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Validation Methodology for addressing multimodal networks of the future: a Simulation-based approach

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Abstract

The following paper presents a methodology we developed for addressing the case of a multi-modal network to be implemented in the future. The methodology is based on a simulation approach and presents some characteristics that make a challenge to be verified and validated. To overcome this limitation, we proposed a novel methodology that implies interaction with subject-matter experts, revision of current data, collection and assessment of future performance and educated assumptions. With that methodology we could construct the complete passenger trajectory Door to door in Europe. The results indicate that the approach allows to approach infrastructure analysis at an early stage to have an initial estimation of the upper boundary of performance indicators. To exemplify this, we present the results for a case study in Europe.
Keywords: transport, logistics, Amsterdam, Hubs

1. Introduction

Multimodality is expected that in the future it could be one of the solutions for the transport of passengers and goods in the most efficient and less polluting way. Due to that, EU has been supporting projects that deal with multimodality of the future; in particular, in H2020 call, the following projects were funded that focused on different aspects of multimodality: Imhotep, Transit, X-Team D2D among others.

The authors participated in the project X-TeamD2D (XTeamD2D 2022) focusing on studying the multimodal transport of the future, putting emphasis on three time horizons: 2025, 2035 and 2050.

During the project, the respective Work package (WP4) devised a concept of operations (ConOps) for the future multimodal network. Our task was to validate the developed ConOps via a simulation framework that consisted of different models working on an integral fashion to allow us simulating the total passenger travel door-to-door using the available network under the ConOps devised. Since the time horizons fall far into the future there is no methodology to validate such an approach, therefore we needed to devise an innovative one that allowed us to get confidence on the models hence confidence in the produced results.

As mentioned, the methodology was developed under the X-TEAM D2D (eXTEnded ATM for Door2Door travel) project which has been funded in the SESAR 2020 Exploratory Research ER4-2019 Call for Research Projects (SESAR 2019). During the execution of the X-TEAM D2D project, the ConOps for seamless integration of ATM and service to passengers within an intermodal transport system has been defined. During the project we developed an innovative verification and validation methodology that we present also in the current paper. The most relevant elements of the project are presented briefly to make the reader notice the challenges faced and the importance of the approach developed. The following table presents the nomenclature used.

Nomenclature

A-CDM	Airport Collaborative Decision Making
A2D	Airport-to-door
APT	Airport
ATM	Air Transport Management
CCAM	Connected, cooperative, automated mobility
ConOps	Concept of Operations
CVSF	ConOps validation simulation framework
D2A	ConOps validation simulation framework
D2D	Door-to-door
eVTOL	electric vertical take-off and landing aircraft
KPA	Key Performance Area
KPI	Key Performance Indicator
LCC	Low-Cost Carrier
PAX	Passengers
PRM	Person with Reduced Mobility
SRA	Short-range airlines
TRL	Technology Readiness Level
UAM	Urban Air Mobility
VFR	Visiting friends and family
X-TEAM D2D	eXTEnded AtM for Door2Door travel
WP	Work Package

1.1. Concept of Operations for Air Transport Management in intermodal transport

WP4 devised the Concept of Operations (ConOps) of the future transport mobility, the focus is put on passengers to manage their on-traveling experience thus making them use the public systems as much as possible to reduce for instance the carbon footprint or general costs at different levels. An increase in satisfied and loyal customers would mean a flourishing overall system and would give value for other stakeholders in the system (ICAO, 2009, De Souza et al 2017). According to the European Master Plan, every aspect of passenger interaction offers an opportunity to create more value for the customer while efficient management and cooperation in the different areas would enable optimization and harmonization of the overall system producing less harm to the environment (SESAR 2018).

The management and service components considered in the ConOps are schematically presented in Figure 1 and the different key elements are briefly described in the following section.

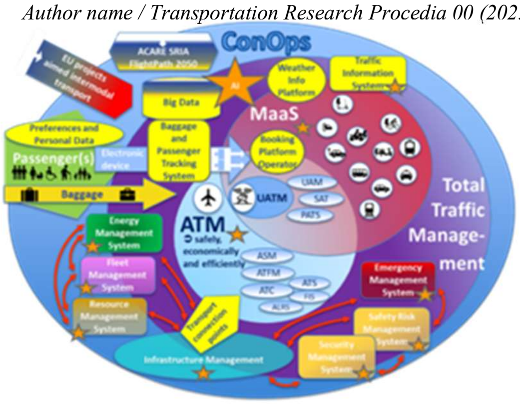

Fig.1. Concept of Operations integrating ATM into an intermodal network (extracted from X-Team D2D final report)

The key elements that compo0se the ConOps are the following ones, in case the reader wants a detailed description, we refer to the *Final Project Report* (X-team 2022).

Artificial Intelligence

The AI component will be necessary for the operational concept of the ATM service for passengers in intermodal transport. The assumption is that AI can make mobility safer, more ecological, more efficient, more comfortable, and more resource-saving. Moreover, that means not only the development of autonomous means of transport but also the implementation and control of inter- and multi-modular networked management systems (Diran 2021).

