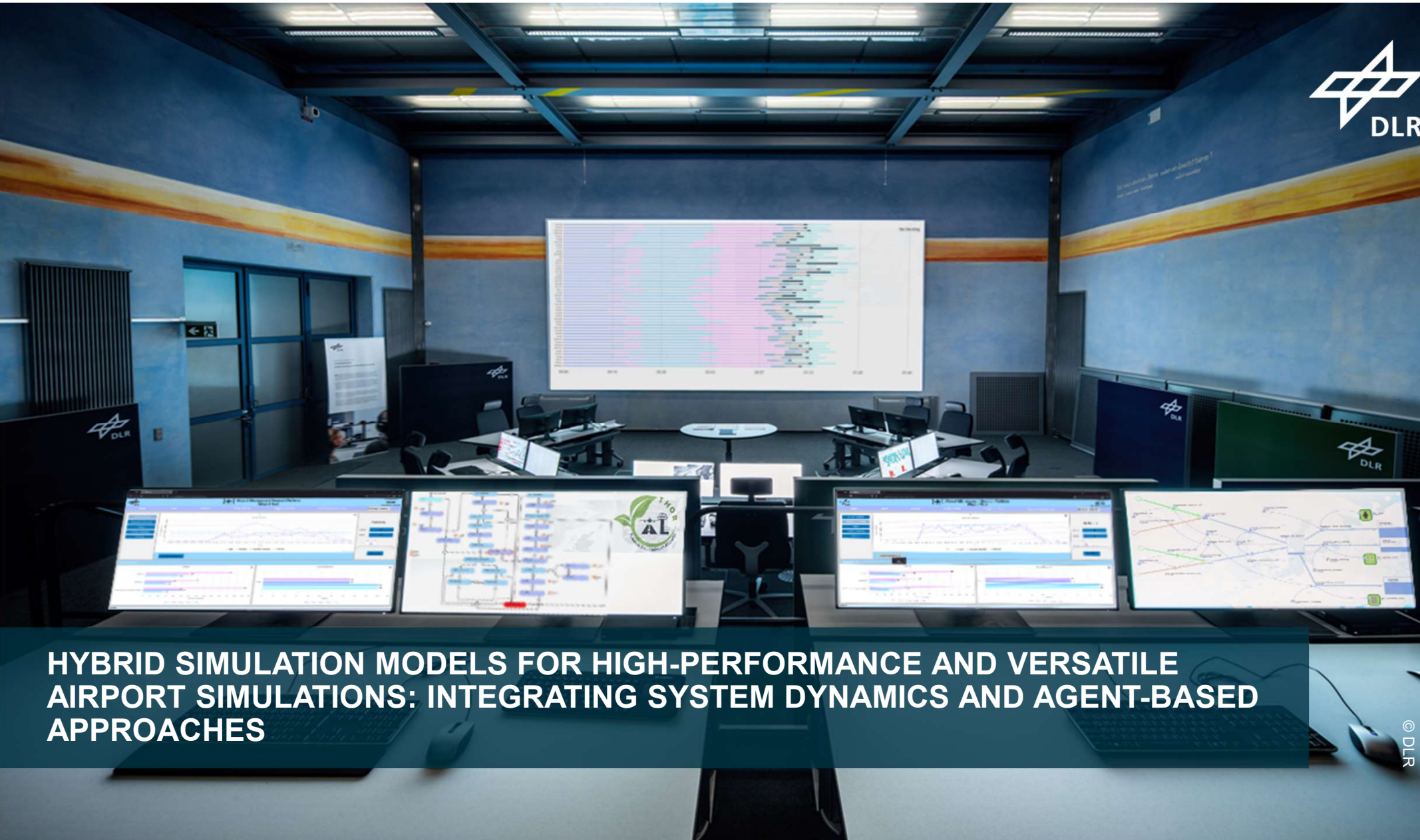


HYBRID SIMULATION MODELS FOR HIGH-PERFORMANCE AND VERSATILE AIRPORT SIMULATIONS: INTEGRATING SYSTEM DYNAMICS AND AGENT-BASED APPROACHES

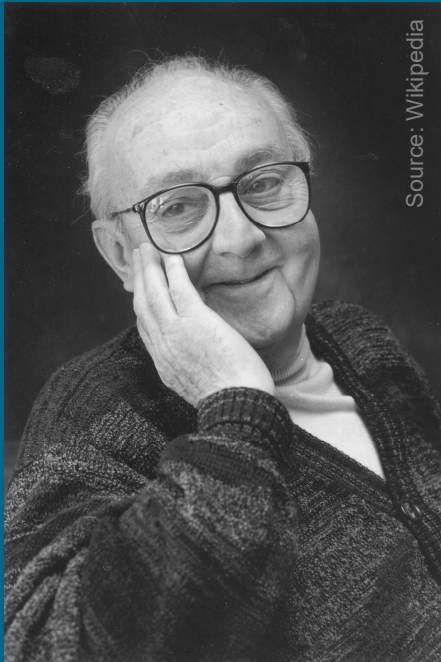
INAIR 2025 - International Conference on Air Transport

F. Rudolph; M. Jung; A.B. Classen



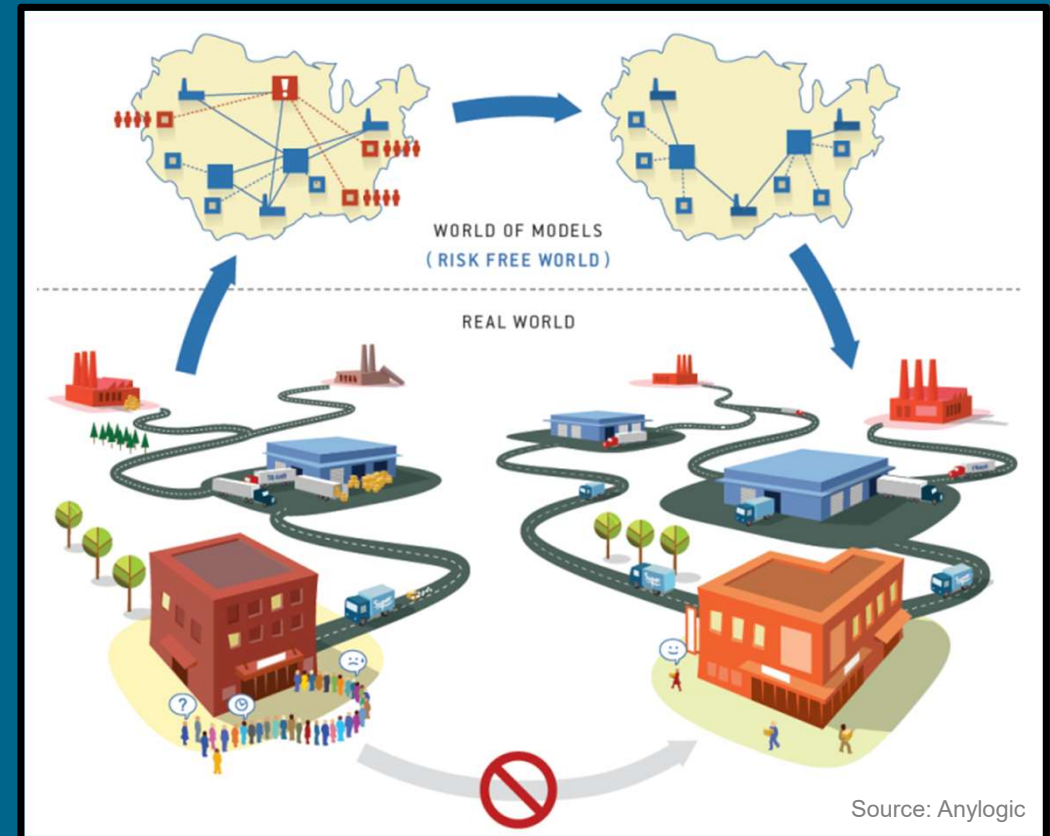
A photograph of a modern control room or simulation laboratory. In the foreground, several computer monitors are arranged on a desk, displaying various simulation data including line graphs, bar charts, and network diagrams. One monitor prominently features the AL (Airport Layout) logo. In the background, a large projection screen displays a complex, multi-colored bar chart. The room has a blue and orange color scheme, with DLR logos visible on the walls and equipment. The ceiling is high with exposed structural elements and lighting fixtures.

