Deliverable 3.4

CCAM local simulations

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101064988.

Version number:	1.0 (final)
Main author:	Tarek Chouaki – IRTX
Dissemination level:	PU
Internal Reviewers:	ICCS, POLITO
Lead contractor:	IRTX
Due date:	13/06/2025
Delivery date:	17/06/2025

Version history			
Version	**Date**	**Main author**	**Summary of changes**
0.1	12/06/2025	IRTX (Tarek Chouaki)	Initial version
0.2	14/06/2025	IRTX (Tarek Chouaki)	Applied comments from POLITO
0.3	17/06/2025	IRTX (Tarek Chouaki)	Applied comments from ICCS
1.0	17/06/2025	ERTICO (Andrew Winder), UNIMORE (Giacomo Cantini)	Final check and submission

Legal disclaimer

Executive Summary

Connected and automated mobility holds great promise for improving the transportation of so-called People with Mobility Challenges (PMC), such as the elderly or mobility-impaired persons. By making specific areas more accessible and extending urban and suburban services in time and space, Cooperative, Connected and Automated Mobility (CCAM) make it possible to offer targeted services to improve social integration.

Previously within the SINFONICA project, a simulation framework has been developed to allow simulations of CCAM services in localized settings and with a high level of configurability. The framework allows to test various CCAM deployment scenarios and assess their performance. Moreover, inclusivity considerations are built in the tool with a distinction between PMC and non-PMC users.

This report presents a tool that builds up on the simulation framework to allow non-experts to interact with the simulation framework on a user-friendly interface. The tool comes with a set of use cases related to the SINFONICA research sites. The work towards the completion of the tool and the included use cases are described in this report.

First, a description of the overall methodology behind this work is given. Then, a background on the simulation framework as well as the additions that were introduced to it in the scope of this task are presented.

An in-depth description of the tool itself is given in the third chapter. The adopted software architecture is outlined and the used technologies are listed. Finally, the report details the use cases that were implemented and included within the tool.

Contents

Tables

Figures

Abbreviations

Abbreviations	Meaning
CCAM	Connected Cooperative and Automated Mobility
KPI	Key Performance Indicator
MATSim	Multi-agent transport simulation
PMC	People with Mobility Challenges

1 Introduction

SINFONICA explores how CCAM services can be designed and deployed in an inclusive and accessible way that provides benefits in mobility to the entire population. The main focus of the project is a co-creational approach in which challenges in terms of inclusivity and accessibility for CCAM, especially for People with Mobility Challenges (PMC), are identified and recommendations and best practices for deployment are formulated. One line of research in the project aims at forming these considerations by simulation-based experiments in which CCAM services are simulated under different service configurations and in varying environments. These investigations are interesting for both cities and CCAM operators. For the former, they would help to make sure that all user groups have equal access to the service. For the latter, they would allow to find suitable trade-offs between inclusivity and overall service performance and cost implications.

The activities around simulation-based assessments in SINFONICA are covered mainly by the two tasks *T2.4: Creation of simulation models for upscaling of measures* and *T3.7: Scaled up impacts on mobility*. The present document presents the final deliverable for task T3.7. Building on the simulation framework developed in T2.4, we develop a user-friendly tool that allows experts and non-experts to investigate deployment scenarios of CCAM service using detailed agent-based simulations that allow to measure a wide set of Key Performance Indicators (KPIs). Several use cases were developed and incorporated within the tool, including the SINFONICA Research Sites (West-Midlands, Hamburg, Trikala and Noord-Brabant)

The inclusivity features implemented in the simulation framework are also reflected in the tool presented here through parameters and KPIs related to PMCs. Furthermore, the present report assesses how two frequently used fleet management algorithms operate in the presence of user heterogeneity and identify issues in terms of fairness towards PMCs and explore pathways on mitigating the problem. This way, a solid technical foundation is set for the experiments to be conducted in T3.7.

1.1 Purpose and structure of the document

The present document constitutes deliverable D3.4 of the SINFONICA project that describes a CCAM fleet simulation toolbox. The work presented here has been implemented in task T3.7. In the following, we introduce both the description of T3.7 and D3.4 and **highlight** the most important aspects that have guided the content of this deliverable.

Task description T3.7: Scaled up impacts on mobility.

In T2.4, SINFONICA proposes to develop a generic framework for the simulation of custom cooperative fleet management simulations, which take explicitly into account individual customer requirements. **This framework will be operationalized in T3.7** to test use case scenarios which are based on the outputs of the other tasks in WP3 and in collaboration with the city partners. **The proposed solutions will reach from door-to-door services to stop-based and line-based operational schemes**. To perform context-relevant analyses for the cities, **four individual demand**

scenarios will be developed that represent well expected passenger flows of potential CCAM services, including special user requirements and constraints.

To that end, **a series of simulation experiments** with **sensitivity analysis** will be defined **covering a wide range of operational assumptions**. The new mobility services' impacts on the mobility of the defined demand population will be assessed in **terms of travel times, cost and reachability for individual origin-destination relations and times of the day**. The **operational economic impact of offering individualized services**, as well as indicators on noise, emissions and congestion will be derived.

Deliverable description D3.4: CCAM local simulations

Exploration of **CCAM local value cases** for the groups of interest, populated with a range of **socio-economic KPI** to support strategic decision-making

In the following, we give an overview of the individual chapters of this report and how they relate to the task and deliverable description.

Chapter 1 introduces the task T3.7 of the SINFONICA project and gives a general overview of the task implementation activities.

Chapter 2 provides the background upon which the developments related to this task have been performed. Mainly the simulation framework developed in T2.4 and presented in D2.3. In this deliverable, we give a brief overview of the simulation framework as detailed in D2.3 and a more detailed presentation of the features that were added to it in the scope of the current task.

Chapter 3 details the architecture of the tool and interface developed within this task. First, the presentation of the overall software architecture allows to understand the main components and how they interact between themselves and with the simulation framework. Then, a user centric perspective is adopted to describe the user workflow up until the visualization of a given simulation results alongside figures of the interface while detailing the available parameters that the user can adjust to explore different CCAM scenarios. A deep dive is then performed on the KPIs and visualizations that were introduced to enable users to assess CCAM solutions. Finally, the packaging of the different components is described and deployment steps are outlined.

Chapter 4 presents the simulation use cases that were developed for various areas, including the SINFONICA research sites: West-Midlands, Noord-Brabant, Trikala, and Hamburg. The types of services considered in the research sites cover the set of service types that are identified in the project's grant agreement. We also present the set of parameter values that are available in the tool for each of the research sites.

Finally, we conclude with **Chapter 5** where we summarize the outcomes of this task and outline the dissemination activities associated with the tool presented in this deliverable.

1.2 Methodology

Tasks T2.4 and T3.7 make use of simulation-based assessments to estimate the impact of a new CCAM system on a specific territory and under specific operational decisions. These decisions include the size of the fleet, the operational mode (door-to-door, stop-based, line-based) and service criteria such as the promised maximum travel time.

The objective of T2.4 was to provide a generic framework for simulating CCAM services while taking into consideration inclusivity aspects and investigating discriminatory behaviour of operational strategies against PMC users. In T3.7, the main goal is to enable non-experts to use the simulation framework on local use cases and investigate a wide range of CCAM service deployment scenarios and assess their impacts on users and implications on operators. An emphasis is then put on the user-friendliness of the tool to be developed, through an intuitive interface and a clear workflow. Moreover, simulation use-cases for the SINFONICA research sites are to be deployed within the tool. In order to achieve this, an incremental and iterative methodology was followed with three parallel axes was followed:

- First, the specification and development of the user interface started very early, even before the task's scheduled beginning. This was necessary to ensure proper time to test various layouts and iterate over interface versions. Early versions of the tool showcase a synthetic scenario with a service area in the Paris region which is regularly considered in simulation related works at IRT SystemX. Moreover, an important part of this work relates to specifying the KPIs that are computed and plots that are generated for display in the interface.
- Second, the specification of simulation use cases for the SINFONICA research sites. In this part of the task, we attempt to build on the knowledge resulting from the data collection activities of the SINFONICA project as well as on the real-world knowledge of relevant members of the consortium.
- Third, as the specification of the KPIs and plots to be produced and the research site use cases to be developed advanced, new functionalities were added to the simulation either to produce more KPIs or to support more service types or configuration parameters.

1.3 Intended audience

As this report presents a tool that brings advanced simulation tools closer to non-experts, the primary intended audience of this report are transport researchers and modellers that are familiar with agent-based transport modelling tools and methodologies. However, non-modelling experts interested in mobility may also be interested by the design choices of the tool, particularly the set of KPIs that were chosen to assess the overall performance and impact of a CCAM service. Beyond directly using the tool developed here, local authorities may be interested in the detailed descriptions given in this document on implemented simulations to better understand how such a methodology can be replicated on their territories.

1.4 Interrelations

This deliverable is linked D1.1 *Mobility needs and requirements of European citizens* as well as the work performed in T1.4 in the report of which relevant user groups for SINFONICA have been identified.

This present deliverable D3.4 links directly to deliverable D2.3 in which the technical components elaborated are used to perform the simulations specific to the use cases considered in this work, including the SINFONICA research sites for Hamburg, West Midlands, Noord Brabant and Trikala.

2 Background

In this section, we present the background behind the developments performed within this task. The principal pre-existing foundation of the tool developed here is the simulation framework developed in T2.4 and detailed in D2.3. In the following, we only succinctly describe the state of the framework as developed in T2.4. We then describe in more details the components added to the framework during this task.

2.1 Simulation framework

The simulation framework developed in T2.4 is built on top of the MATSim[1] simulation software (Horni et al., 2016). It is an open-source multi-agent transport simulation tool that is widely use by a large number of academics, industrials, and mobility practitioners around the world. The topics on which MATSim is applied range from the analysis of road-pricing to the deployment of automated vehicles, to the measurement of noise emissions and the analysis of mitigation measures for train perturbations. The large community of maintainers and contributors behind MATSim allows it to be constantly updated with new functionality.

Within SINFONICA and T2.4 in particular, IRT SystemX developed components that allow to simulate travellers that interact with the service in a heterogeneous way. Namely, a user-dependant pickup and drop-off time was implemented in contrast with the initial state of the tool where all users always had the same values for these durations. This allowed to consider PMC passengers that require more time for pick-up and drop-off than non-PMC ones. Simulations presented in D2.3 featuring PMC users allowed to uncover discriminatory behaviour against them where they were subject to higher rejection rates and wait times. Furthermore, mitigation strategies were proposed to reduce the discriminatory behaviour. Among them, allowing PMC exclusively users to book requests in advance yielded the best results. The related functionality has also been implemented within the simulation framework and has been the topic of a conference paper (Chouaki & Hörl, 2024) presented at the hEART 2024 conference.

Finally, by focusing on CCAM service simulations, the simulation framework greatly simplifies the necessary inputs and configurations to run a simulation.

By the end of D2.4, the simulation framework was able to simulate door-to-door services under the presence of a mixed demand of PMC and non-PMC users and with the possibility of enabling prebooking for PMC users only or for all users. The necessary files to run a simulation were simply a vehicles file (containing capacities and initial location of the fleet vehicles), a demand file (containing origins, destinations, departure times and other operational constraints of the trips), and a file containing the road network description. A simulation could be started by passing the paths to the relevant files as well as the desired locations for output files through the command line.

[1] https://matsim.org/

2.2 Added components

In addition to the features implemented within the simulation framework during T2.4, other features were added during T3.7. These were identified mainly during the specification of simulation use cases for the research sites.