Resource Management Systems

Resource management focuses on Quality-of-Service requirements, among others. An efficient resource management mechanism for vehicular multimedia applications is essential to obtain the most valuable and complete traffic information, including location coverage. It should identify resources required to achieve the organizations' objectives. To ensure that resources are used effectively and efficiently, processes are required to provide, allocate, monitor, evaluate, optimize, maintain, and protect these resources (SESAR 2018). SESAR provides open information standards for a centralized wireless system to disseminate passenger flow information at major airports to include ground transportation connectivity, weather, delays, parking availability and check-in times within a single network.

Traffic Information System

The exchange of information between the infrastructure and transport vehicles of all types, including air vehicles, is generally considered an enabling technology to reduce accidents, congestion, and peaks in the long term and improve traffic efficiency.

Mobility as a Service

The mobility services can be provided by different suppliers and are to be offered and billed as a combined, multimodal service. This requires joint route planning of the individual mobility services and their joint billing (Eurocontrol 2017).

Energy Management Systems

Energy management will play a key role in achieving efficient energy consumption of electric vehicle technology on the ground and air. Another issue is the charging infrastructure and power plants needed to support the electrical infrastructure.

Fleet Management System

The fleet management must ensure that all vehicles within the system and the integrated providers are used economically, and that sufficient transport capacity is available for all processes (Hoogendoorn et al, 211, AGTI, 2022), for these situations AI solutions will be fundamental to provide the best managerial solutions.

Emergency Management Systems

The ConOps system must be resilient and robust to respond to failures and/or interruptions. This includes contingency measures to ensure continuity of operations in the event of major outages, natural disasters, security threats or other unusual circumstances.

Safety Management System

Safety is promoted by using an integrated Safety Management System approach for identifying and managing potential hazards. This includes equipment, organizational, operational or systems problems.

Security Management System

Secure infrastructure (e.g., train stations, terminals, airports, and take-off-and-landing areas) must have an integrated facility security system that can adapt to different capacities, accesses, and risk situations.

Infrastructure Management System

Intermodal ground access to all transport connection points is essential for intermodal networks. Functioning and passenger-appealing transitions in the form of transport interconnection points are needed to link transport networks within a regional system and enable more efficient traffic flow. Joint management of the infrastructure would bring precise quality control and set the standards in the system (Deloitte,2021).

Authoritative Weather Info Platform

This integration of weather information platform, combined with probabilistic forecasts to account for weather uncertainty and improved forecast accuracy will minimize the impact of weather on traffic.

Baggage and Passenger Tracking System

The passenger and baggage tracking system allow baggage handling to be carried out in a remote area of the airport if required. This increases capacity, reduces check-in time and staffing requirements, and enables transparency for passengers.

This system aims to ensure that, by taking greater account of passengers' preferences, safety is improved, and capacity and operational efficiency are increased. This is achieved by building processes and systems to help passengers realize their preferences. In addition, information is collected, collated, monitored, evaluated, and shared through the management systems.

Interactions and relations between the management systems

The management systems must interact, or the actors and systems must interact with one another. This interaction is closely linked to the concepts of communicating, acting, planning, working with each other and – finally – informing one another.

With regards to the ATM of the future, it is expected to become passenger-centric oriented where the passenger will regain control over its journey particularly in the year of 2050.
The following subsections go deeper into the operational characteristics and then how the scientific group faced the challenge of developing a methodology for assessing such a system that has the following characteristics:

- Is not existent
- Its operation is expected to be in place in some decades
- Historical information of some elements is inexistent
- Some technology is under development
- High uncertainty

The article continues as follows; section 2 presents the general methodology developed to face this challenge. Section 3 presents the particular of the methodological approach to validate the ConOps devised for the project, Section 4 presents an example of how we applied the methodology; section 5 presents the results from the case study and finally we conclude in section 6.

2. Methodology for Assessing future systems

For addressing the system conceptualized in the project we devised the following general methodology. This methodology was applied during the whole project life and the different activities were performed by different WPs.

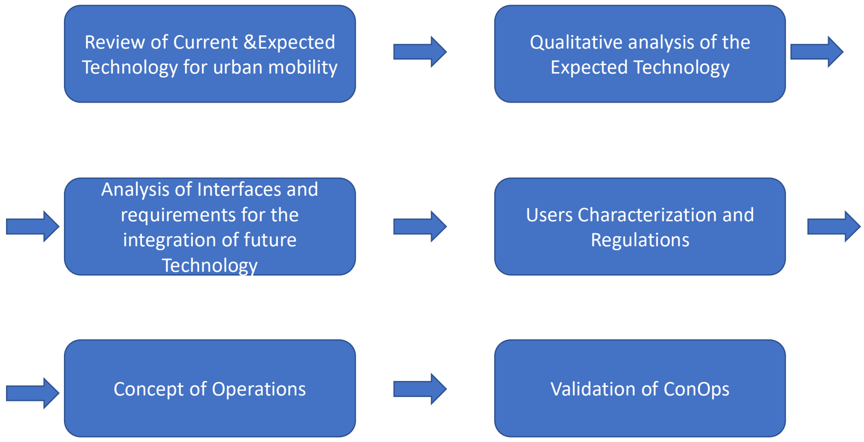

Fig.2. Methodology for assessing a future dynamic system

Figure 2 illustrates the general methodology devised during the project. It consisted of several phases where in each phase the uncertainty of the future was progressively reduced while more information was obtained.