HYBRID SIMULATION MODELS FOR HIGH-PERFORMANCE AND VERSATILE AIRPORT SIMULATIONS: INTEGRATING SYSTEM DYNAMICS AND AGENT-BASED APPROACHES



Source: Wikipedia

„All models are wrong, but some are useful.“
George Box



Source: Anylogic

Hybrid Simulation Models for high-performance and versatile airport simulations: Integrating System Dynamics and Agent-Based Approaches



Content

- A-CDM Milestone Simulation
 - Network
 - State Charts
 - System Dynamics
- Mapping the milestones in the simulation
- Output used as a forecast
- Example: De-icing
- First Results and discussion of What-if Forecast Example
- Conclusion & Outlook

Introduction



- Modern airports provide a complex infrastructure and many different players are active at the airport.
- An airport is viewed as a holistic system with various operational areas and stakeholders.
- Airports face a variety of challenges including growing flight movements and passenger demand, stringent security regulations, unpredictable disruptions (e.g. severe weather or even a pandemic), and immanent interdependencies between infrastructure, staff and operations.
- Against the backdrop of the intensifying climate crisis, the transformation process in aviation is gaining more attention.
- In order to capture these complexities, **simulation modelling** has become integral to strategic and operational decision-making.

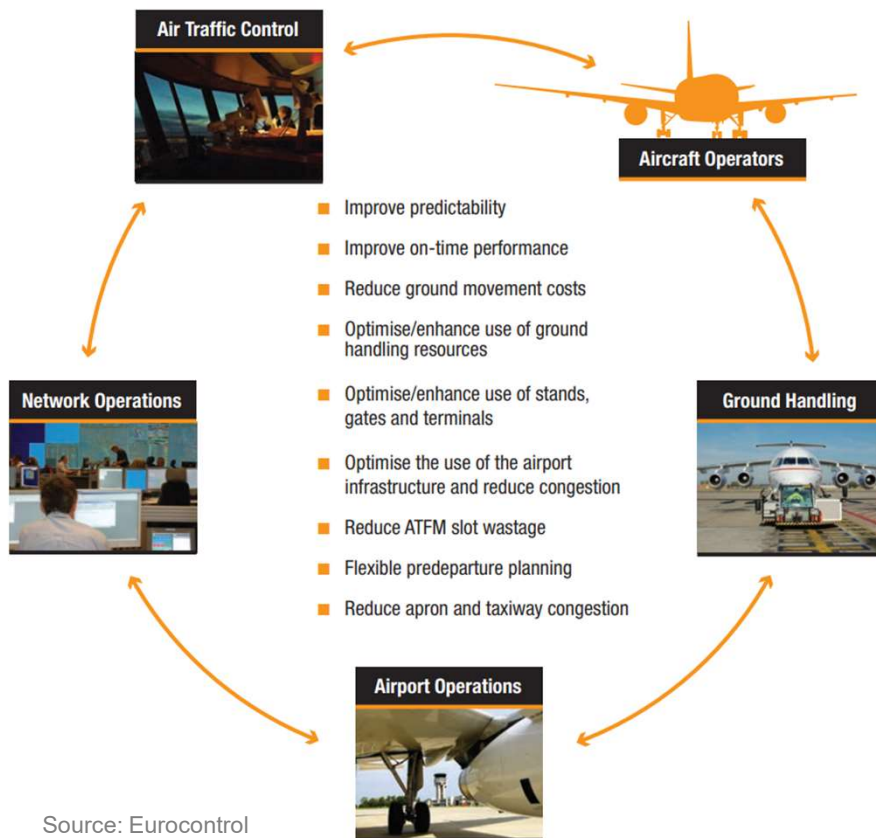


Source: DLR

Airport Collaborative Decision Making (A-CDM) I/III



AIRPORT CDM COMMON OBJECTIVES



Source: Eurocontrol

- In our Milestone-Simulation Network, we use A-CDM as operating principle.
- Aim of A-CDM is to increase operational efficiency of airports by making aircraft turnaround processes faster and more predictable.
- This is achieved by the stakeholders at the airport (airport operators, airlines, ground handlers and air traffic control) and the network manager working together transparently and cooperatively in operations and exchanging relevant, accurate and timely information.

Airport Collaborative Decision Making II/III



Number	Milestones	Time Reference	Mandatory / Optional for Airport CDM Implementation
1	ATC Flight Plan activation	3 hours before EOBT	Highly Recommended
2	EOBT – 2 hr	2 hours before EOBT	Highly Recommended
3	Take off from outstation	ATOT from outstation	Highly Recommended
4	Local radar update	Varies according to airport	Highly Recommended
5	Final approach	Varies according to airport	Highly Recommended
6	Landing	ALDT	Highly Recommended
7	In-block	AIBT	Highly Recommended
8	Ground handling starts	ACGT	Recommended
9	TOBT update prior to TSAT	Varies according to airport	Recommended
10	TSAT issue	TOBT -30 mins to -40 mins	Highly Recommended
11	Boarding starts	Varies according to airport	Recommended
12	Aircraft ready	ARDT	Recommended
13	Start up request	ASRT	Recommended
14	Start up approved	ASAT	Recommended
15	Off-block	AOBT	Highly Recommended
16	Take off	ATOT	Highly Recommended

Source: Eurocontrol - Airport CDM Implementation Manual

- The A-CDM Milestone approach to the turnaround process tracks the progress of a flight through a continuous sequence of different events, called milestones.
- Rules are set for updating downstream information and the accuracy of estimates.
- Different Airport-CDM partners can be responsible for different milestones, with the aim of integrating all milestones into a common seamless process for each flight.
- Main objective of the milestone approach is to further improve the common situational awareness of all partners during the approach and turnaround phases of the flight.

A-CDM III/III → Milestones → Examples Off-Block-Time



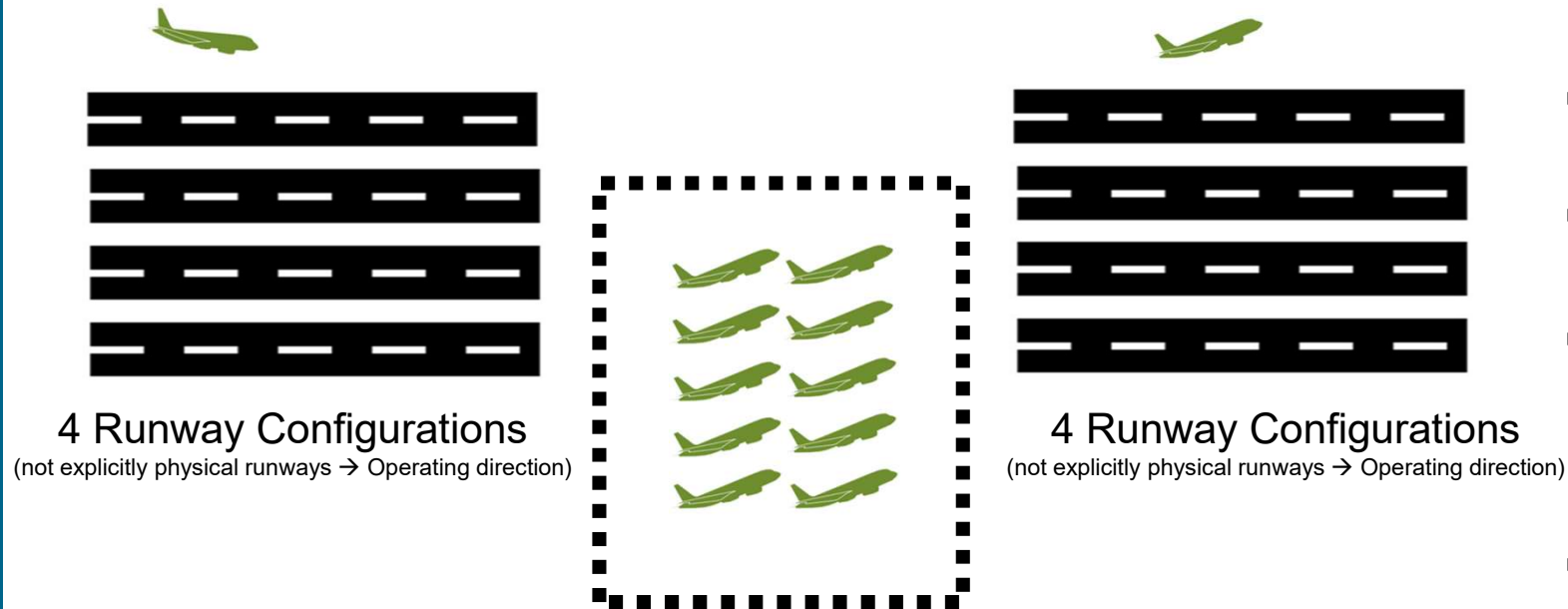
SCHEDULED	CALCULATED	ESTIMATED	TARGET	ACTUAL
Scheduled Off-Block Time The time that an aircraft is scheduled to depart from its parking position		Estimated Off-Block Time The estimated time at which the aircraft will start movement associated with departure (ICAO)	Target Off-Block Time The time that an Aircraft Operator or Ground Handler estimates that an aircraft will be ready, all doors closed, boarding bridge removed, push back vehicle available and ready to start up / push back immediately upon reception of clearance from the TWR	Actual Off-Block Time Time the aircraft pushes back / vacates the parking position

