development and testing of the VA prototypes has also revealed the existence of a complicated problem, which can be characterised as a conceptual mismatch between ML/XAI models and approaches, on the one side, and human mental models and ways of reasoning, on the other side [[1]]. This problem can be solved through incorporation of human expert knowledge into ML methods and models, which opens an interesting and challenging direction for future research.

References

- [1] N. Andrienko, G. Andrienko, L. Adilova and S. Wrobel, "Visual Analytics for Human-Centered Machine Learning," in IEEE Computer Graphics and Applications, vol. 42, no. 1, pp. 123-133, 1 Jan.-Feb. 2022, doi: 10.1109/MCG.2021.3130314.
- [2] G. Andrienko, N. Andrienko, J. M. Cordero Garcia, D. Hecker and G. Vouros, "Supporting Visual Exploration of Iterative Job Scheduling," in IEEE Computer Graphics and Applications, doi: 10.1109/MCG.2022.3163437.