Stop-based services: one of the envisioned types of CCAM services limits pick-up and drop-off to certain locations, typically already existing public transport stops, instead of everywhere on the road network. Users would then need to walk from their origin to the pick-up location and from their drop-off location to their destination. In order to enable a stop-based service, the simulation framework now requires an additional file containing the stop coordinates. A point of attention is that, when simulating a stop-based service, one needs to make sure that the demand is covered by the stops, i.e., each trip origin and destination must be within at most 400 meters of a stop.

Line-based services: another envision type of CCAM services operate on pre-determined roads only instead of allowing vehicles to spread out on the road network to optimize travel times. This has been implemented within the simulation framework which requires a file containing the IDs of the roads on which the fleet vehicles are allowed to run. As with the stop-based services, demands to be simulated with line-based services must have origins and destinations located on the roads on which the service is allowed to operate. However, if the service is both line-based and stop-based, this obligation falls on the stops and the demand origins and destinations only need to be within 400 meters of the stops.

More flexible configuration: With the increased capabilities of the framework and the additional files that can be required, providing everything through the command line is more cumbersome and more prone to human error. To address this, a configuration file was defined for the framework. Such a file, in a YAML format, contains all the required elements and is the only needed argument for the command line interface. Users can still override some of the file's configuration elements through the command line if desired. If the YAML file refers to other files using relative paths, those paths are interpreted relative to the location of the YAML file itself, not the working directory.

Figure 1 shows an example configuration file for a stop-based service.

```yaml
requests: "requests.csv"
network: "network.xml.gz"
output: "../output"
operators:
  ccam:
    vehicles: "vehicles.csv"
    stops: "stops.csv"
    line: null
```

Figure 1 Example configuration file for the simulation framework

3 SINFONICA CCAM designer

In this section, we present the structure of the user-interface developed in this work (we call it SINFONICA CCAM designer). First, we present and motivate the software architecture choices that were made during the implementation. Then we detail the user workflow and show the views that are displayed for the user throughout the interaction with the tool. Afterwards, the visualization of simulation results is detailed as well as the sets of KPIs that are proposed. Finally, we describe the packaging of the tool and how it can be efficiently deployed.

3.1 Software architecture overview

The architecture of the SINFONICA CCAM designer tool is structured as follows:

Simulation pipelines: for each use case included within the tool, a simulation pipeline is built. Starting from relevant input data, a sequence of processing is performed to build the files compatible with the simulation framework and reflecting each of the scenarios that fall in the scope of the combination of values available in the interface for the given use case. A step of the pipeline is then to run the simulation using the framework detailed in Sections 2.1 and **Error! Reference source not found.**. Afterwards, the simulation results are processed to compute the KPIs and generate the plots for all the scenarios, each scenario is associated one json file containing the KPIs and the plots. Finally, all scenario files are compiled into a database of the use case's simulation results. Currently, the database is stored in a zip file. These pipelines are defined in Python using the ***snakemake***[2] library (Mölder et al., 2021). Its main advantage is that it allows to have processing steps implemented by heterogeneous technologies (simple Python scripts, Jupyter notebooks, command line scripts…) and that it natively handles parallelization of steps where applicable. The latter point allows to fully utilize computer resources and dramatically speed-up the database generation process.

Backend: The generated databases are then transferred to the backend of the SINFONICA CCAM designer. Its main function is to handle requests from the frontend to fetch the results of a given simulation and send them for display. The backend is written in Python and uses the **Flask**[3] library and communicates with the frontend through HTTP requests. To increase request-response speed, all simulation results for all use cases are loaded in memory at the start of the backend process, this way they are simply fetched from there to the frontend end without having to reload the database file at each request.

Frontend: The user interaction with the tool happens within the frontend interface which consists of a web page displayed on a web browser. The technologies used to develop the interface consists in **HTML** and **CSS** that are common in web development as well as JavaScript. More precisely, the **Bootstrap**[4] library is used for the overall layout and styling while the **Vue.Js**[5] library is used to

[2] https://snakemake.github.io
[3] https://flask.palletsprojects.com/en/stable/
[4] https://getbootstrap.com
[5] https://vuejs.org

structure the various components of the interface. The JavaScript **Plotly**[6] library is used to display the plots fetched from the database. Finally, map-related functionalities are implemented using the **Deck.GL**[7] library.

In the following section, we present the user workflow in the interface and show the views displayed to the user at each step of the interaction.

3.2 Introductory views and use case selection

Upon first accessing the interface through a web browser, the user is faced with a built-in introductory slide deck presenting the overall approach behind the tool and the context of the SINFONICA project (Figure 2, Figure 3, and Figure 4 respectively show the first, fifth and last slides of the deck). This provides the user with a light description of the background of the tool and the overall context within the SINFONICA project and the focus on inclusivity and refer to the relevant project deliverables for more information.