Availability

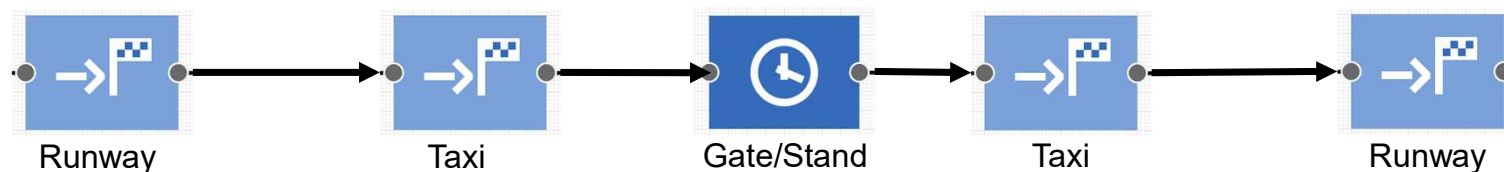
Accuracy

Source: own illustration based on Eurocontrol

Agent based (network) Simulation of A-CDM milestones I/IV



- Generic network model
„Airport in a nutshell.“
- Simulation without geographical representation
- Interactions between the simulation agents (aircrafts) implemented via resources and their capacities
- Characteristics of the airport are described via database
- Initialization of the model takes place when the simulation is started



Source: DLR

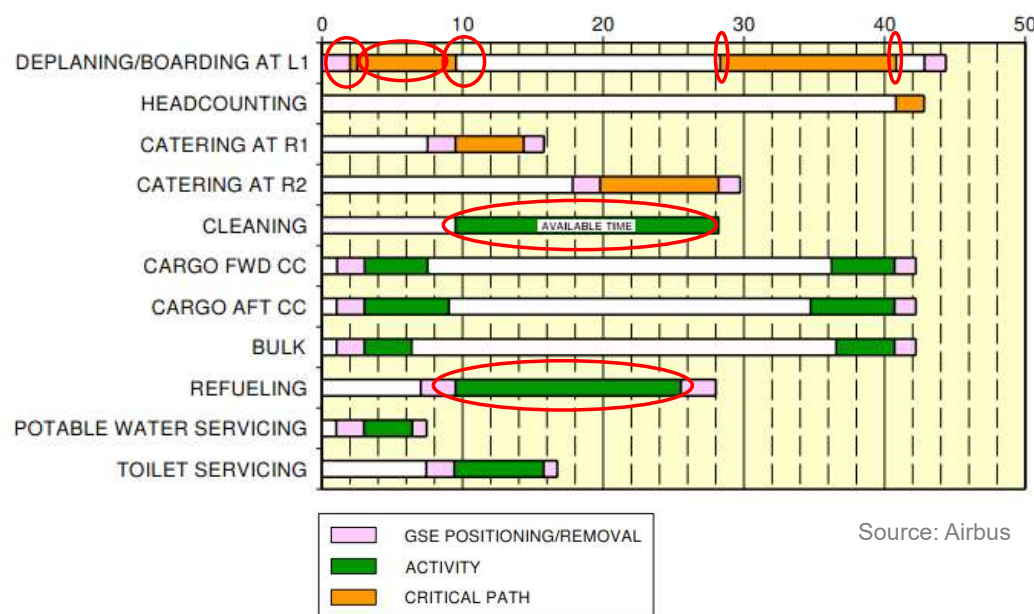
Agent-based simulation of A-CDM Milestones II/IV Turnaround