Phase #1: Consisted of making a review of the current technology and the current technological developments that might be in place in the future e.g., eVTOLs, Hyperloops, electric mobility among others. During this phase the initial operational characterization of the different elements that will conform the future transport system is collected and reviewed.

Phase #2: Once all the expected technology is collected, then it is analyzed to identify what their characteristic would be and what barriers against air integration or requirements to be integrated would be in place.

Phase #3: The next stage was to identify which interfaces were going to be required to seamless integrating the newcoming technology within the systems.
Phase #4: Another important aspect is to characterize the potential users and profiles of the passengers that will use the technology.
Phase #5: Once the different elements are analyzed and identified what is the expectation of integration, operation and requirements from the users in the future, the next stage is to devise the conceptual operation i.e., Concept of operations.
Phase #6: The final stage on analyzing this type of system is an approach to validate the expected operation, or *Validation of ConOps*. For this final stage the authors proposed the use of a simulation framework that considered the most relevant elements from the devised ConOps.

In the following subsection we put focus on the developed elements of Phase 6 where the simulation framework was constructed and itself required a novel methodology due to the system under study.
For a complete description of the initial phases, we refer again to the reader to the final report

3. Methodological approach for a Simulation Framework

In the project, three-time horizons were considered (2025, 2035, 2050); in this work, we presented just the case of 2050 to illustrate the methodological validation approach for the future system.

As the modelling and analysis of future systems is not a standard task, in this project the challenge was to develop one that fulfils the characteristics of :

- Plausible
- Feasible
- Replicable
- Correct
- Valid
- Logical

To achieve these characteristics, the scientific team in charge of developing the validation phase developed an approach that made a combination of quantitative and qualitative exercises to get these characteristics. Figure 3 illustrates the different elements of the approach.

Fig. 3. ConOps validation process

The following is a description of the methodological approach followed for validating the framework.

Stage I: Plausibility verification

The first stage focuses on analysing the expected operations, assumptions, integration and characteristics of each of the elements that are included in the model versus the current characteristics of similar elements e.g., high speed trains, electric motorcycles, when information is not in place. In the case of vehicles that are under development like flying vehicles (eVTOL) or the high-speed train, we considered the operational characteristics reported by the manufacturers.

The complete characteristics of operations, assumptions and elements considered were reviewed by external experts to the scientific members of the project to verify that the approach made sense based on the available information. Such verification was performed by the committee of subject matter experts external to the project and invited for this task in the form of the Advisory Board. During this activity, the consortium partners presented the framework, relevant material, results, assumptions, case studies and initial model outcomes to the experts in different areas to evaluate the approach's plausibility and identify behaviour and obstacles that can be considered unlikely or challenging to happen. The experts that performed this activity had knowledge ranging from maritime to aviation and having also technical one with regards to computer simulation/optimization. These characteristics were key for this stage of the process They performed at this stage a conceptual model validation and operational one (Sargent 2013).

Stage II: Simulation framework verification and validation

Once the framework is considered plausible on their different aspects, the next step is to validate their individual characteristics. This is done in the next stage called verification and validation of the simulation framework. The simulation framework validation can be defined as the evidence "that a model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model" (Sargent 2013). To achieve this, we followed a proven methodology that is illustrated in the following figure.

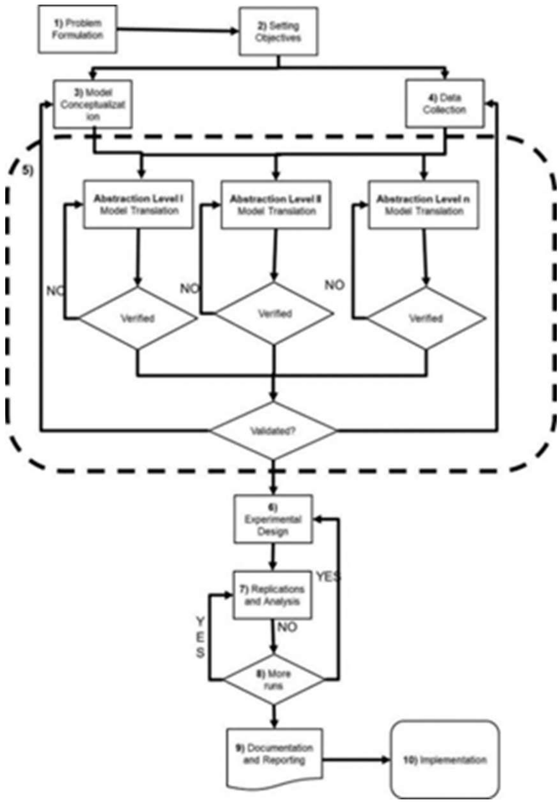

Fig. 4. ConOps validation process

This methodology for constructing an accurate model has been refined and applied by the consortium members (Mujica et al., 2018) in the aviation area. The main steps are the following:

1. Problem formulation. In this step, the problem under study should be clearly described, using descriptive elements that help provide a clear understanding of the nature of the problem.
2. Setting objectives. Based on the problem formulation, the analyst should set the objectives pursued by the study. This step is fundamental since it will determine different key decisions, such as the abstraction level and boundaries of the study (i.e., what is included and what is excluded).
3. Model conceptualization. In this step, the logic of the model and the artefacts that are within the model's scope are defined. The analyst can make use of descriptive tools like flowcharts or Petri nets for this task.
4. Data collection. This step will iterate with the previous elements to identify the data that is required beforehand, what sources of data are available, and which need to be collected or not.
5. Model translation, verification, and validation (V&V). It is in this step that the proposed methodology differs from those presented by other authors. In this case, the models with different abstraction levels are developed and verified. If the data and information are available, then the different models are validated. This step is a combination of models, which can number more than two, but the modelling effort will depend directly on the number of models to be developed.
6. Experimental design. In this step, and once the model(s) are validated, an experimental design is performed, using the different developed model(s) and identifying the outcomes that should be in line with the objective stated. The experimental design must deal not only with the combinatorial nature of the decision variables of each model but also with the outcomes of the interaction of the models once the cycle is progressing.

7. Replications and analysis. This corresponds to the definition of the sample size of the model and the analysis of the data it generates. Compared to standard methodology, this activity is more time-consuming since the number of replications will increase linearly with the number of models in the cycle.

8. More runs. More replication runs are executed to obtain statistically relevant data and consider the impact of all stochastic events in the model.

9. Documentation and reporting. This step relates to the description of the analysis and the reporting of results used by decision-makers.

10. Implementation. In the best situation, the insight gained from the model(s) analysis is implemented in the real system. Due to the nature of the project, we only obtained initial insight into future performance which will serve as a steppingstone for future technology development. This action minimizes the risk of failure or over-/under-design in infrastructure projects.

The simulation framework was considered verified and validated when this activity was performed and agreed to be correct (Sargent, 2013). Furthermore, in the experimental phase, the framework can be analyzed by making experiments and extracting data from the models. These data can be compared to available data of the technologies used in the simulation models and investigate if the results are reasonable.

Stage III: ConOps validation exercise

The ConOps validation process starts when the framework was verified and validated. This stage consists of getting information and performance results and KPIs directly from the simulation framework. The different elements of the framework are allowed to interact with each other and then analysis is performed putting focus on the Key performance areas characterized by the corresponding Key performance indicators. The results obtained at this stage will give the first insight related to the system under study. Normally for these types of systems, the combination of alternatives is high due to the elements in place and the inputs considered, this is the reason a proper experimental design should be designed to put focus on the KPAs.

At the end of this activity, the expected performance of the future system could be foreseen, and potential inefficiencies and emerging behavior that might affect the efficiency of the integration of technologies was identified.

4. Case Study: A door to door journey in a multi modal network

In this section we present a brief example of how we could apply the aforementioned methodology and what is a typical outcome from the different activities to validate such a framework. The example provided is the case studied in the Project X-Team D2D for the 2050 horizon which is a good example to illustrate the approach.

3.1 System Description of the 2050 timeframe

The following are the characteristics expected to be in place in 2050:

- Highly automated ATM system with an all-weather operation
- Safety level above the current one.
- Service - and passenger-oriented management
- High automation, and digitalization.
- C-ITS will be characterized as cooperative, connected, and automated.
- Transparency will be increased as collected data will be shared amongst the stakeholders.
- Strategic planning of traffic flows will be improved, reducing the imbalance between capacity and demand.
- Disruptions can be absorbed by the system
- Mobility-as-a-Service will be possible for every traveler for door-to-door travel, including the flight segment.

The following figure illustrates the elements that expected to be present in the 2050 horizon.