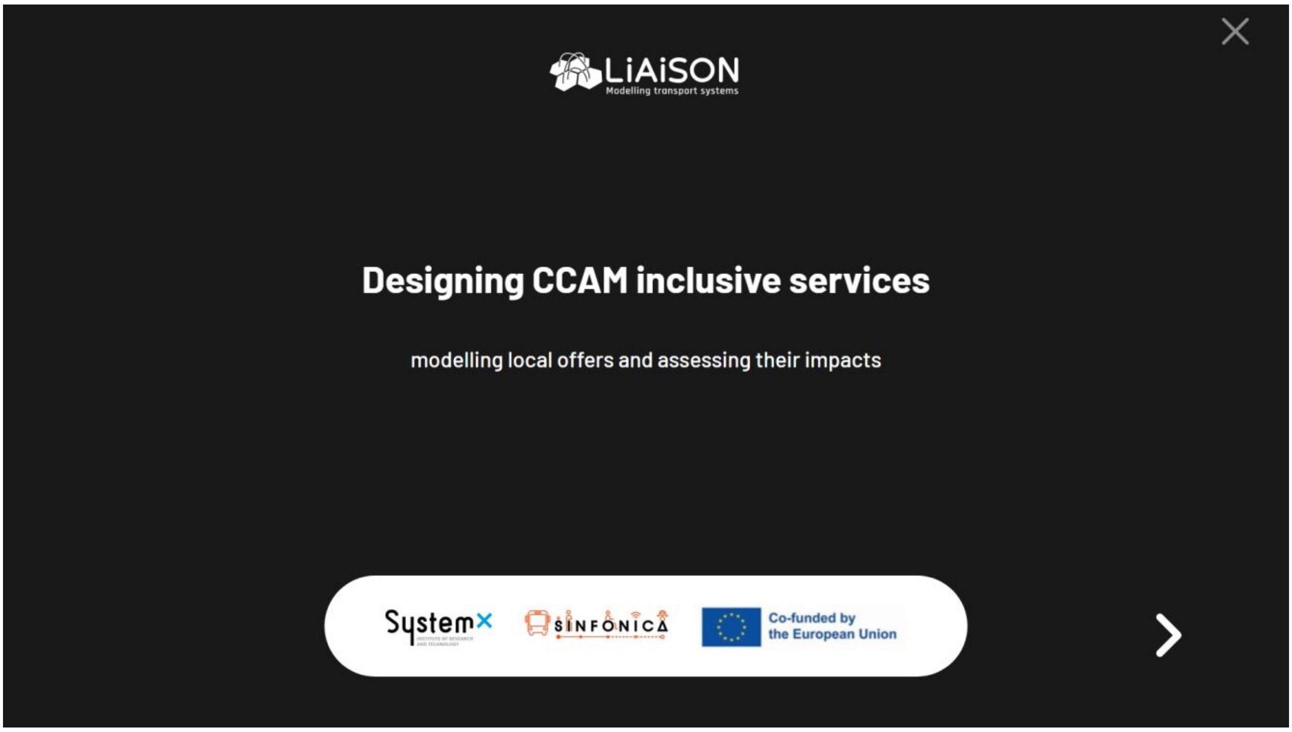

Figure 2: First slide of the tool's introductory slide deck

[6] https://plotly.com/javascript/
[7] https://deck.gl

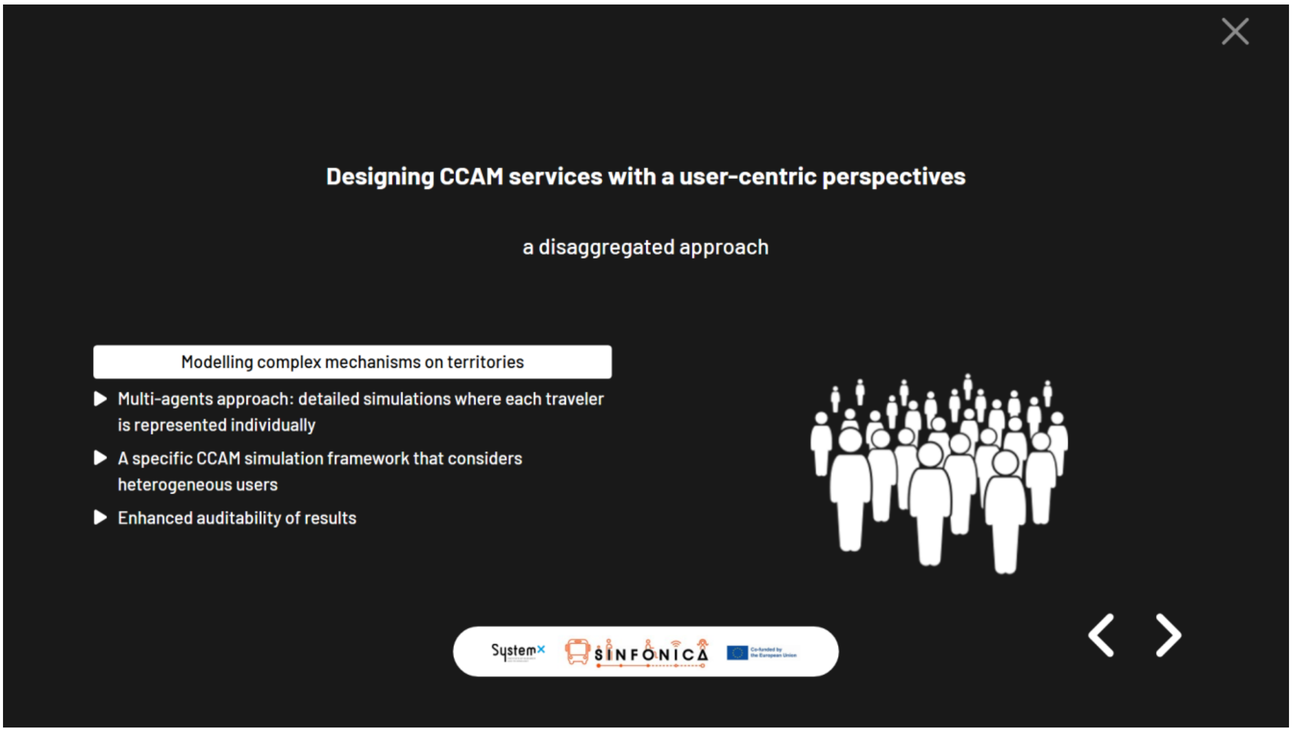

Figure 3: Fifth slide of the tool's introductory slide deck

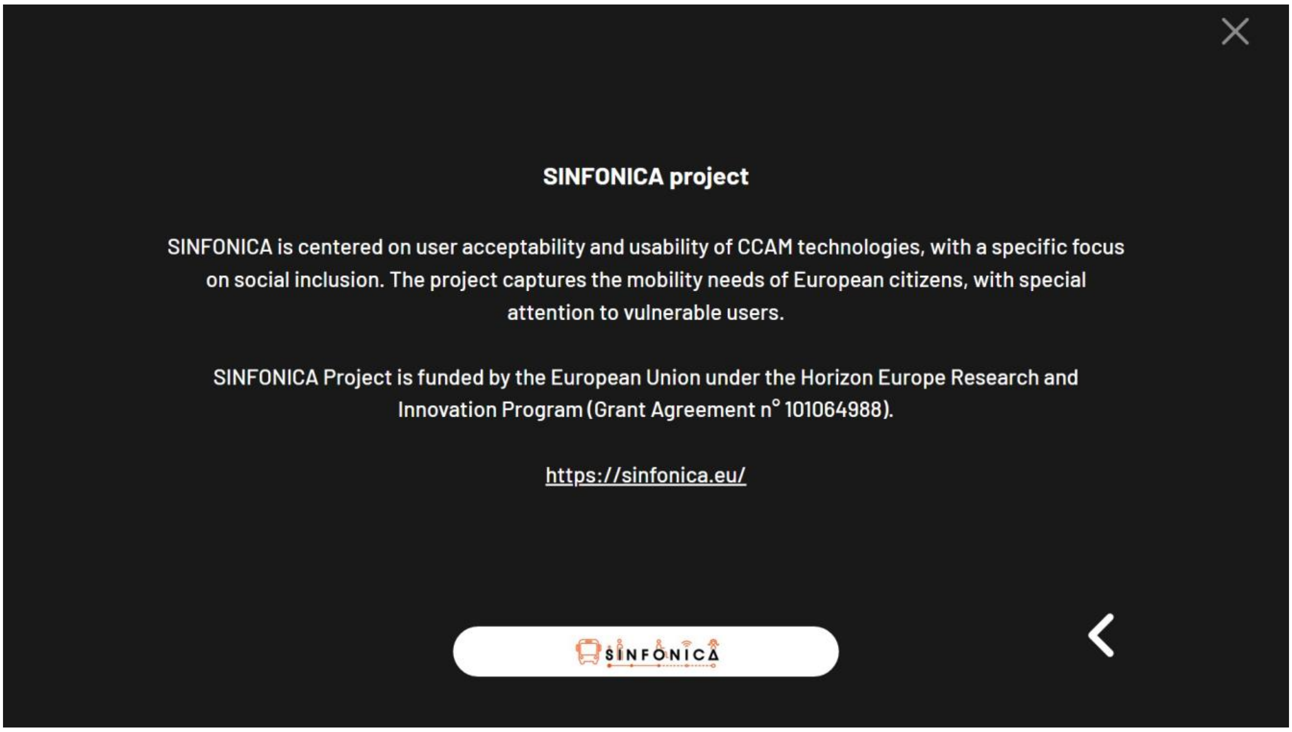

Figure 4: Last slide of the tool's introductory slide deck

The cross button on the top-right corner of each slides allows the user to close the deck and switch to the main home page of the tool depicted in Figure 5. The header and footer of the page are constant throughout the other views and provide a few links: on the top left corner, the SINFONICA logo also acts as a button that allows the user to go back to the home page, the SystemX logo on the top right corner acts a link to the IRT SystemX website[8], and the underlined SINFONICA text in the footer allows to reach the project's website[9].

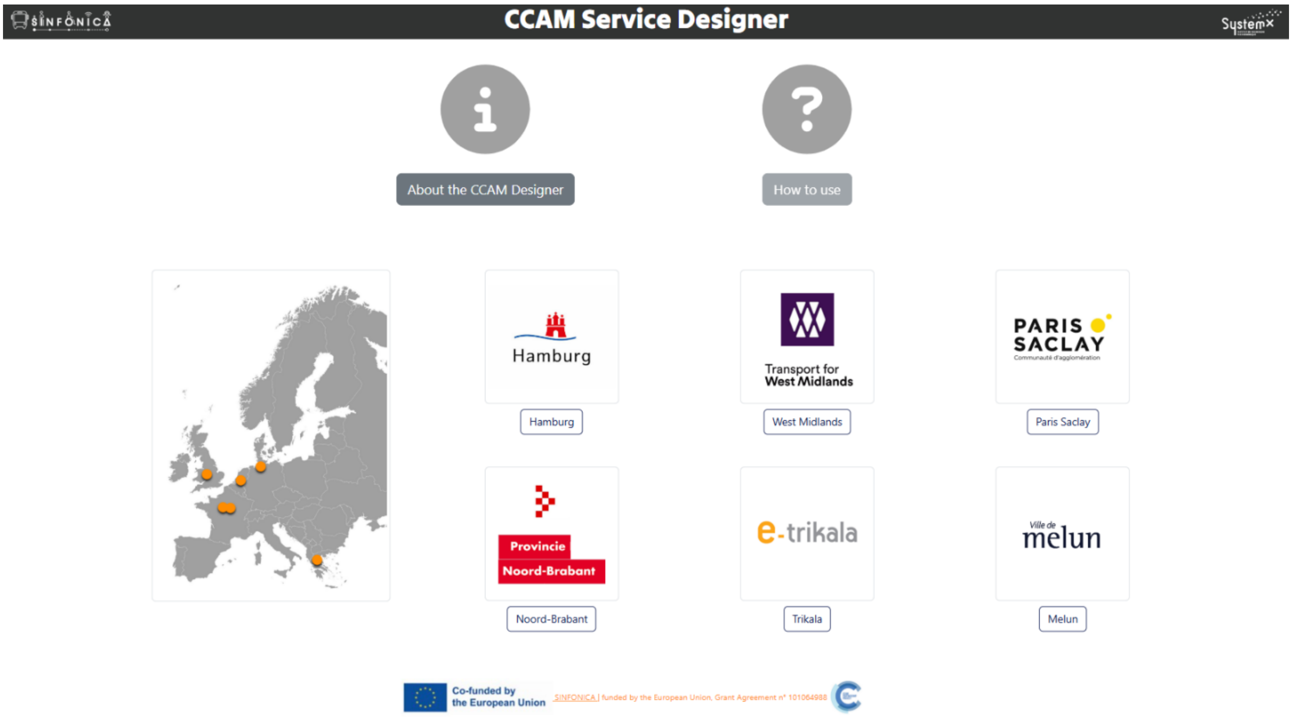

Figure 5: Main home page of the interface

In the top section of home page's body, two buttons are provided. The "About CCAM Designer" allows to re-display the slide deck while the "How to use" button shows a brief documentation on how to interact with the tool.

The bottom section shows the catalogue of available use cases. A static map image on the left simply shows the locations of these use cases while the listing on the right allows the user to select a use case on which to investigate simulations.

Upon clicking on one of the buttons below a use case's logo, the user is redirected to a page presenting an overview of the study area and a background on the particular type of CCAM services that is considered within this use case alongside links to relevant references. Figure 6 shows an example of such a page for the use case of West Midlands. Upon clicking on the "Design CCAM services for …" button, the user is directed to the main page allowing to configure, manage and investigate CCAM deployment scenarios.

[8] https://www.irt-systemx.fr/en/
[9] https://sinfonica.eu

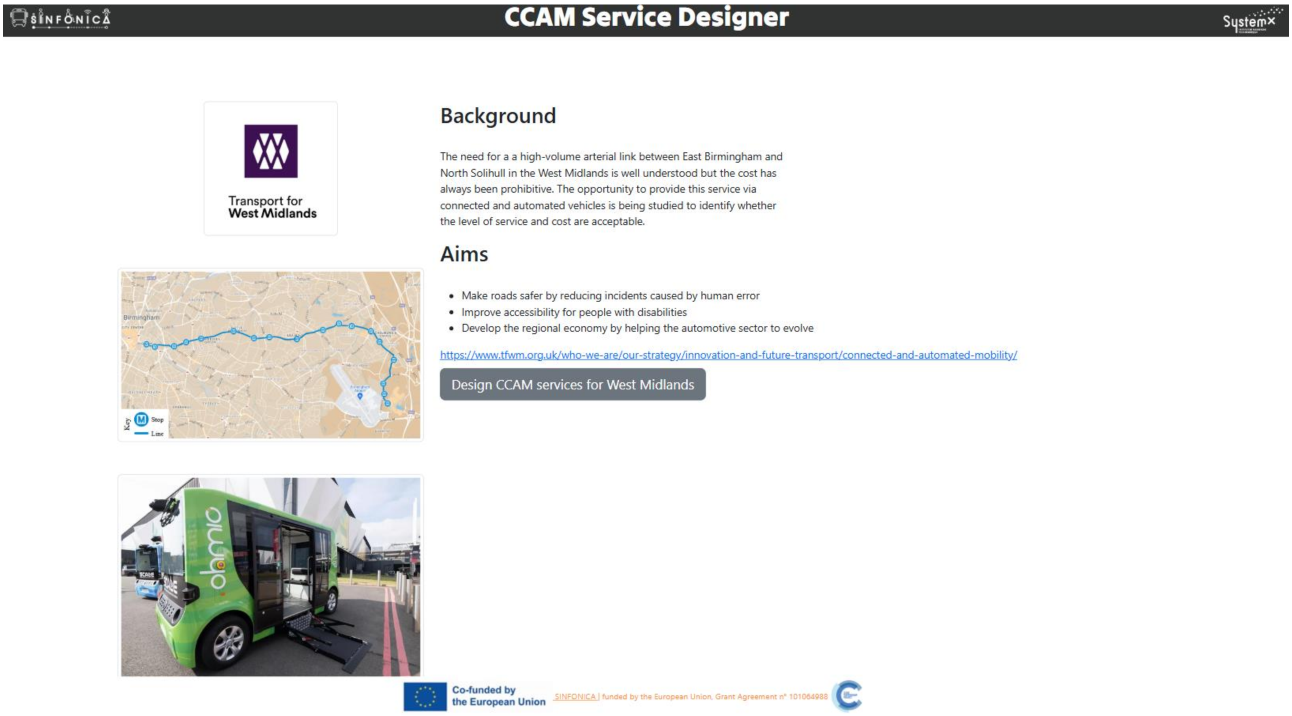

Figure 6: West Midlands example of a use case overview page

3.3 Main page

The tool's main page is the one that provides the most interaction with the users. It is structured in three main sections as depicted in Figure 7 showing the initial state of the page under the West Midlands use case. The left section provides a form that allows to configure a CCAM service and create a simulation scenario corresponding to the configuration. The middle section lists the already configured scenarios and allows to select one whereas the right section alternates between two states: an overview of the use case and a display of the selected scenario. In the following, we detail the first two sections and the first state of the third section.

3.3.1 Scenario configuration

The configuration form is structured in 4 parts. First, the user can configure one element of the travel demand, which is the percentage of PMC users to consider. The choice was made to make this ratio available as a parameter to be set by the user rather than a fixed value to allow investigating different assumptions on the volume of PMC users within a single use case and assess its impact. Second, some elements on the way that users interact with the service are provided: The prebooking scope specifies whether all users or PMC users only are allowed to submit their travel request in advance; the Prebooking horizon specifies how much in advance do prebooking-concerned users send their requests; and the maximum delay on arrival sets the constrained delay above which the user rejects the trips. The third part is related to the CCAM fleet composition and allows the set the fleet size and the passenger capacity of the CCAM vehicles. The last part of the configuration form is related to the operation cost of the CCAM service. Having the latter value as a parameter allows to not be tied to only one assumption on the CCAM vehicles and their price.

Once the configuration form is completed, a name can be given to the scenario before saving it into the library. The form checks that no already existing scenario has the same name or the same combination of parameter values.

Two utility buttons are available on top of the form: the first allows to clear all the fields while the second one sets all the field randomly while ensuring that the resulting combination of values does not appear in any existing scenario. This enables users to quickly fill the library.