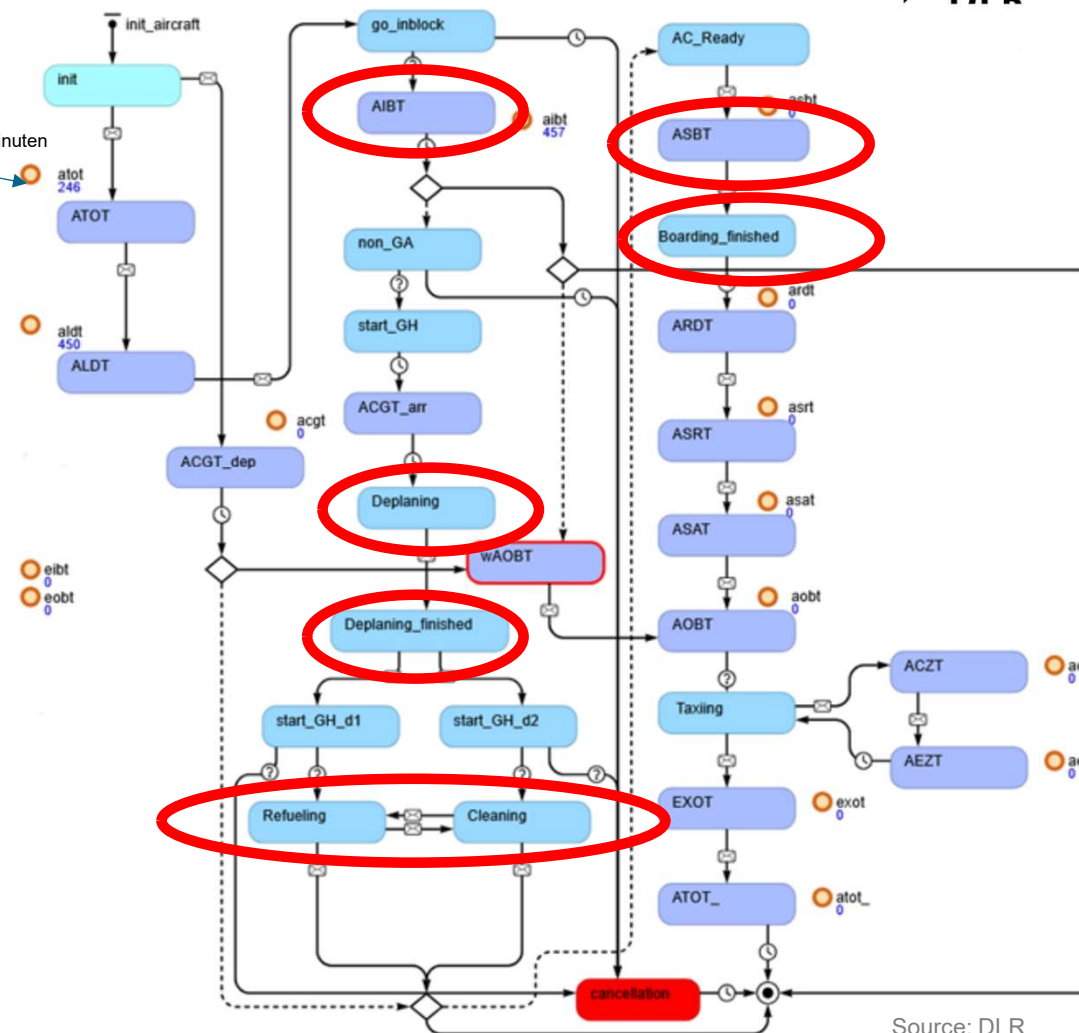
Gate/Stand

TRT: 44 min

Meilensteine in Simulationsminuten

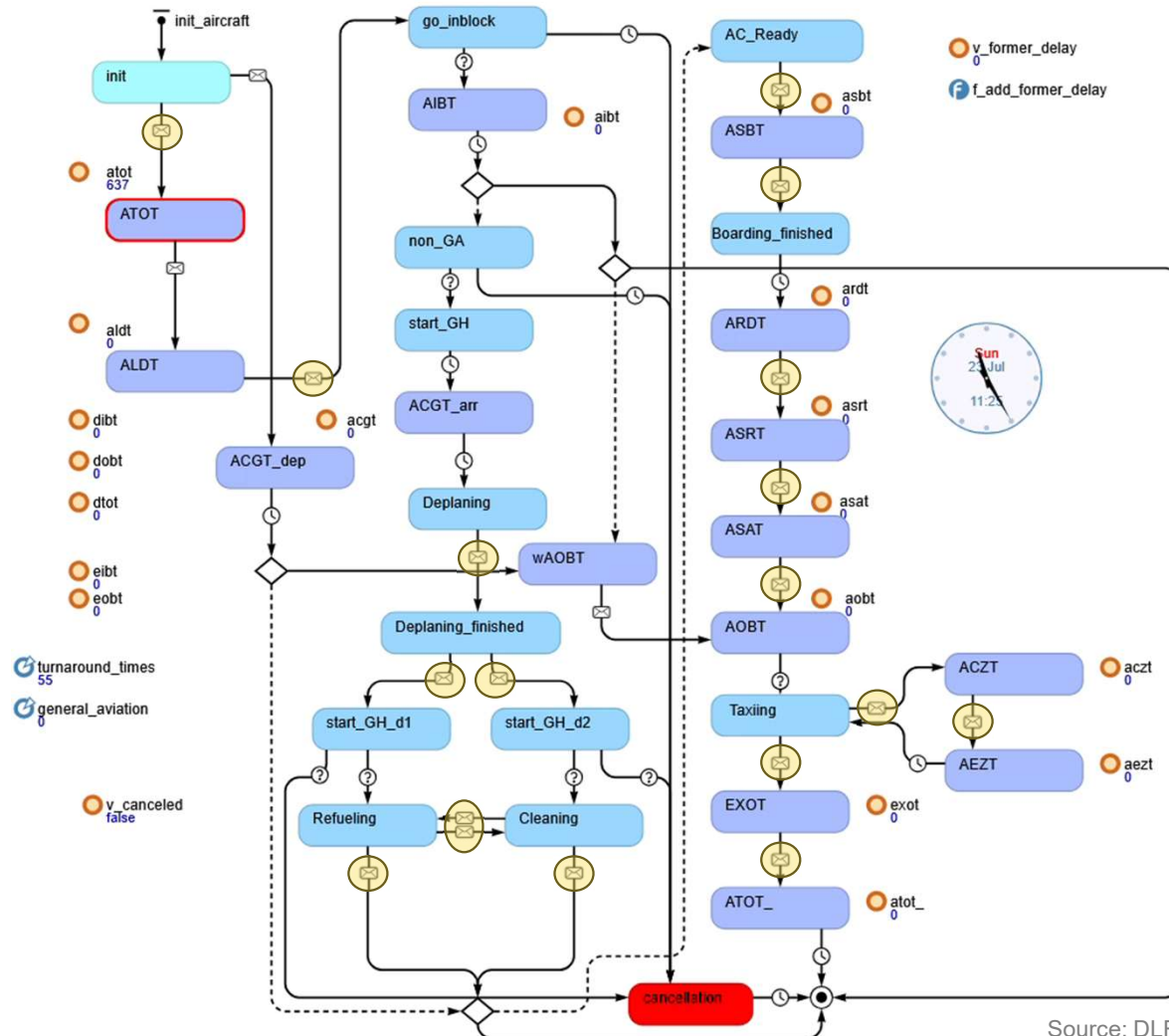


Source: Airbus



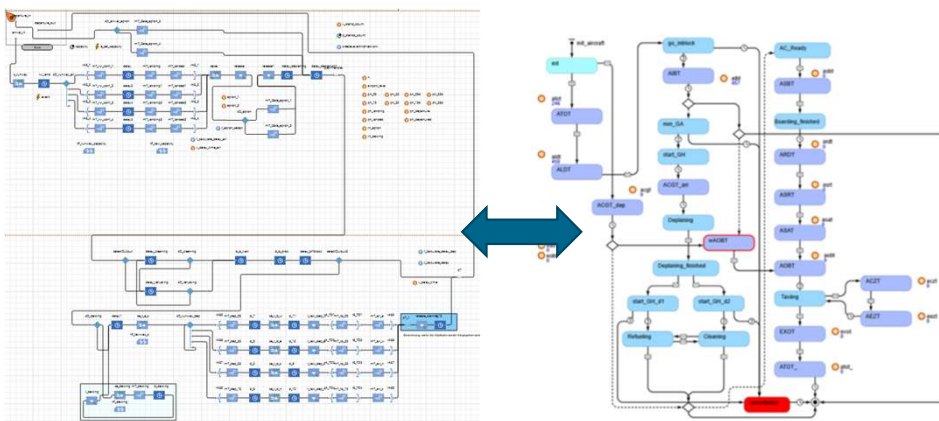
Source: DLR

Agent based (state chart) Simulation of A-CDM milestones III/IV



- The aircraft milestone simulation provides a forecast of A-CDM milestones and maps them with modelling methods from software engineering, in this case as a state chart diagram as part of the Unified Modelling Language.
- With this variant, the dependencies between the milestones can be mapped very specifically.
- Acting as a simulation agent, each aircraft has certain initialization parameters and individual control of the state chart diagram model for the aircraft's A-CDM milestones.
- The individual states of the aircraft are controlled via messages. If the aircraft reaches a certain process in the network simulation, a message is sent to the simulation agent.

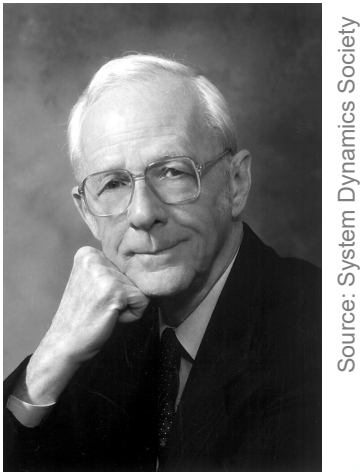
Agent-based simulation of A-CDM Milestones IV/IV



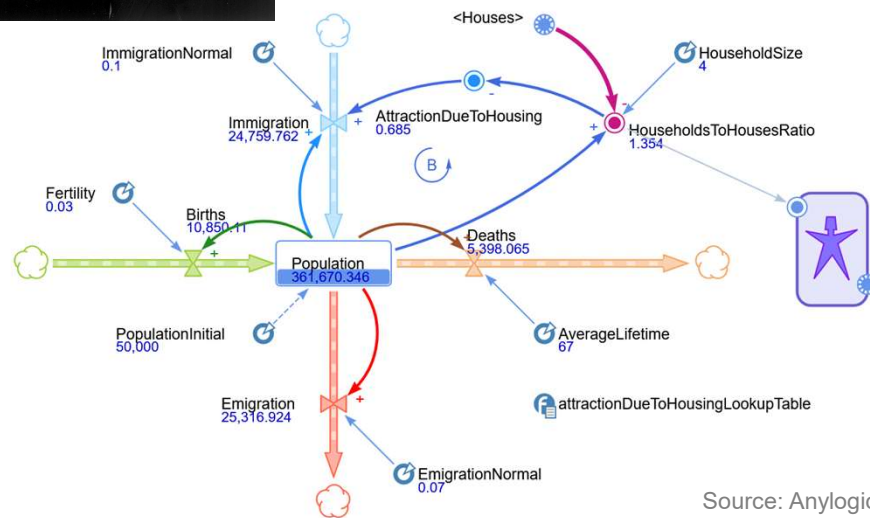
simtime	id	registration	type	callsign_a	callsign_d	sobt
435	497	LZEAD	both	AIZ211	AIZ212	06:54
sibt	atot	aldt	aibt	acgt	asbt	ardt
05:56	04:12	05:42	05:56	06:01	06:20	06:39
asat	aobt	aczt	aezt	atot	delay	dur_tax
06:57	06:58	00:00	00:00	07:13	4	15

- Status changes are triggered by the network simulation via messages. When an aircraft reaches a certain node in the network, it receives the message for the status change.
- If a milestone is reached as a status, it is stored in a database and can be made available to the management system.
- The network model provides the geographical path-time interrelations as well as the queue processing at the corresponding neuralgic points where only sequential processing of aircraft is possible.
- This combination of state charts and network simulation thus provides a digital twin for determining the A-CDM milestones.