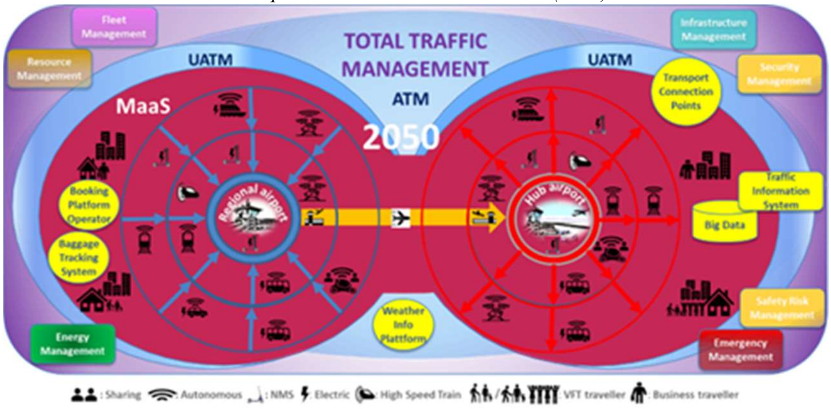

Fig. 5. Total traffic management in 2050 (extracted from XTeam D2D final report)

As with the ConOps, the figure illustrates that in the expected horizon, the flying vehicles that improve the urban mobility are in place, the system is quite transparent with the support of TIS and lots of data is generated and use for a better management of the system. Diverse transport alternatives are present for the passengers like flying vehicles, electric vehicles, under a MAAS environment where the mass transport becomes a feasible alternative for reduce environmental impact, reduce time in transport and reduce operational costs.

3.2 User Characterization

The passenger profile is summarized in Table 1 for Business travelers and Table 2 for other travelers which are the categories defined for the future users of these systems:

Table 1 Characteristics of the Business passengers

Time horizon	Business Traveller (profile B)
2050	Travels alone (mainly)
	Expect a very high comfort standard
	Expect a very short travel time
	Has few budgets' limits
	Might travel for long stays (as short travels for face-to-face meetings will dramatically reduce) with large/heavy luggage
	Is a frequent flyer/traveller
	Is an adult (18-75 years) with possible physical or sensorial impairments
	Relies on dedicated business services for travel arrangements (no reservation or payment methods constraints)
	Has full flexibility for travel plans change
	Must comply with environmental performance targets set by his/her company

Table 2 Other passenger profile characteristics

Time horizon	Other travellers (profile V)
2050	Travels in small or larger groups (mainly)
	Unless specific travel reasons (a ceremony, family issues, etc.) has relatively low time constraints
	Has only personal items/small luggage as luggage will be picked up and delivered door to door (except for walking aids/stroller)
	Has budget limits
	Has not constraints for reservation or payment methods
	Does frequent short stay/medium distance travels
	Might need assistance (children, elderly, disabled people)
	Can be of any age range, from baby/children to very elderly
	Can have any kind of physical or sensorial impairment
	Is free to arrange/rearrange the travel according to the preferences
	Is sensitive to the environmental footprint of his/her journey
	Has no communication limitations (due to good education and/or technology support)

For the ConOps devised, D2D international travel was considered using air transport involving two types of airports defined following the categorization of Kwasiborska (2021):

• Regional airport – a non-hub airport without transfer traffic. For modelling purposes, Hannover airport in Germany was taken as a base case for modelling such an airport. In this document, this airport will be referred to as APT-R.

• Hub airport – an airport that serves as a node for connecting different flight legs for several airlines. For modelling purposes, Schiphol airport in Amsterdam, The Netherlands, was taken as a base case for modelling such an airport. In this document, this airport will be referred to as APT-H.

The ConOps for the 2050 horizon consists of the description of the elements and the expected interaction for the time frame under study. As mentioned, we devised a methodology that combines subjective analysis and objective ones. The subjective analysis consists of evaluating by subject matter experts the characteristics of the different elements that compose the sub models that put together compose the framework that enables us to simulate the door-to-door trajectory.

For the case of 2050, table 3 presents the expected characteristics.

Table 3 Overview of ConOps Key characteristics expected in 2050

Horizon	Expected characteristics
2050	All cars will be electric and mostly highly automated and autonomous. In urban areas, the car-sharing model will be dominating. In densely populated areas, car traffic will be forbidden, (electric) micro-mobility (soft) means of transport will be the only personal means of transport with a significant share (besides public mass means of transport). Public transport network will reach the maximum available density to meet increased demand, offering the highest possible accessibility level and shortening the first and last multimodal travel legs. SRA connections operated by zero-emission aircraft will remain the transport mode with the highest potential impact on the efficiency of the transport system by data sharing, connecting a hub airport with regional or two regional airports (point-to-point connections). UAM dedicated to passenger transport will be available in Europe, offering direct access to densely populated city areas. Regional range air travels will also be possible using new concept aircraft, VTOL, multirotor and fixed-wing aircraft, depending on appropriate infrastructure availability. Due to the high operational cost, passenger UAM will be mainly for high-income and high value-of-time PAX and operating between airport and business centres and public services (like HEMS, police). UAM will not significantly impact mobility in metropolitan areas but will be considered essential and often necessary from a social point of view. Hub airport connects with the city by numerous collective, autonomous transport modes complementing electric car-sharing services. From the hub airport, there is no direct access to e-bikes, e-scooters sharing system due to the remote location of the hub airport from the city. Regional airports provide access to more than one collective autonomous transport service (train, bus). Electric shared cars or NMS services, including e-bikes or e-scooters, are commonly used as airport cities develop (depending on the location and size of the airport). Large water reservoirs in metropolitan areas and autonomous ferry services can support the multimodal journey in favourable conditions.