Another function of the form is searching through existing scenarios for certain parameters combination. As the user starts setting parameters values, scenarios in the middle section that have the same parameter values are highlighted. For instance, if the user only sets the fleet size to 20 vehicles and the operating cost to 0.30 €/km, all scenarios that have both the same values for these parameters are highlighted.

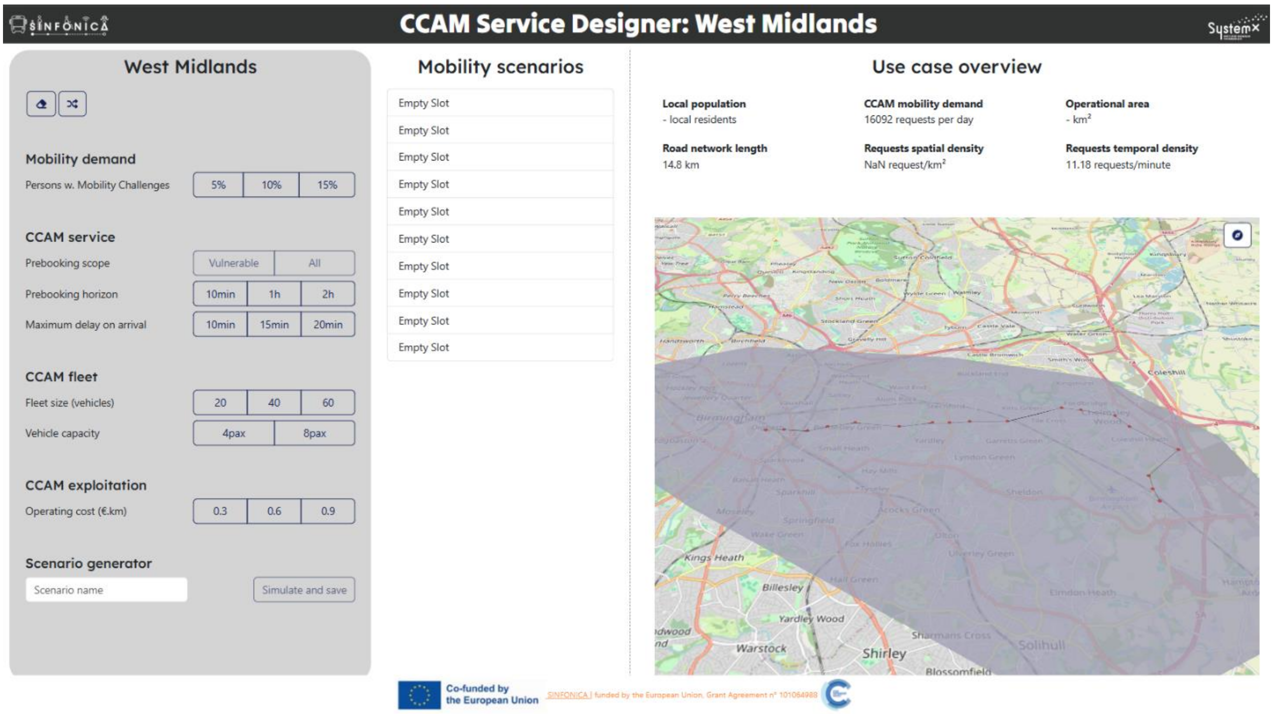

Figure 7: Initial state of the main page on the West Midlands use case

3.3.2 Scenario management

The second section of the main page allows to list and manage the previously created CCAM deployment scenarios. The number of scenarios that can coexist in the library is limited in the tool to ensure staying within reasonable computational resource requirements. If the library is full, no scenario can be added before one is deleted.

Figure 8 shows the state of the main page on the West Midlands use case with a full library of scenarios. At each row of the library, the scenario name is displayed with an inspection and removal buttons on the right and a radio button on the left. Clicking on the inspection button allows the user to check the parameter values behind the scenario by reflecting them on the configuration form. This can also serve as a basis to quickly make a new scenario on the basis of the inspected one and changing some parameters. The removal button allows to clear the slot occupied by the related scenario.

The radio button on the left of the name selects the scenario for displaying its results in the left section of the page. The presentation of results is described in Section 3.4.

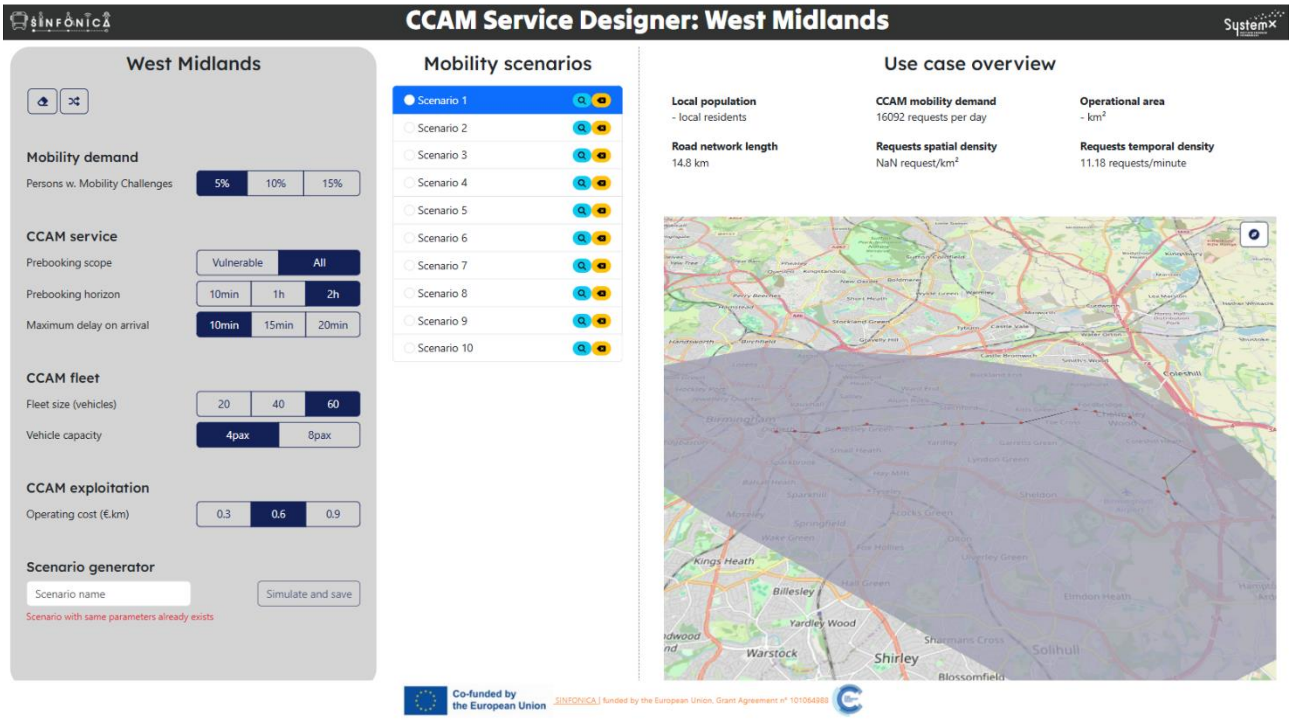

Figure 8: The main page on the use case of West Midlands with a full library of scenarios, one of them with parameters reflected in the configuration form.

3.3.3 Use case overview

The right section of the main pages presents high-level characteristics of the use case. The top part shows a set of KPIs that describe the study area. These are: the volume of the local population targeted by the service as identified in with the scenario specification; the mobility demand that is considered for the CCAM service to be deployed in the current perimeter; the surface of the service's operational area; the total length of the road network where CCAM vehicles can operate; the special and temporal density of requests. Note that not all KPIs are available for all use cases. For instance, in line-based services, we do not have an operational area surface in km² or a spatial density in requests/km².

The bottom part of the use case overview section shows an interactive map on which use-case dependent layers are displayed. These can be: the origins or destinations of the travel demand, the operating area, the stops for stop-based services, the line pathway for line-based services…etc. The user can slide, zoom in and out, rotate, and tilt the map view using the mouse. A button located on the top-right corner of the map allows to reset the view state to the initial one.

3.4 Simulation results visualisation

When clicking on one of the radio buttons of the scenario library, the related scenario is selected for displaying its simulation results. This is done in the right section of the main page on the same space of the map which is no longer displayed as shown in Figure 9.

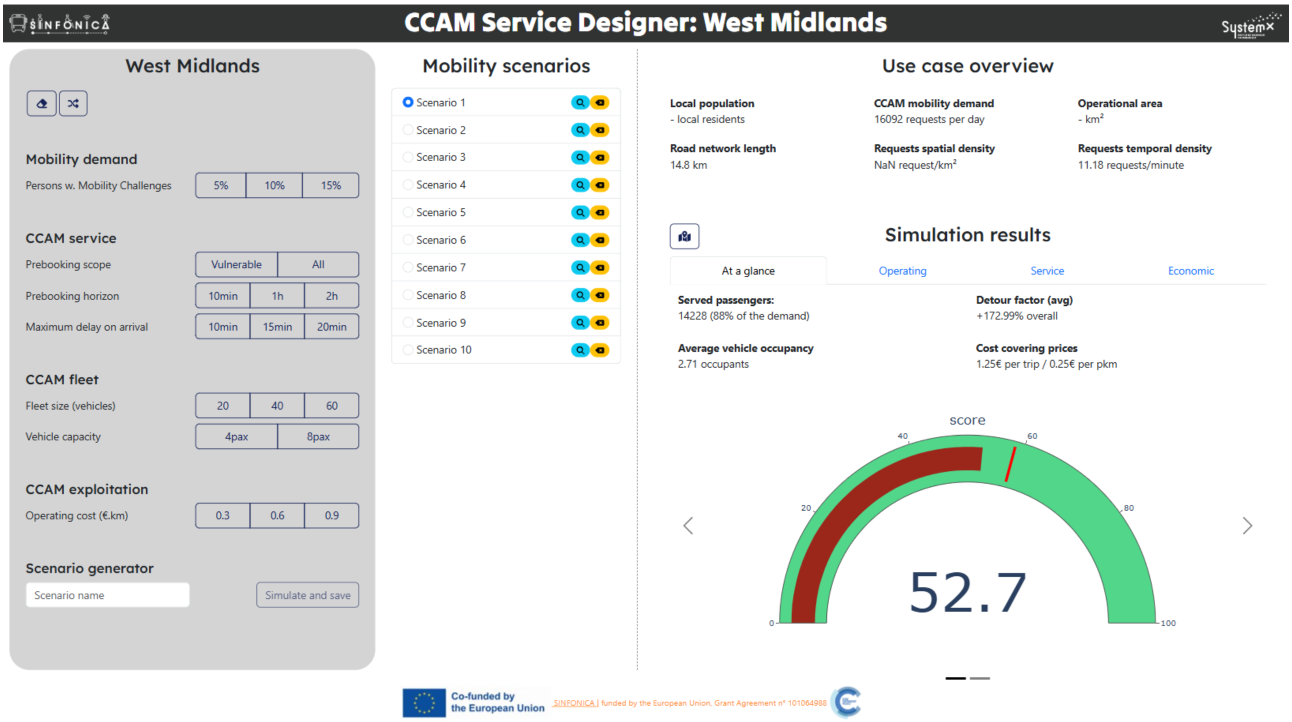

Figure 9: The main page on the West Midlands use case with one scenario selected for displaying simulation results.