Energy flow Simulation in System-Dynamics I/II



Source: System Dynamics Society

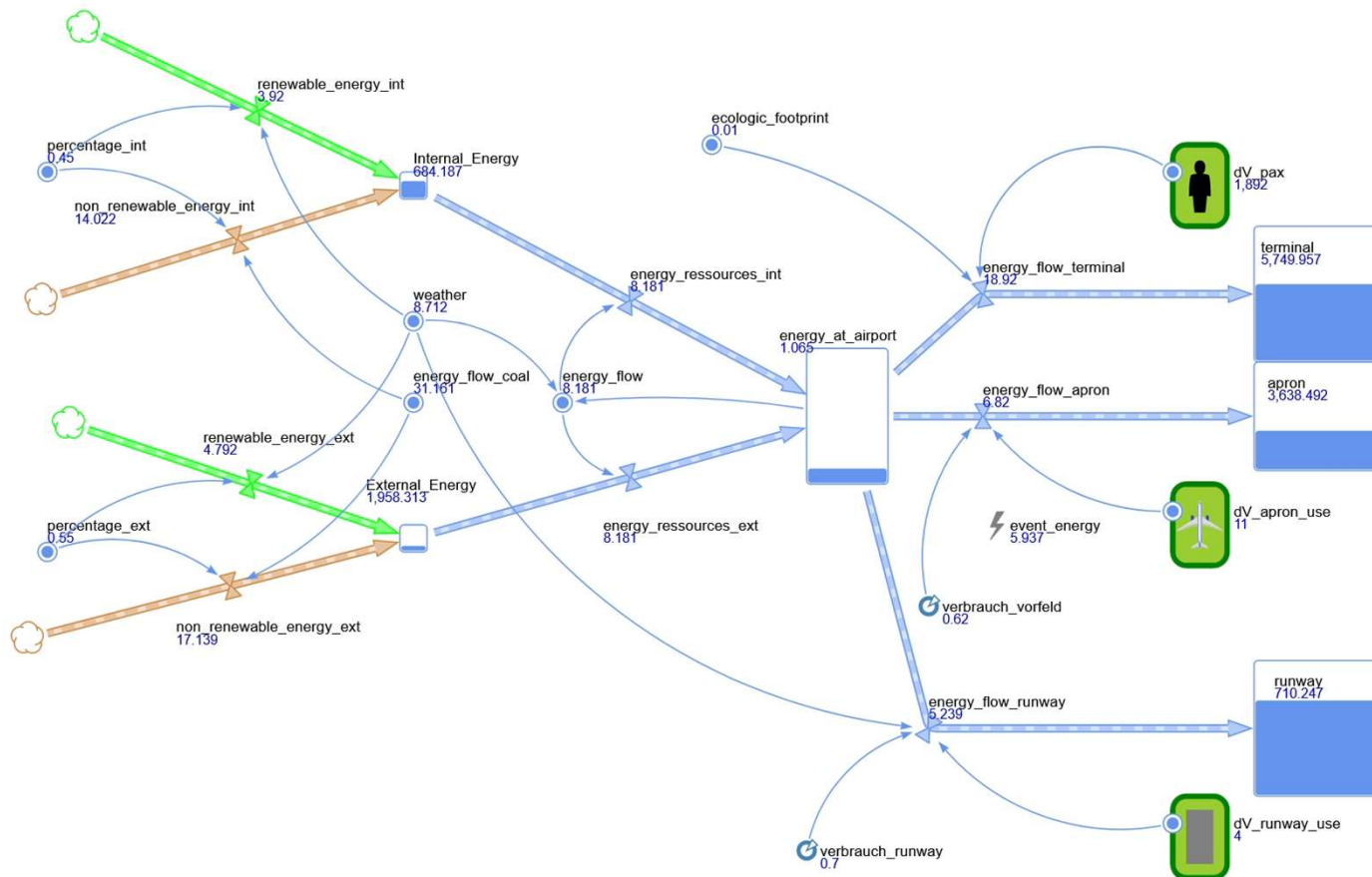


Source: Anylogic

Using the paradigm of system dynamics simulation

- System Dynamics (SD) is a methodology for modelling and simulating complex systems, particularly in the context of energy consumption.
- SD was developed in the 1950s by J.W. Forrester.
- Among other things, Forrester's methods formed the basis of the Club of Rome's 1972 book *The Limits to Growth* - A published study on the future of the global economy.
- It uses and visualizes stocks, flows, internal feedback loops, table functions and time delays to model a system.

Energy flow Simulation in System-Dynamics II/II

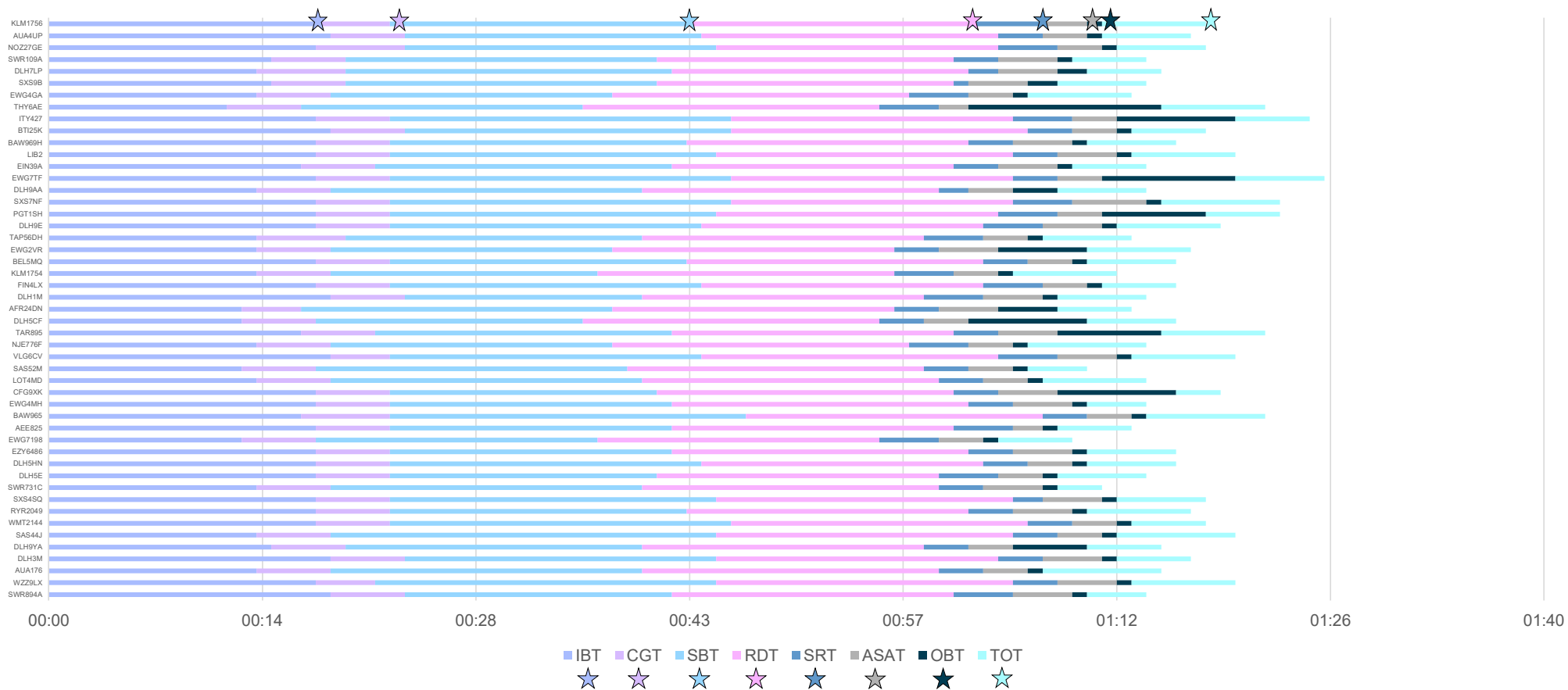


- The simulation provides a holistic view of the airport by considering interconnected components, feedback loops, and dynamic behavior of all airport parts and stakeholders to visualize causal relationships.
- Focus on a first simulation prototype to examine the technical feasibility, possibilities and limitations in the combination between agent-based network simulation and system dynamics.

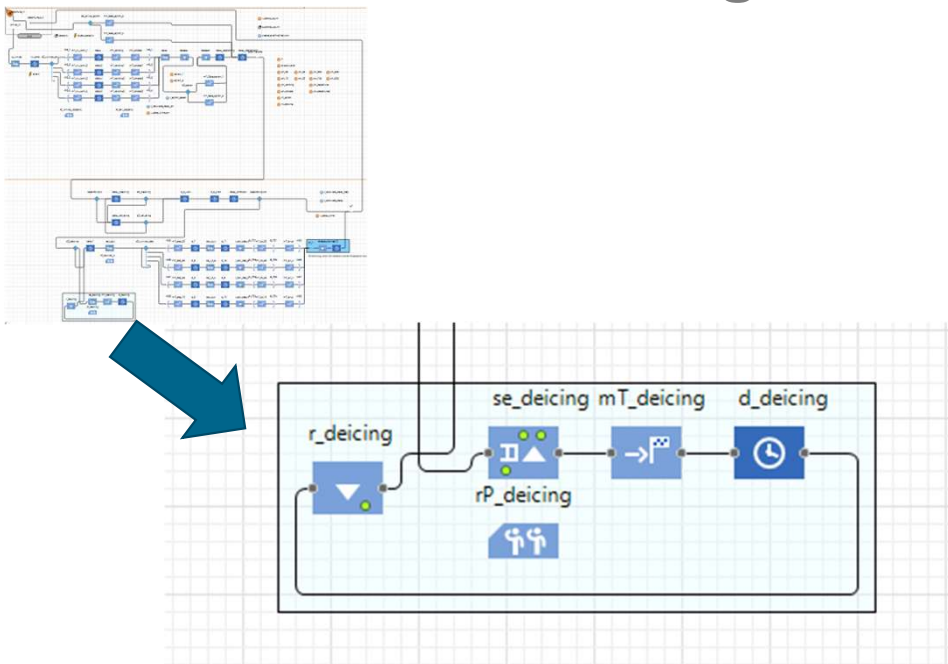
Simulation output → Example Milestone evaluation I/III