3.3 Plausibility Verification

The following is an example of the outcome from the expert opinion after they analysed the different elements of the framework and studied all the relevant material. It is important to note that this activity was an interactive one where the model was progressively refined until the experts were satisfied with the assumptions, performance, and behaviour of the different elements in the models of the framework. The feedback provided by the subject matter experts were included in the framework until it was properly specified.

Table 4. Example of Feedback from the Plausibility verification exercise.

EXPERT, Institution, Main Expertise/Experience		
ITEM	SCOPE	Action on V&V
All on-request carriers operating passenger traffic to/from the airport must be included, including, i.e., private bus shuttles, car-parking shuttles, collective taxis. This group is difficult to include in just-in-time planning.	Methodological	NONE
Probability of Failure is not presented in the material. Associated risks and uncertainty is not evaluated	Methodological for the experiment outcomes	NONE
Probability of Failure is not presented in the material. Associated risks and uncertainty is not evaluated	Methodological for the experiment outcomes	NONE
The validation and verification of the simulation model are not covered at least in the article for EUROSIM.	Technical	Validation action
Necessary changes to the infrastructure were taken into account to a small extent.	Methodological	NONE

The assumption that luggage may not travel directly with the passenger is difficult to include in the analysis. Will it be possible to include in simulation scenarios?	Methodological	NONE
From the standpoint of the passenger, the principal energy source is also a motivating aspect to investigate, for which the notion is lacking.	Methodological	NONE
Adoption and passenger mindset are significant barriers that have not been addressed.	Methodological	NONE

As it can be noticed, the comments are diverse from conceptual to technical, and this exercise allowed us to challenge the framework and identify inaccuracies on the assumptions, in the elements or when it was necessary to explicitly take out of the scope some elements of the framework. After some rounds of refinement, the framework can be considered plausible enough for the objectives pursued in the study.

3.4 ConOps Validation

Due to the complexity of the future system, the concept to be validated in the framework cannot include all the elements defined in the system description, it should be an abstraction that consider the most relevant elements to give insight of the expected characteristics and performance characterized by KPIs values. If it necessary, the framework can be progressively refined to include more elements and at the same time reduce the risk of inaccurate outcomes.

In our example, the models consisted of the following elements.

1. ConOps logic
2. Multimodal transportation network conceptual design
3. Modelling assumptions and implementation
4. Simulation framework
5. Experimental scenarios

The validation framework was implemented in a general-purpose discrete event simulation software and was based on a multiple-layer approach, where first, the existing transportation network was created. Then, future transport technologies were added as an additional layer considering relevant time horizon assumptions and the ConOps. Such an approach allowed simulating the time horizon under study and in our example, it enabled us to simulate the complete door to door journey of the future.

The architecture of the simulation framework is schematically presented in Figure 6. The framework consists of two main models: the first model represents the Door to Airport part of the passenger journey, and the second model represents the Airport to Door segment. The two models are coupled using a weighted edge representing the flight time from a regional airport to a hub airport. This time considered the time between the aircraft take-off at a regional airport and landing of the aircraft at a hub airport which are the main connecting elements of the two legs considered.

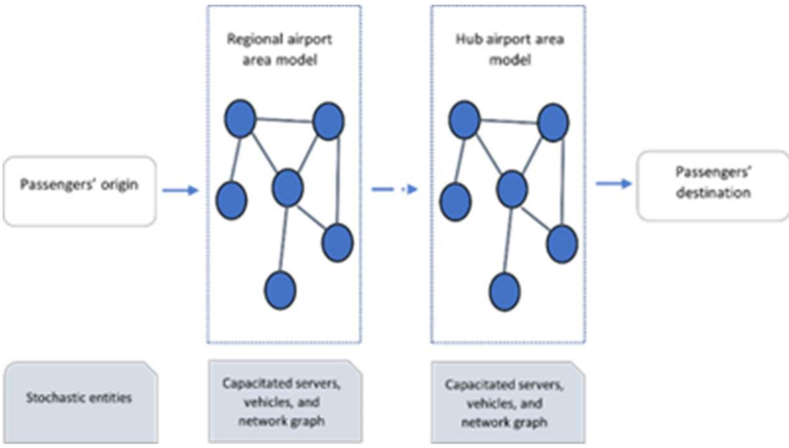

Fig. 6. ConOps validation framework structure

There are three groups of elements implemented in the model. The first group, dynamic entities, represents passengers and vehicles transporting passengers from their origin to the airport. The second group, static elements, represent transport stations the passengers use to embark/disembark on and off transport vehicles. These stations serve as the entry, transfer, and exit points between elements in the modelled system, with a fixed location for the interconnected multimodal transport networks and are modelled as capacitated servers. The third group is the set of nodes and weighted edges connected into a scaled network that vehicles and passengers use to move through the space between transport stations.