The simulation results are in turn organized into four tabs grouping KPIs and plots into different categories: At a glance, Operating, Service, and Economic. All tabs are similarly organized with KPIs displayed at the top and a carousel of plots in the bottom, allowing users to slide left and right to go through the available plots. Figure 10 compiles screenshots of each of the four tabs upon selection. In the following, we detail the elements that are featured in each tab.

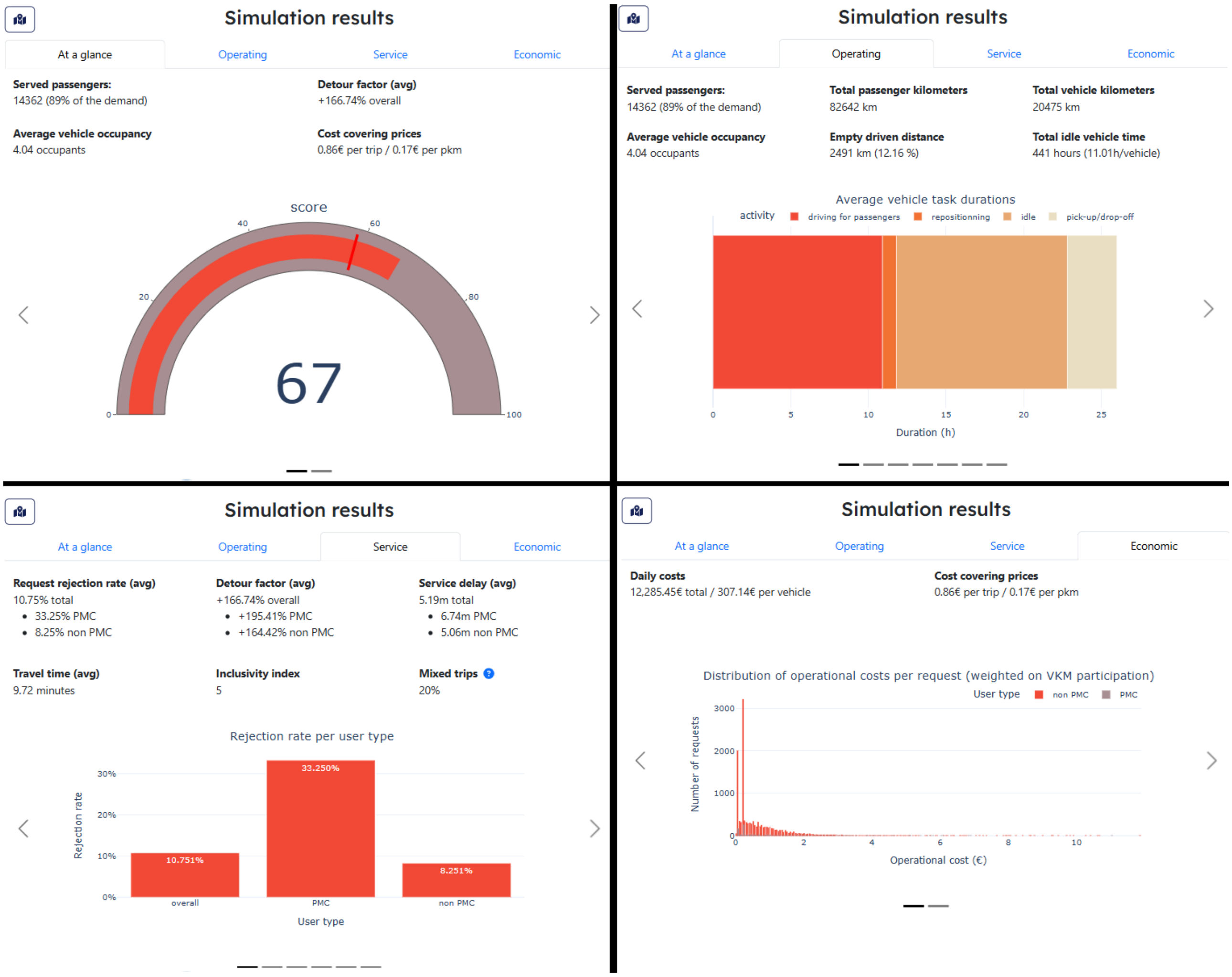

Figure 10: Compilation of screenshots of the four simulation results tabs

3.4.1 At a glance

This tab is meant to enable the user to quickly grasp the quality of the scenario across various axes relatively to the other scenarios. The displayed KPIs are gathered from the three other tabs and show: the number of served passengers and its percentage relative to the total demand, the average detour factor, the average vehicle occupancy and the cost covering prices.

Moreover, two plots are available within this tab, the first is a gauge chart displaying the overall score of the scenario. This score, comprised between 0 and 100, is computed by averaging four sub-scores, all of which are obtained by comparing a specific KPI between the current scenario with the rest of scenarios of the same use case:

- The demand satisfaction score: by dividing the number of requests served in this scenario over the maximum number of requests served across all scenarios, then normalizing to 100.
- The occupancy score: by dividing the occupancy rate in this scenario over the maximum occupancy rate observed across all scenarios, then normalizing to 100.

- Detour score: by dividing the average detour factor achieved by this scenario over the maximum detour factor observed, then subtracting the resulting value from 1 (since the detour factor is a quantity that we would want to minimize), then normalizing to 100.
- The pricing score: by dividing the achieved cost covering price per passenger kilometre observed in this scenario over the maximum observed one in the current use case, then subtracting from 1 before normalizing to 100.

The gauge chart also features a bar corresponding to the median score observed across all scenarios. This allows to quickly identify whether the current scenario is in the top 50% performing ones.

The second plot available in this tab is a scatter plot showing the relationship between total operation costs (on the x-axis) and scenario scores (on the y-axis) with a rectangle around the point representing the current scenario. The points are coloured according to fleet size and their radius determined by vehicle capacity. An example is shown in Figure 12.

Figure 11: Example of a chart on the relationship between the total operation cost and the scenario scores

3.4.2 Operating

This tab encapsulates the operator's perspective with KPIs and plots that are relevant to the understanding the overall performance and efficiency of the service. The KPIs shown within the operating tab are the following:

- Number of served passengers and their percentage relatively to the total number of requests.
- Total passenger kilometres: for each transported passenger, we consider the distance driven by the CCAM vehicle while the passenger was on-board. We then sum these values for all passengers to obtain the total passenger kilometres.
- Total vehicle kilometres: the sum of total distances driven by vehicles throughout the day.
- Average vehicle occupancy: this value is comprised between 0 and the vehicle passenger capacity considered in the current scenario. It reflects the average number of occupants per vehicle at any time of day. Note that the value of vehicle kilometres is not necessarily greater

than the value of passenger kilometres as more than one passenger can be simultaneously on board the same vehicle.

- Empty driven distance: the sum of distances driven by the vehicles while they were empty. These distances are typically travelled to go pick-up a passenger or simply to relocate the vehicle in an area where requests are expected to originate in the future. This value is expressed in kilometres and in percentage relative to the total vehicle kilometres
- The total idle vehicle time: the times during which vehicles are idle. This value is expressed as the sum over all vehicles and as an average per vehicle.

The operating tab also presents a number of charts. First, a horizontal stacked bar chart exemplified in Figure 12 shows the average CCAM vehicle schedule observed in the simulation of the current scenario. This allows to quickly see how much time on average is spent by CCAM vehicle on each type of activity. We consider the following activity types: driving for passengers, repositioning (moving an empty vehicle to an area where requests are expected to originate in the future), idle, and pick-up or drop-off.

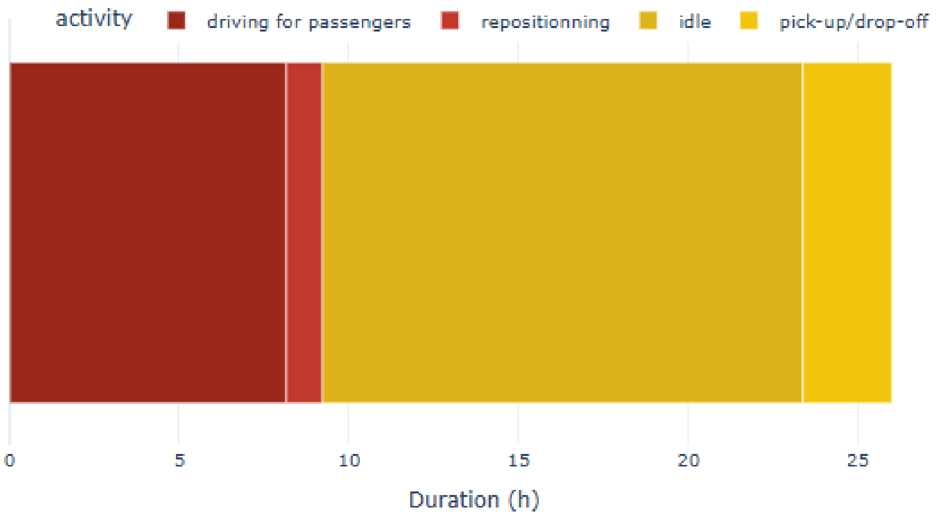

Figure 12: Example of a chart showing the average vehicle schedule

Another chart (Figure 13) shows the distribution vehicles' total idle times. This can be of interest to the operator to check whether the overall effort is evenly distributed throughout the fleet or a small share of the vehicles explore perform more or less than the others. A third chart focusing on the fleet usage consists in a bar plot showing for each hour of the day and each possible vehicle occupancy (ranging from 0 to the configured vehicles' capacity), the number of vehicles that have the given occupancy at the given time. Such a chart, shown in Figure 14, allows to quickly determine if the fleet is oversized in terms of vehicle capacity.

Finally, the Operating tab features a chart showing histograms the distribution of accepted and rejected requests during the day with different colours.

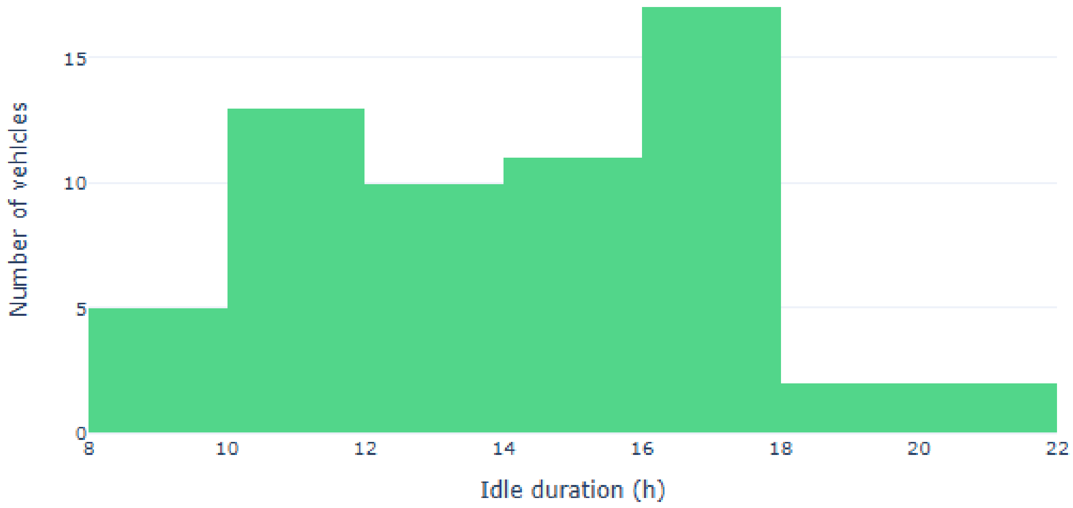

Figure 13: Example of a chart showing the distribution of CCAM vehicles' idle durations