time_diff between ALDT and ATOT

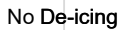


Resource Pool De-icing / Example Scenario II/III

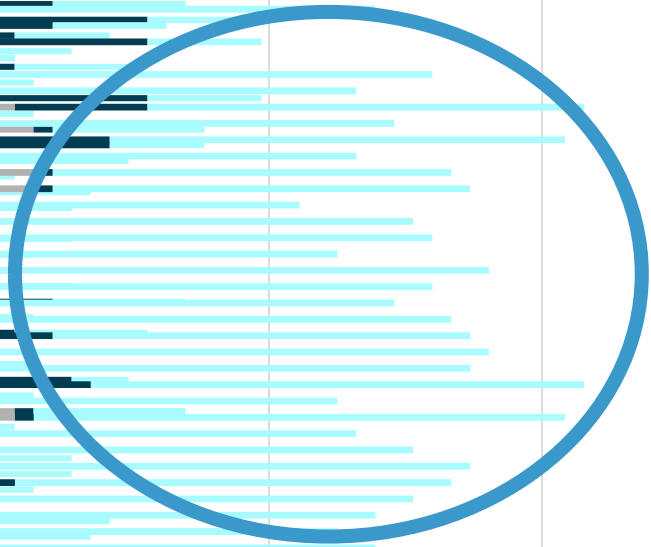


Source: DLR

- Sub-Model „de-icing“
- Resource pool for capacity control
- Example scenario
 - Flight plan based on an international airport in Germany (approx. 120,000 flight movements in 2023)
 - Deicing in the simulation approx. from 8:45 - 12:30
 - Effects on milestones of the affected flights



	No D
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First Results and discussion of What-if Forecast Example I/VI

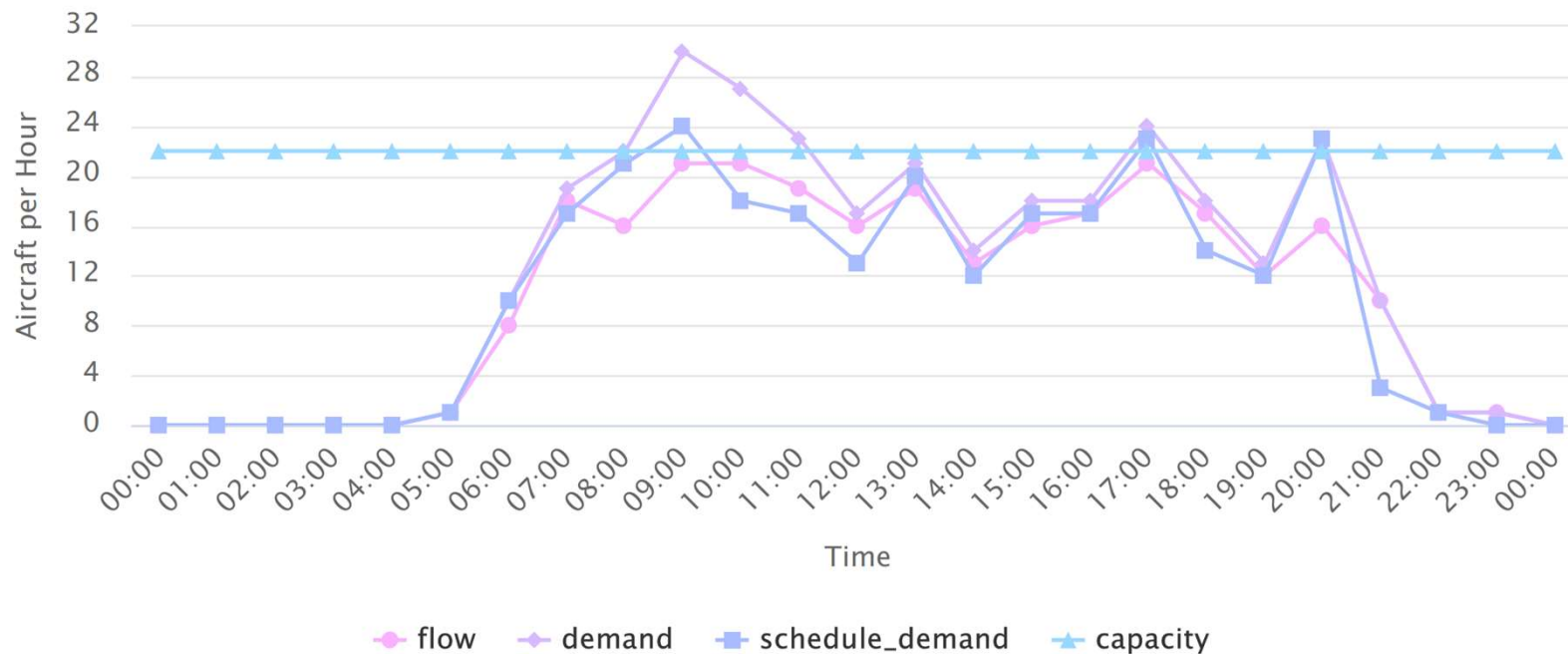


- Integration of the forecast simulation into a What-if management platform
- easy to enter actions for the simulation directly
- results from these simulations are directly analysed and displayed in an aggregated form

Source: DLR

First Results and discussion of What-if Forecast Example II/VI

Arrival_Runway



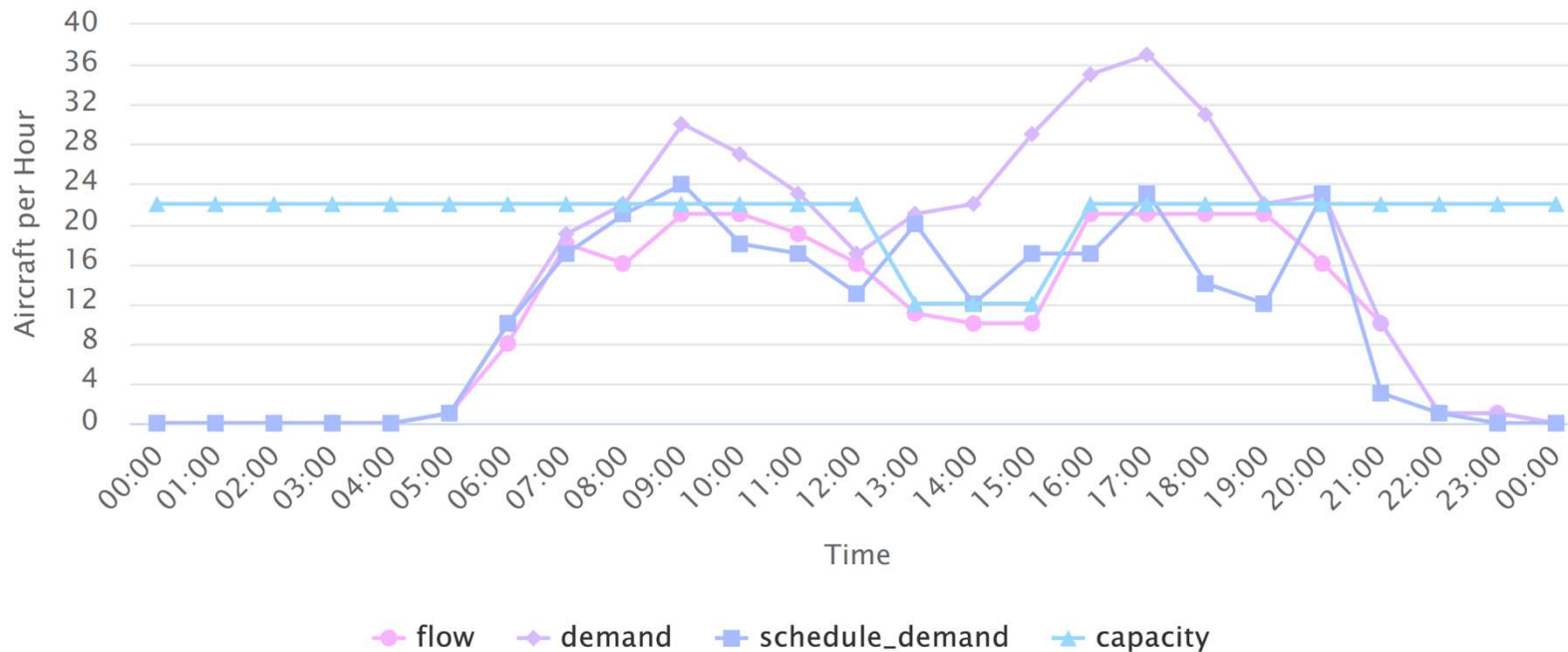
Example scenario

- Origin Flight plan based on an international airport in Germany (approx. 120,000 flight movements in 2023)
- Based on a predicted air traffic development in Europe for the year 2050 a future flight plan for the airport in question was applied.
- In total, our air traffic scenario runs a full day of operations from 0:00 to 23:59 and comprises a total of 527 flights (263 arrivals and 264 departures).