The model was built using GIS information from OpenStreetMap (2022) so that the weighted edges consider the real scale under study. The main purpose is to model the movement of vehicles and passengers through the multimodal transport network in a realistic fashion. Owing to this, interactions of IT systems or management aspects of transport systems were not explicitly modelled.

Within the framework, the arrival of passengers and most transportation means was generated stochastically based on the project assumptions. Some transport means (such as buses and trains) were generated on a schedule, as observed in real-life operations.

Modelling D2A journey

A 2D view of the D2A model is shown in Figure 7. There are two segments in this model. The right part represents the origin town for passengers (Brunswick in Germany), and the left represents the destination city which encompasses the regional airport (Hannover). These urban areas are located approximately 60 km from each other. For modelling purposes, the road and railway networks connecting these two areas were simplified into straight edges, simulating a total travel distance between two chosen points in each of the areas.

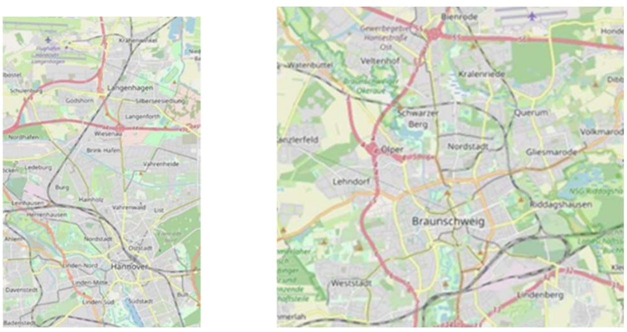

Fig. 7. Regional airport area model (GIS layer) – D2A

All passengers were stochastically generated in Brunswick at a source element considering the relevant scenario assumptions. In this element, PAX group entities were created, and their properties, such as PAX profile, walking speed and group size, were set and the info related to the passenger were tracked during the simulation runs.

After all initial PAX properties have been set at the beginning of the journey, the PAX entity moved to the next step of the journey, which simulates PAX leaving their house and walking to the first transport mode station or PAX waiting at their doorstep for a transport vehicle to pick them up from their house. In this step, a random location of PAX origin was simulated. To simulate the random location of PAX origin within Brunswick, the PAX travelled distance on this part of the journey is adjusted by a random value. The next figure illustrates the logic and variability behind the Pax journey and its steps, the other ride alternatives follow a similar logic.

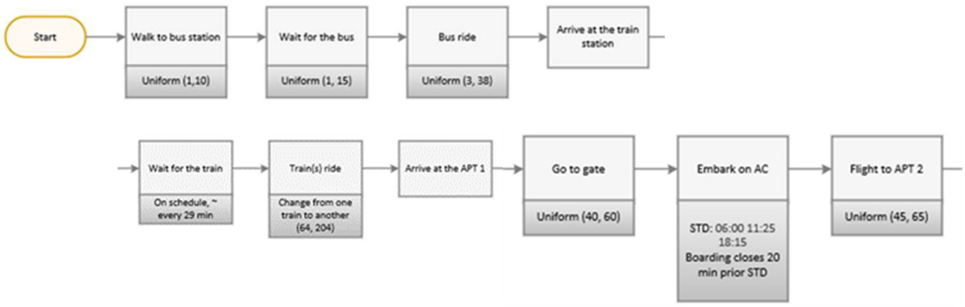

Fig. 8. PAX journey from Brunswick to Hannover APT in D2A

Depending on the type of airport of the segment, the PAX was delayed simulating walking to the gate and various airport security procedures. After that, it could board an aircraft and the second leg follows the same logic but on reverse sequence.

An example of one of the alternatives of traveling toward the destination in the second leg of the model of our example (in or case towards Haarlem in The Netherlands) is presented in the following figure with a pax trajectory defined in stochastic steps.

Fig. 9. PAX journey from APT to Haarlem via Amsterdam

3.5 System performance KPIs

To judge the performance of the ConOps we evaluated the efficiency and quality of the system elements by defining some KPIs for the relevant KPAs, some of them are shown in Table 5.

Table 5. Overview of all KPAs and KPIs relevant for ConOps validation

KPA	KPI	Measurement	Comments
D2D journey efficiency	Total distance travelled	Door-to-door distance	per PAX
	Total travel time	Door-to-door time	per PAX
	Average travel speed	Total distance travelled / Total travel time	per PAX
D2D journey quality	Waiting time at interconnections	(Egress time – Access time)/ Total travel time	per PAX
	Probability of delays from breakdowns/maintenance	Total time of delay/total operating time (on a weekly/monthly base)	per operating line

5. Outcomes and Analysis

The following graphs are examples of the results achieved after the framework is run and the experimental design performed. It is relevant to note that these results are the first insight on the performance of such a system and they could have some level of inaccuracy; however, they can be considered as a reference for what is expected, and it enables to determine elements in the system like bottlenecks or inefficient steps in the journey that need to be improved during the implementation phase. As it can be seen they present the situations of no disturbance, with ad-hoc disturbance and a disturbance 5hr-prior to Departure (X-Team D5.1, 2022).