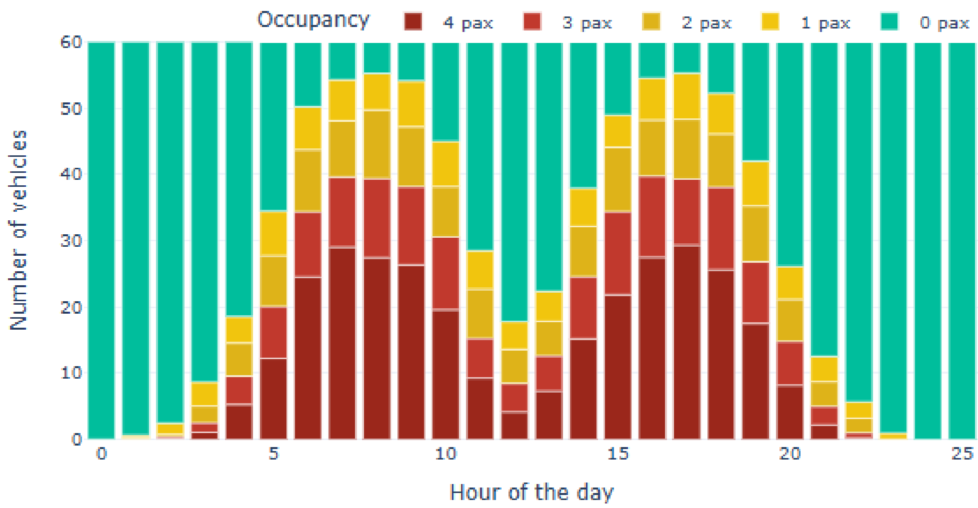

Figure 14: Example of a chart showing vehicle occupancies during the day

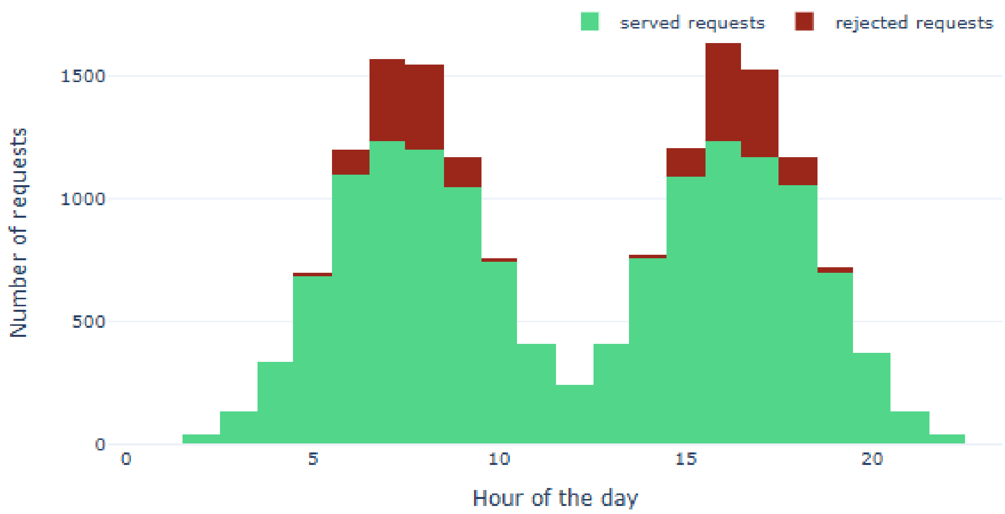

Figure 15: Example of a chart showing the distribution of served and rejected requests during the day

3.4.3 Service

The Service tabs adopts a user perspective with KPIs and plots that present that reflect elements meant to capture the service quality perceived by the users, with a consideration for PMC users. The KPIs chosen to consider are the following:

- Rejection rate: the percentage of requests that were rejected by the service because they could not be satisfied while obeying the maximum delay constraint. This value is calculated for all travellers and separately for PMC and non-PMC users.
- Detour factor: the average percentage of the time travelled by users relative to the time that they would have travelled using a privately-owned vehicle. The latter represents the shortest possible path between the origin and destination, thus the percentage cannot be lower than 100%. This value reflects the extra time spent by users due to the detours made to pick-up and/or drop-off other passengers along the way. This value is also calculated for all travellers and separately for PMC and non-PMC users.
- Service delay: the average delay (in minutes) experienced by the users relative to the desired arrival time. The desired arrival time is computed on the basis of the departure time buy assuming immediate departure and a travel time 50% longer than the trip of a private car. The delay value is also calculated for all travellers and separately for PMC and non-PMC users.
- Travel time: average user travel time in minutes.
- Inclusivity index: this KPI attempts to capture the level of inclusivity of the service in regards to PMC and non-PMC users. It is computed by aggregating the differences in service quality (rejection rate, wait time, delay) experienced by PMC users and non-PMC users.
- Mixed trips: the percentage of travellers that encountered another traveller from a different category (PMC user encountering a non-PMC one and vice versa). The inclusion of this KPI within the tool is motivated by the observation that PMC users are more isolated within the service than non-PMC ones.

Regarding the charts, the first one shown in this tab is a bar plot that visualizes the rejection rates also visible in the KPIs as shown in Figure 16. The next chart shows the distribution of average wait times during the day for all users, PMC users only and non-PMC users only as shown in Figure 17. A similar chart is proposed for the distribution of detour factors during the day (see Figure 18). A last chart depicted in Figure 19 shows the distribution of the detour factors experienced by travellers separately for PMC and non-PMC users.

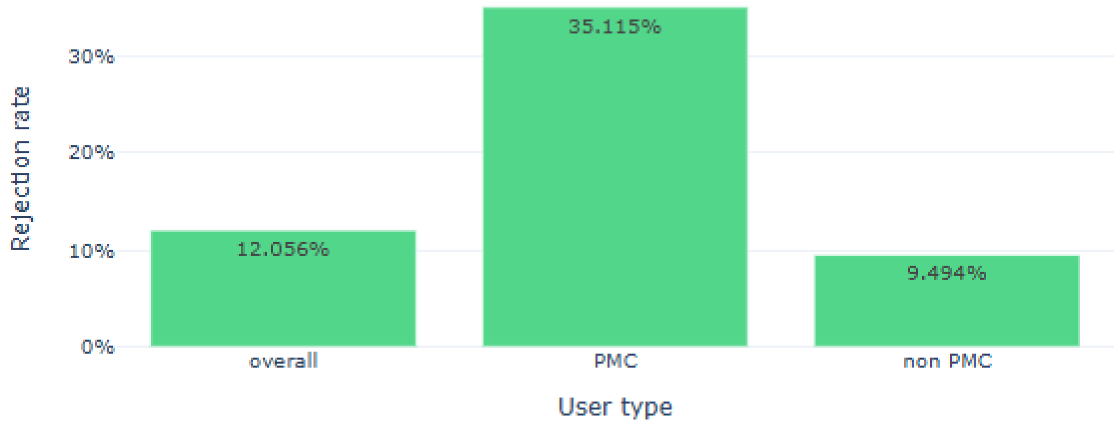

Figure 16: Example of a chart summarizing the rejection rates observed by all users and also separately by PMC and non-PMC users.

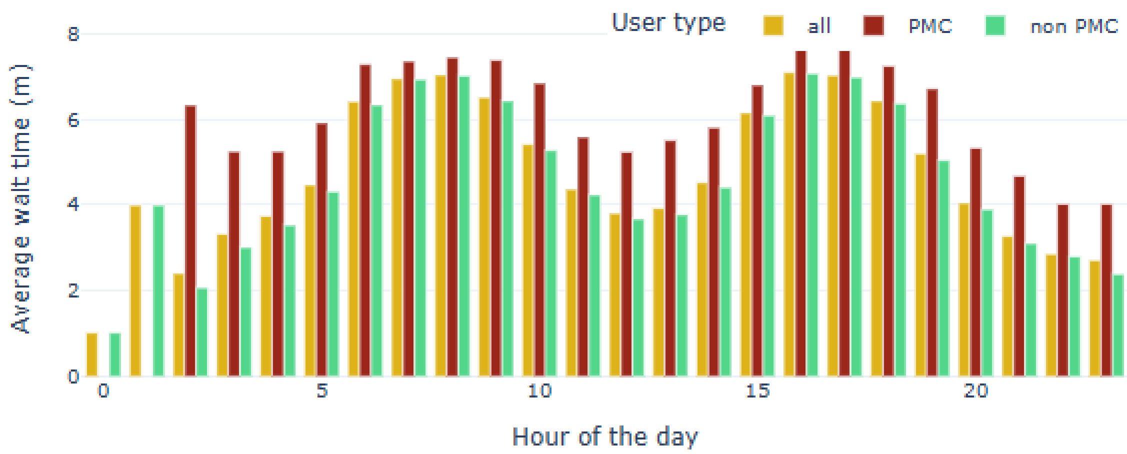

Figure 17: Example of a chart showing the distribution of average wait times experienced by all users, PMC users, and non-PMC users during the day.

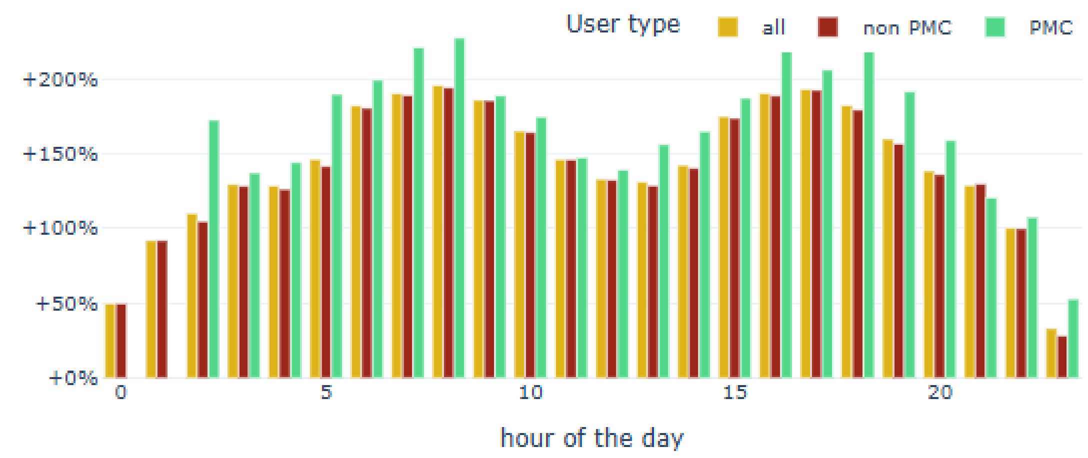

Figure 18: Example of a chart showing the distribution of average detour factors experienced by all users, PMC users and non-PMC users during the day.