- utilisation of the arrival runway
- the flow is shown as a **pink** graph of the simulation result
- the schedule_demand (**blue**) represents the utilisation of the runway based on the planned flight schedule
- the actual accumulated demand (**violet**) is calculated by comparing unhandled arrivals from the schedule_demand with the simulated flow
- the **light blue** graph shows the runway's actual capacity, which is 22 arrivals per hour in this case.

First Results and discussion of What-if Forecast Example III/VI

Arrival_Runway

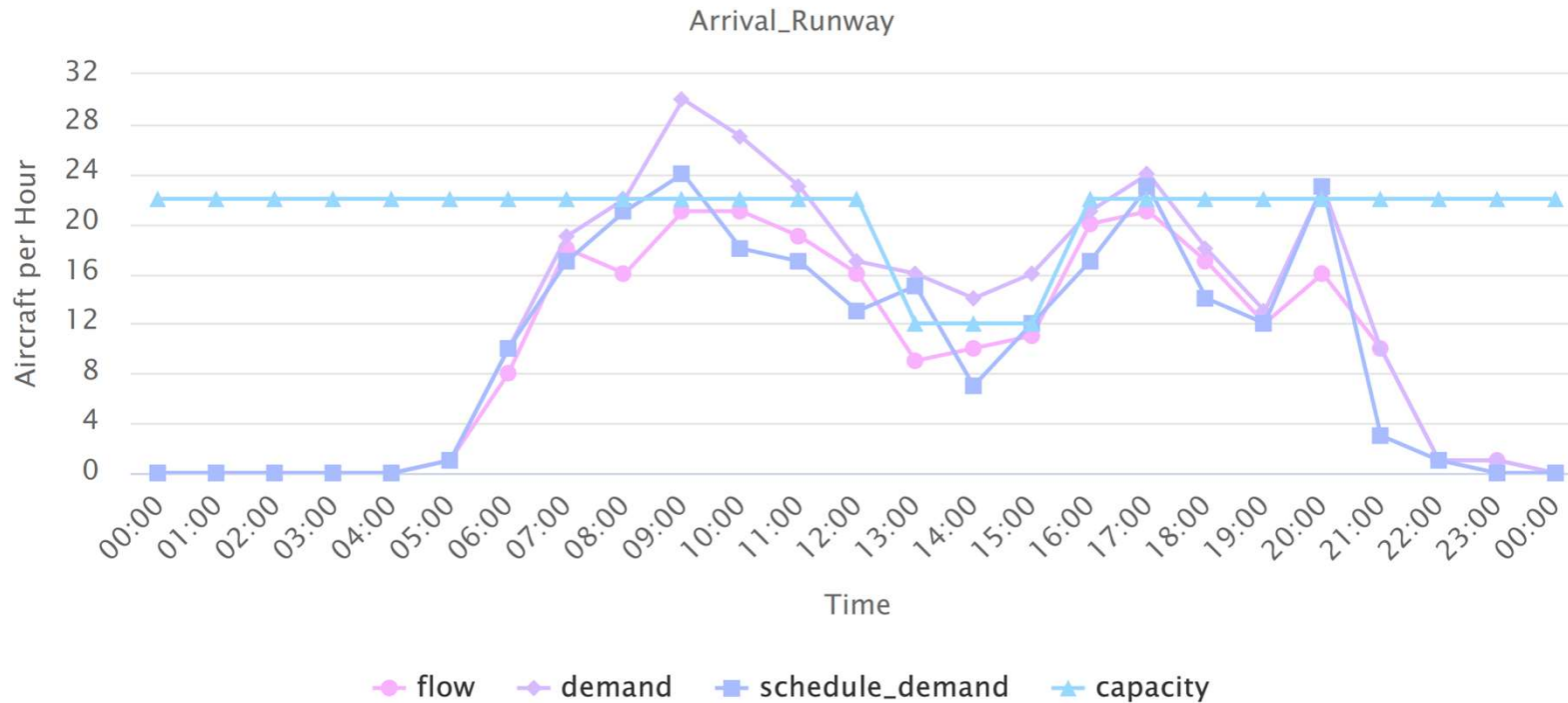


Example scenario

- Origin Flight plan based on an international airport in Germany (approx. 120,000 flight movements in 2023)
- Based on a predicted air traffic development in Europe for the year 2050 a future flight plan for the airport in question was applied.
- In total, our air traffic scenario runs a full day of operations from 0:00 to 23:59 and comprises a total of 527 flights (263 arrivals and 264 departures).

- a bad weather event makes it necessary to increase the distance between approaching aircraft, thereby reducing the overall capacity
- the **capacity** is reduced to 12 landings between 12:00 and 15:00
- the **flow** adapts to this restriction and then remains close to the actual capacity limit of the runway until around 21:00
- the **demand** continues to build up due to the unhandled flights and then only adapts to the flow around 21:00

First Results and and discussion of What-if Forecast Example IV/VI



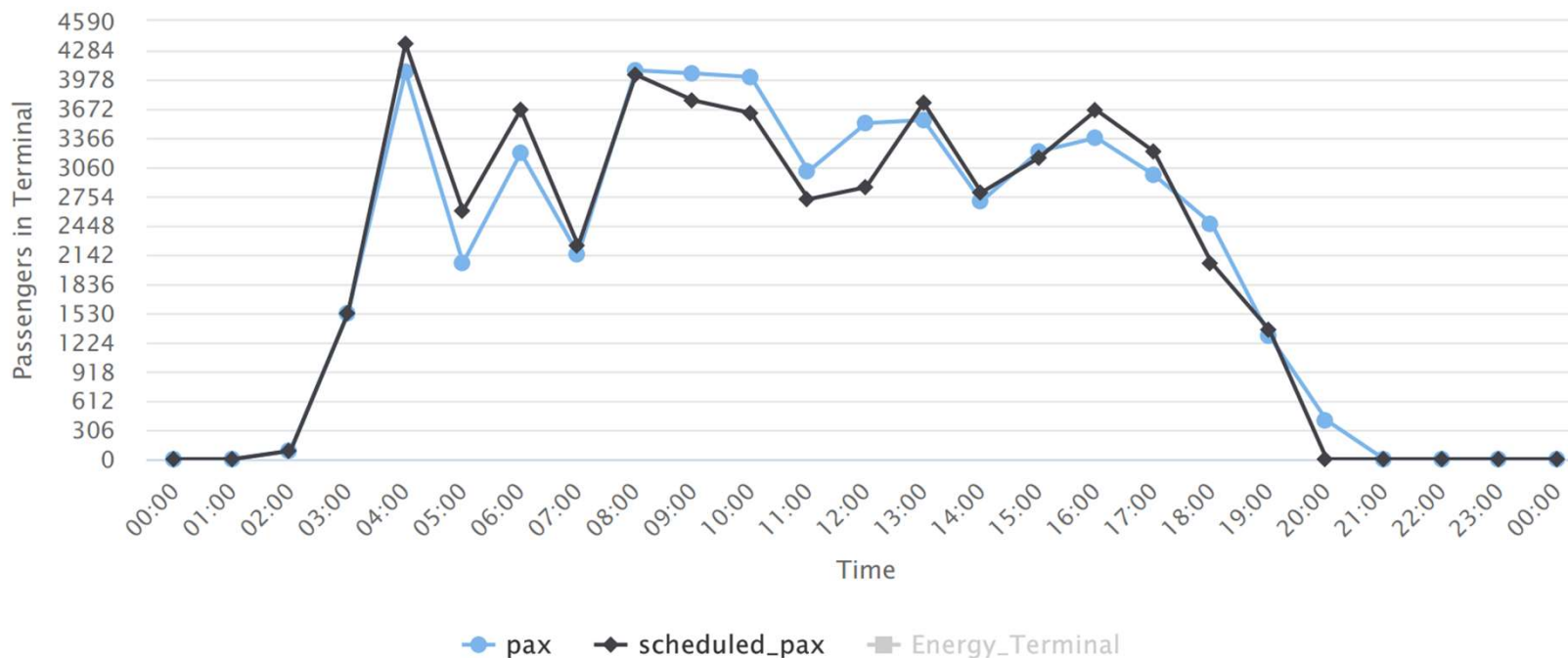
Example scenario

- Origin Flight plan based on an international airport in Germany (approx. 120,000 flight movements in 2023)
- Based on a predicted air traffic development in Europe for the year 2050 a future flight plan for the airport in question was applied.
- In total, our air traffic scenario runs a full day of operations from 0:00 to 23:59 and comprises a total of 527 flights (263 arrivals and 264 departures).