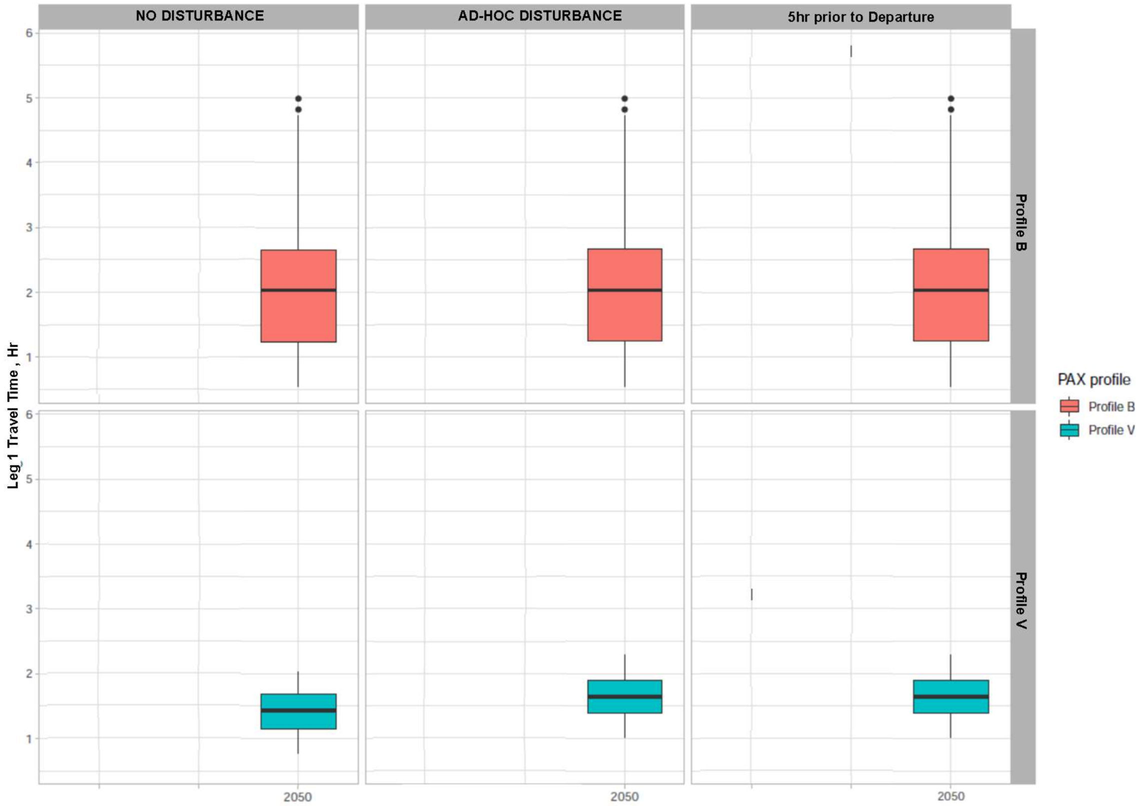

Fig 10. Travel time in LEG 1: D2A

In the graph it can be noticed that for the disturbance situations, the travel time the disturbances have almost no effect in the travel time revealing the capacity of the system to absorb problems in the network (resilience).

Fig11. Travel Time in LEG2: A2D

With regards to the 2nd leg of the trajectory, the graphs reveal that this part of the journey is less resilient than the first one and points towards an area of research to understand why this is happening. By doing this, the framework supports on signalizing the directions where potential bottlenecks or emergent behavior appear that might affect the performance of the whole system.

6. Conclusions and future work

We have presented the methodology for addressing such a complex system like a multimodal network. Like any system one of the main approaches are the development of a model. In our study we addressed the case of a multimodal network of the future; being a system that is still not in place, the challenge is major. To achieve it we devised a methodological approach for constructing a model that considers in an integral fashion the most relevant elements depending on the objective pursued. A particular challenge represented the verification and validation of a system in the future. We devised an innovative approach that reduced risks of inaccuracies and unreal or unreasonable results always considering the information at hand and following reasonable assumptions. We were able to apply the methodology which, to the knowledge of the authors, is the first one that aims at model and simulating a multimodal network for the first time producing results summarized in KPIs that give us insight of the performance of the system even with some decades in advance. The methodology is a first approach to analyse the system and different avenues are missing that can be investigated in future projects, (like environmental aspects or financial ones) but the methodology is general enough and provides the different steps to follow if someone is interested in doing a similar study.

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