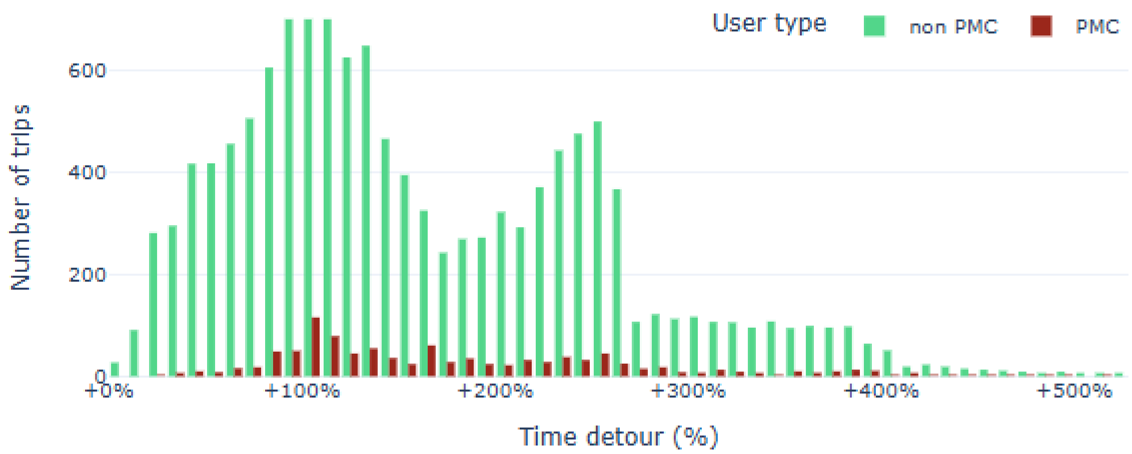

Figure 19: Example of a chart showing the distribution, over requests, of the detours experienced by non-PMC and PMC users.

The ability to assess the service quality separately for PMC and non-PMC users represents a key characteristic of the SINFONICA approach to CCAM service evaluations through agent-based simulations.

3.4.4 Economic

Finally, this last tab shows the economic implications of operating a CCAM service as configured in the current scenarios. Here we focus on two main KPIs:

- The daily operation cost: derived from the vehicle kilometres by applying the unitary cost (€/km) configured within the scenario. This cost is expressed in € for the whole fleet as well as the average cost per vehicle.
- The cost covering price: since the simulation model does not consider the service price and its impact on traveller behaviour and thus the final demand on the service, we chose to provide as a simulation output the cost covering price which would need to be set to cover the daily operational costs. This price can be set either by trip, by dividing the fleet-wide

operation cost over the number of trips, or by passenger kilometres. In the latter case, we divide the total operational cost by the sum of trips' shortest path distances in order to not reflect the detour-incurred kilometres on the users.

As for the charts available under this tab, there are also two. The first one shows the distribution of operational costs per passenger trip for non-PMC and PMC travellers as depicted in Figure 20. The calculation of the request-based is performed on the basis of the passenger kilometres weighted by the occupancy of the vehicle during each part of the trip. For instance, let's assume that a vehicle picks-up passenger A, drives 5km to pick-up passenger B, then 5km to drop passenger B then another 5km to drop passenger A. Passenger A accounts for 100% of the distance driven by the vehicle in the first segment, 50% of the distance of driven in the second segment, and 100% of the last segment's distance, thus contributing with 12.5km. On the other hand, passenger B accounts only for 50% of distance of the second segment contributing with 2.5km. Each traveller's contributed distance is then multiplied by the unitary cost to obtain the passenger incurred operational cost. Note that with this definition, passengers are not responsible for the totality of the service's operational costs as empty driven distances are not considered.

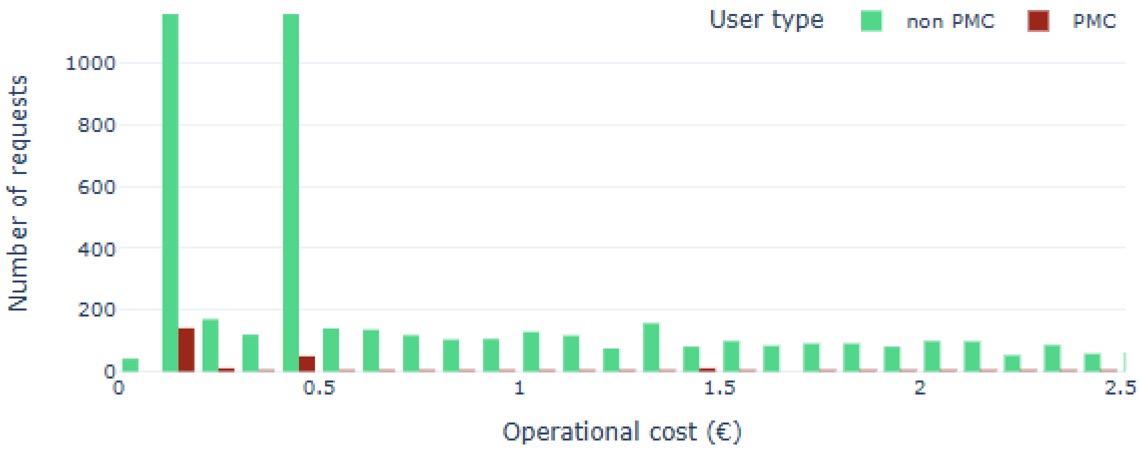

Figure 20: Example of a chart depicting the distribution of operational costs by traveller.

The second chart (Figure 21) also shows the distribution of operational costs but rather among vehicles instead of passengers. It directly reflects the distribution of vehicle driven distances within the fleet.

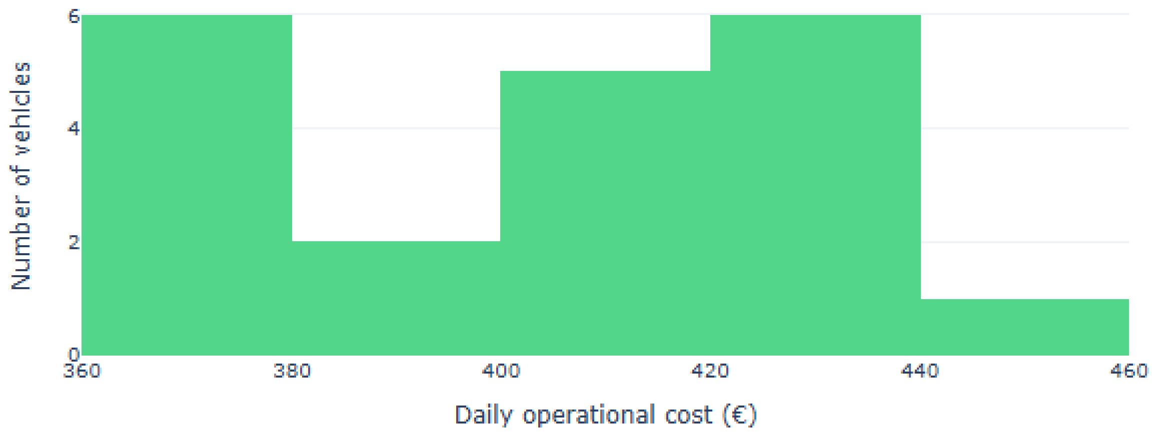

Figure 21: Example of chart showing the distribution of daily operation costs per CCAM vehicle.

3.4.5 Conclusion

The mixed representation of simulation results in the form of KPIs and charts and their grouping into thematical tabs allow the user to browse them in a smooth and interactive way. Moreover, all the charts can be interacted with, users can zoom-in specific areas of the chart or toggle on/off certain colours to focus on specific aspects (user types, occupancy values, vehicle activity types…).

The KPIs and chart presented above are subject to small evolutions between the submission of the deliverable at hand and the SINFONICA final event where the tool will be demonstrated.

3.5 Validation of the tool

The technical validation of the tool, and particularly the user interface, has been a continuous process throughout the development cycle. Two simulation use cases requiring minimal effort to build have been implemented at the start of this task and have been used to test various components of the user interface and iterate over possible solutions.

Regarding user-testing, a demonstration of the tool was performed on 18 March 2025 during an event gathering SINFONICA partners and other researchers and professionals interested in CCAM. The live demo was performed on a large touch screen allowing for a smoother interaction (and natively supported by the interface). The feedback collected during the demonstration were taken into account in the specification of the interface.

3.6 Packaging and deployment

The overall code base necessary to build the use cases, perform the simulations and deploy the tool is distributed in three repositories. The first contains the snakemake pipelines that prepare the necessary files for simulations and perform the analysis of the results and compile the databases to be included in the backend. The second repository contains the simulation framework and is referenced within the pipelines. The third repository contains the backend and frontend codes.

The modular architecture of the tool allows a step-by-step deployment. The first step is the preparation of simulation databases by running the pipeline associated to each use case. Then, these databases are to be included in the backend which can then be deployed and started on any machine with Python installed. As for the frontend, it requires NodeJs and npm to be installed and the other dependencies will be automatically fetched. The only configuration element of the frontend is the location where the backend server can be contacted.

Having all the simulations performed at once at the very beginning of the process allows to do so on large computer clusters that might not be adequate for the deployment of web applications. Once the databases are generated, the do not need to be edited again and they can be simply transferred to the backend that can in turn run on all modern computers.

Finally, the decoupling of the backend and the frontend enables the deployment of each one on separate computers if desired.

4 Implemented use cases

This chapter presents the set of use cases implemented and made available within the tool. In total, six use cases were constructed, the first two, city of Melun and Paris-Saclay, represent French areas and were constructed early in the tool's development to allow for quick testing. As the two areas were already the subject of CCAM service simulations at IRT SystemX using a well-known realistic synthetic population (Hörl & Balac, 2021), implementing the corresponding use cases was relatively straightforward. The other four scenarios are related to the SINFONICA research sites: West Midlands, Hamburg, Noord-Brabant and Trikala. Within each use case, a certain type of CCAM service (door-to-door, stop-based, line-based…) with the goal being to cover all possible types of services that are allowed within the simulation framework as presented in Table 1. Additionally, a travel demand is generated for each use case. In the following of this chapter, we detail each use case.

Use case	Scope	Mode	Demand Volume
Melun	Municipality of Melun	Door-to-door	36
Paris-Saclay area	Inter-municipality of Paris-Saclay	Door-to-door	600
West Midlands	EBNS corridor, Birmingham area	Stop-Line Based	16000
Hamburg	Harburg District, Hamburg metropolitan area	Mixed stop-based and door-to-door service	5000
Trikala	City of Trikala, Grece	Line-Based	500
Noord-Brabant	Efteling Park, Noord Brabant	Stop Based	30

Table 1: Overview of the use cases that were implemented and made available in the tool.

4.1 City of Melun

The first use case focuses on Melun, situated in the Île-de-France region. With approximately 42,000 residents and an urban area spanning 8 km², Melun represents a mid-sized city with a compact spatial structure. In this use case, we consider a door-to-door CCAM service aiming to serve 36 passengers over the course of a day. The demand data was derived through a sampling process applied to a synthetic population representative of Melun's demographics and travel patterns, ensuring that the origin-destination pairs used in the simulation align with actual mobility behaviours in the area.

Within the tool, users can view a detailed map displaying the urban boundaries of Melun along with the locations of the trip origins. This provides immediate insight into the spatial concentration of demand and helps assess how the proposed service would respond to local needs. Moreover, the rather small scale of the use cases allowed for fine-grained investigation of the simulation results during development steps and would be similarly relevant for decision-makers to help understand the service dynamics.

4.2 The Paris-Saclay area

The second use case explores the Paris-Saclay area, a strategic innovation and academic hub also located in Île-de-France. This territory encompasses 27 municipalities working together on various policy domains, including mobility topics. With a total population of approximately 316,000 and covering an area of 180 km², Paris-Saclay presents a more dispersed and complex mobility landscape compared to Melun.

A door-to-door service model is again considered, but with a significantly larger scale, accommodating a daily demand of 630 trips. This demand is also generated from a synthetic population and thus reflects realistic commuting patterns, particularly those linked to the area's numerous research institutions, business zones, and residential neighbourhoods.

The larger operating area of this use case and the relatively lower density of the demand offers an interesting variation of the operational implications on CCAM services in terms of efficiency, as vehicles typically need to travel greater distances.