- 5 flights per hour are diverted in the above-mentioned time period
- the **demand** does not build up to the same extent as it would have done without this measure
- although it is slightly above the capacity limit, the impact on the **demand** is less significant than before
- from 18:00 the **demand** is already back to the level before the event, and the simulated **flow** is also reduced
- rerouting 5 flights in the 3 hours would be sufficient in this case to return to normal operations as quickly as possible

First Results and discussion of What-if Forecast Example V/VI

Terminal

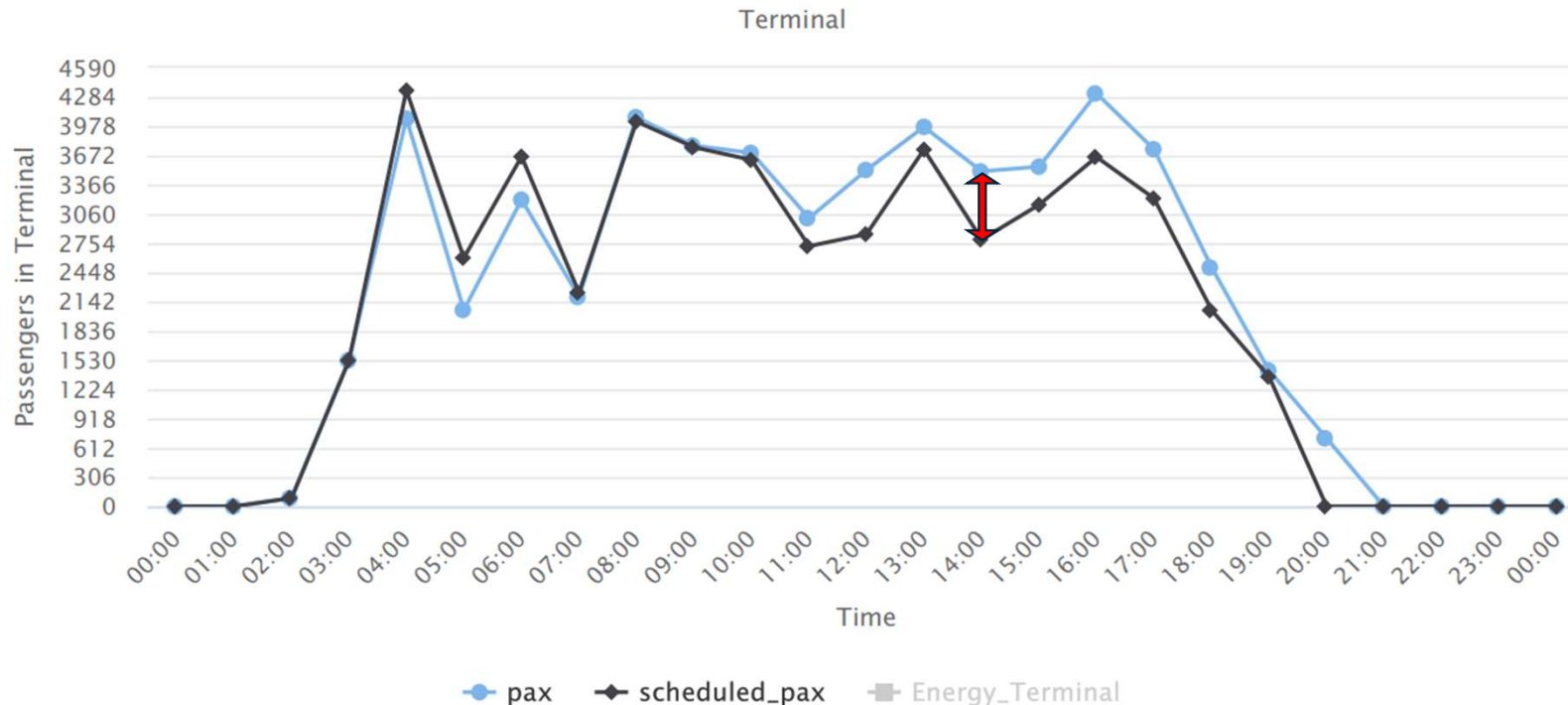


Example scenario

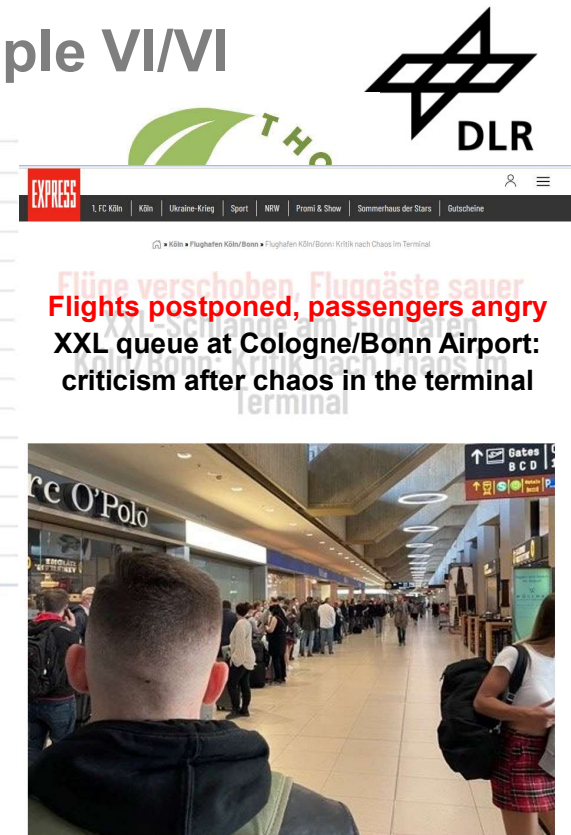
- Origin Flight plan based on an international airport in Germany (approx. 120,000 flight movements in 2023)
- Based on a predicted air traffic development in Europe for the year 2050 a future flight plan for the airport in question was applied.
- In total, our air traffic scenario runs a full day of operations from 0:00 to 23:59 and comprises a total of 527 flights (263 arrivals and 264 departures).

- the system-dynamics simulation model also examines how the number of passengers in the terminal changes over time
- the **blue** curve represents the simulated values
- the **black** curve represents the planned values for the number of passengers in the terminal at the corresponding times

First Results and discussion of What-if Forecast Example VI/VI



- the simulation results differ from 14:00 onwards
- fewer aircraft will be able to land from 12:00 because of the reduction in arrival capacity, meaning that later take-offs will also be delayed → more passengers have to wait in the terminal
- around 700 more passengers are expected in the terminal at 14:00, bringing the total to 3,500 instead of 2,800
- even if the graph does not differ significantly from the scheduled values, an increase of more than 500 passengers at the airport terminal can have a significant impact on the airport processes



Hybrid Simulation Models for high-performance and versatile airport simulations: Integrating System Dynamics and Agent-Based Approaches



Conclusion

- Investigation of the combination of several simulation models to support the airport operator
- Hybrid simulation useful for ad-hoc forecasts and What-if
 - enabling a quick response to unforeseeable disruptions (e.g. severe weather) and inherent interdependencies between infrastructure, personnel and operations.
 - quickly determine the impact of events (De-Icing) and decisions
 - all in one solution (sim_time < 5 sec.)

Outlook

- Integration in management platform
 - for event evaluation
 - Human in the loop – Trials (planned Dec. 25)
 - KPI Integration
 - e.g. delays, cancellations, ecological footprint, costs
 - What-if studies (online - planned Nov. 25)
 - energy consumption

„All models are wrong, but some are useful.“
George Box



Source: DLR

Thanks for your attention ...



```
1 System.out.println("I will be happy to answer your questions.");
2
3 while (questions > 0) {
4     question_string = voice.readLine();
5     String answer = answer_question(question_string);
6     System.out.println(answer);
7
8     questions--;
9 }
10 System.out.println("Thank you for your attention.");
```



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