4.3 West Midlands – East Birmingham and North Solihull (EBNS)

This use case is based on a feasibility study commissioned by the West Midlands Combined Authority in the United Kingdom, focusing on the deployment of an automated shuttle service in the East Birmingham and North Solihull (EBNS) corridor (McCool, n.d.). As depicted in Figure 22, the service was conceived as a line-based CCAM service with 18 pre-determined stops, operating between Birmingham city centre and Birmingham International Airport (BHX). This corridor is of strategic importance due to its mix of residential zones, employment hubs, and airport-related travel.

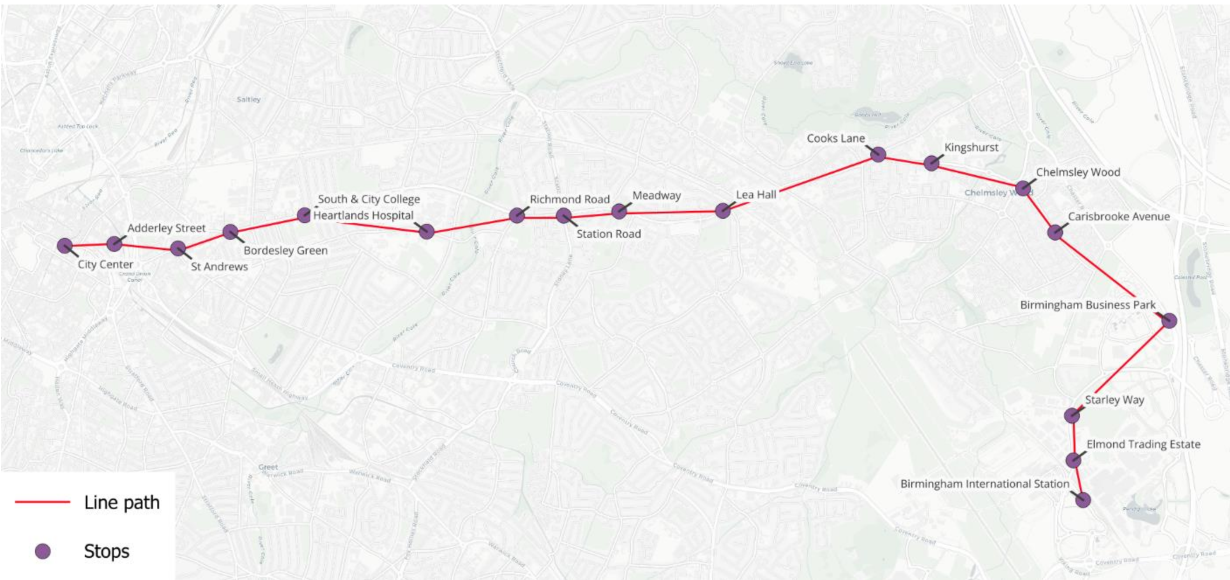

Figure 22: outline of the EBNS corridor line modelled for the West Midlands use case and position of stop locations.

The simulation scenario replicates the parameters outlined in the feasibility study, including the defined route and stop locations. Demand is modelled using an origin-destination matrix provided in the original study, which indicates the volume of trips expected between each pair of stops, with a total of 16000 trips per day. To introduce temporal realism, the departure times of these trips are distributed using a Gaussian mixture model, emphasizing morning and evening peak periods. This scenario offers a concrete illustration of how simulation tools can build upon existing studies to explore operational performance, assess potential ridership, and inform decisions about service configuration and investment.

4.4 Hamburg - Harburg District

The fourth use case focuses on the Harburg district in Hamburg, Germany, specifically its eastern section, located south of the city's core. This scenario introduces a hybrid operational model that combines door-to-door and stop-based service modes. A key feature of this use case is the differentiation between passengers with reduced mobility (PMC users) and other travellers. While PMC users are assumed to access the service only via fixed public transport stops, non-PMC users are served through flexible door-to-door operations.

This differentiation is integrated at the demand generation stage, ensuring that the trip origins and destinations respect the mobility characteristics of each user type. The resulting simulation offers valuable insights into how inclusive mobility policies can be translated into operational strategies, and how such strategies may affect service efficiency, accessibility, and user equity. The Harburg use case is thus particularly relevant for policymakers aiming to improve service provision for vulnerable populations while optimizing resources. A total of 5000 trips are sampled in this use case.

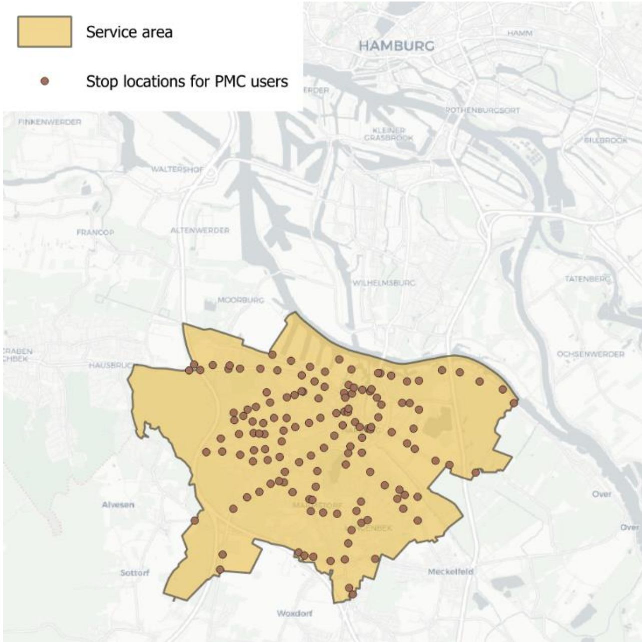

Figure 23: overview of the operating area in the Hamburg use case and the stops available for PMC users.

4.5 Noord-Brabant - Efteling Park

The fifth use case is situated in the Noord-Brabant province of the Netherlands and centres on Efteling Park, one of Europe's most visited theme parks. The study area includes the park itself and its surrounding zones, including the main bus stop located at its entrance. A stop-based service is modelled, designed to facilitate movement between different park zones and provide connectivity to the external transport network.

A distinctive feature of this scenario is the consideration of "Villa Pardoes," a facility providing holiday accommodation for families with children affected by serious illnesses or disabilities. The simulation increases the likelihood that PMC users will travel to or from this location, reflecting its special role within the site. The use case also draws on data from a pilot shuttle bus service operated in the summer of 2024, which recorded an average of 30 daily passengers. Anticipating higher interest with the transition to an on-demand model, the simulated demand is scaled to five times this figure. This use case illustrates how historical data can be used to estimate future service uptake, and how on-demand mobility can support inclusive access in recreational and semi-public environments.

4.6 Trikala

The final use case examines the city of Trikala in Greece, a medium-sized municipality with a population of around 61,000 residents. A door-to-door service model is simulated, offering flexibility in a city that has been recognized for its innovative approach to digital mobility. However, in this case, the absence of a detailed synthetic population dataset or granular travel demand assumptions required the generation of random trip origins and destinations within the city limits.

To ensure temporal realism, the trip scheduling follows a Gaussian mixture distribution, creating peak periods during the morning and evening hours. This scenario serves as a valuable example of how the tool can be applied even in contexts where detailed mobility data may not yet be available. It demonstrates the tool's flexibility and its utility in early-stage planning or exploratory policy scenarios, where initial simulations can guide further data collection and stakeholder engagement.

5 Conclusion and next steps

In this deliverable, we successfully developed local CCAM simulation use cases for various areas, including the SINFONICA research sites: West Midlands, Noord Brabant, Trikala, and Hamburg. In order to make these simulation models configurable and accessible to a wide range of users, a user-friendly tool equipped with an intuitive interface has been developed.

The tool’s software architecture is detailed. Its modularity allows for a flexible and customizable deployment. Decoupling the simulation framework from the tool and having all possible scenarios simulated before deployment allows the interface to run on regular computers and the users to have immediate access to the simulation results of their configured CCAM scenarios.

The user workflow in the interface is relatively straightforward. An introductory slide deck is built-in to explain the context of the work, especially for users that are not familiar with the SINFONICA project. The catalogue of available is uses is displayed in a comprehensive manner and each available area is accompanied with a description motivating its interest and the type of CCAM services that are considered.

Various aspects of CCAM deployment scenarios can be configured, from the fleet size and CCAM vehicles capacity, to operational considerations such as prebooking and the cost of operating the service. Moreover, inclusivity considerations that core to the SINFONICA project are reflected in this tool. Users can configure the share of PMC travellers to consider in the scenarios, assess the inclusivity of CCAM services, and configure and test strategies to mitigate potential behaviours.

Regarding simulation results, they are grouped into different themes, and for each one of them multiple number figures and charts are given. An emphasis is made in this deliverable on the KPIs and charts that were implemented. Their variety makes the tool, and the underlying simulation framework useful for different mobility stakeholders such as operators, municipalities, and local mobility regulation authorities.

In addition to the four SINFONICA research sites, two other use cases are included in the tool. These two areas are located in the Paris region in France and the previous experience of IRT SystemX in building simulation models for them allowed to have real simulation data early in the development phase.

Overall, the implemented use cases cover a wide range of CCAM service types, ranging from door-to-door services, to stop-based and line-based ones. Moreover, the variations between use case characteristics such as the size of the operating area, the volume and density of the demand, and the road network structure. This allows to appreciate the implications of these characteristics on the operators in terms of service sizing, the ability to reduce empty driven distances and increase overall vehicle occupancy, the cost of operating the service and in turn the cost covering prices on the users.

The work presented in this deliverable is expected to be disseminated in various circles. First, the simulation framework and mitigation strategies for discriminatory behaviour will be presented at the TRISTAN 2025 conference (the 12th Triennial Symposium on Transportation Analysis

Conference). Then, the tool itself will be presented and demonstrated at the CASPT conference (the 16th international Conference on Advanced Systems in Public Transport and TransitData). As the two conferences will be held in Japan, this is also an opportunity to disseminate to a not-necessarily European audience. Finally, it is also planned to demonstrate the tool at the SINFONICA final event in August 2025.

While the views and interface structure shown in this deliverable are fixed overall, some aspects can be the subject to minor changes in anticipation of demonstration events.

6 References

Chouaki, T., & Hörl, S. (2024). Comparative assessment of fairness in on-demand fleet management algorithms. *The 12th Symposium of the European Association for Research in Transportation (hEART)*.

Hörl, S., & Balac, M. (2021). Synthetic population and travel demand for Paris and Île-de-France based on open and publicly available data. *Transportation Research Part C: Emerging Technologies*, *130*, 103291. https://doi.org/10.1016/j.trc.2021.103291

Horni, A., Nagel, K., & Axhausen, K. (2016). *The Multi-Agent Transport Simulation MATSim*. https://doi.org/10.5334/baw

McCool, D. (n.d.). *Commercialising Connected and Automated Mobility: East Birmingham to North Solihull Automated Shuttle Feasibility Study*.

Mölder, F., Jablonski, K. P., Letcher, B., Hall, M. B., Tomkins-Tinch, C. H., Sochat, V., Forster, J., Lee, S., Twardziok, S. O., Kanitz, A., Wilm, A., Holtgrewe, M., Rahmann, S., Nahnsen, S., & Köster, J. (2021). Sustainable data analysis with Snakemake. *F1000Research*, *10*, 33. https://doi.org/10.12688/f1000research.29032.2

For more information

SINFONICA Project Coordinator

UNIMORE – University of Modena and Reggio Emilia

Via Giovanni Amendola, 2

42122 Reggio Emilia, IT

sinfonica@sinfonica.eu

www.sinfonica.eu

Funded by
the European Union

SINFONICA Project has received funding under the Horizon Europe Research and Innovation Program (Grant Agreement n° 101064988).