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**DIGITĀLO DVĪŅU KONCEPCIJAS IZSTRĀDE UN TESTĒŠANA  
KĀ PROCESU DATU NOLIKTAVA LIDOSTU VIRSZEMES SATIKSMES  
VADĪBAS SISTĒMĀS**

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**TRANSPORT AND TELECOMMUNICATION INSTITUTE**

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**DEVELOPMENT AND TESTING OF THE DIGITAL TWIN CONCEPT  
AS A PROCESS DATA STORE IN GROUND TRAFFIC CONTROL SYSTEMS  
AT AIRPORTS**

**DOCTORAL THESIS**

to obtain the scientific degree Doctor of Science in Engineering

Scientific area “Civil Engineering and Transport”  
Scientific subarea “Telematics and Logistics”

**Scientific supervisor:**  
Dr.habil.sc.ing., professor  
Jurijs Tolujevs

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## ANOTĀCIJA

Promocijas darbu “Digitālo dvīņu koncepcijas izstrāde un testēšana kā procesu datu noliktava lidostu virszemes satiksmes vadības sistēmās” ir uzrakstījis Farid Saifutdinov, Dr.habil.sc.ing., profesora Jurija Tolujeva vadībā.

Kā pētījuma objekts šajā darbā ir noteikta modernas lidostas virszemes transporta sistēma. Darbs ir vērsts uz perspektīvās problēmas risināšanu, izstrādājot automātiskās vadības sistēmas gaisa kuģu un virszemes transportlīdzekļu kustībai lidostas lidlauka zonā. Organizācija IATA (The International Air Transport Association) šādu uzdevumu formulēja 2011. gadā dokumentā “Vision 2050”.

Šā darba pamatā ir apgalvojums, ka nevienu sarežģīta tehniskā objekta vadības sistēmu nevar ieviest ekspluatācijā, nepārbaudot to, izmantojot vienu vai vairākus matemātiskās modelēšanas veidus. Lidostas virszemes transporta sistēma pieder pie tādām sistēmām, kuru izpētei ir jāpielieto datorsimulācija. Īpašs simulācijas modeļu izmantošanas veids ir emulācijas režīms, kad modelis mijiedarbojas ar reālu vadības sistēmu. Šis darbs neattiecas uz pašu vadības programmu izstrādi, bet tajā ir ierosināts rīks to apmācībai un testēšanai, kas vērsts uz simulācijas modeļu izmantošanu emulācijas režīmā.

Vadības sistēmai jāsaņem pilnīga un precīza informācija par vadības objekta stāvokli, kuras vākšanai un glabāšanai var izmantot Digitālo dvīni. Darbā ir aprakstīta autora izveidota universāla datorprogramma, kas paredzēta kritisku situāciju simulēšanai lidostas transporta sistēmā. Šādu situāciju iestāšanās un novēršanas scenārijus nosaka eksperts, un pēc to īstenošanas, izmantojot simulācijas modeli, Digitālais dvīnis reģistrē visu objektu kustību tādā formātā, kas atbilst mērījumu datiem, kuri iegūti, izmantojot reālas iekārtas kustīgu objektu atrašanās vietas noteikšanai. Digitālajā dvīnī uzkrātā informācija ir paredzēta izveidotās lidostas virszemes transporta vadības sistēmas apmācībai.

Šī pētījuma novitāte un mērķis ir izstrādāt un eksperimentāli pārbaudīt datorsimulācijas un emulācijas metožu pielietošanas koncepcijas, lai izveidotu Digitālo dvīni, ko var izmantot kā informācijas avotu reāllaika vadības sistēmai gan tās apmācības režīmā, gan normālā ekspluatācijā.

Darba galvenie rezultāti ir prezentēti 5 starptautiskās zinātniskās konferencēs un publicēti 7 zinātniskajos rakstos. Promocijas darbs sastāv no 5 nodaļām un tajā ir 135 lpp., 52 attēli, 2 tabulas pamattekstā, 2 pielikumi un 163 atsauces bibliogrāfijā.

## **ABSTRACT**

The thesis “Development and testing of the Digital Twin concept as a process data store in ground traffic control systems at airports” is written by Farid Saifutdinov under the supervision of Dr.habil.sc.ing., professor Jurijs Tolujevs.

As an object of research in this work, the ground transport system of a modern airport is determined. The work is focused on solving the promising problem of developing automatic control systems for the movement of aircraft and ground vehicles in the airside zone of the airport. The organization IATA (The International Air Transport Association) formulated such a task in 2011 in a document called “Vision 2050”.

This work is based on the assertion that any control system for a complex technical object cannot be put into operation without testing it using one or several types of mathematical modelling. The ground transport system at the airport belongs to a class of systems for the study of which it is necessary to apply computer simulation. A special way of using simulation models is the emulation mode when the model interacts with a real control system. This work does not concern the development of control programs themselves, but it proposes a tool for their training and testing, focused on the use of simulation models in emulation mode.

The control system must receive complete and accurate information about the state of the control object, for the collection and storage of which Digital Twin can be used. The work describes a universal computer program created by the author, which is designed to simulate critical situations in the airport transport system. The scenarios for the occurrence and elimination of such situations are set by an expert, and after their implementation using a simulation model, Digital Twin records the movement of all objects in a format that corresponds to the measurement data obtained using real equipment for determining the location of moving objects. The information accumulated in the Digital Twin is intended for training the created airport ground transport control system.

The novelty and purpose of this study is to develop and experimentally test the concepts of applying computer simulation and emulation methods to create a Digital Twin, which can be used as a source of information for a real-time control system both in its training mode and in normal operation.

Main results of this thesis are presented at 5 international scientific conferences and published in 7 scientific papers. The thesis consists of 5 chapters and includes 135 pages, 52 figures, 2 tables in the main body, 2 appendixes and 163 references in the bibliography.

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**LIST OF ABBREVIATIONS AND ACRONYMS**

AC – Aircraft

A-CDM – Airport Collaborative Decision Making

ADS – Automatic Dependent Surveillance

ADS-B – Automatic Dependent Surveillance-Broadcast

A-GPS – Assisted GPS

AGV – Automated Guided Vehicles

AIBT – Actual In Block Time

ALDT – Actual Landing Time

ANSP – Air Navigation Service Provider

AOBT – Actual Off-Block Time

APTR – Alternative Parallel Taxi Routing

ARMG – Automated Rail-Mounted Gantry Cranes

A-SMGCS – Advanced-Surface Movement Guidance and Control System

ATM – Air Traffic Management

ATS – Air Traffic Service

A-VDGS – Advanced Visual Docking Guidance System

BHS – Baggage Handling Simulation

BLE – Bluetooth Low Energy

CARMA – Car Management on Aprons

DGPS – Differential Global Positioning System

DSS – Decision support system

DT – Digital Twin

ED-APF – Enterprise Dynamics Airport Passenger Flows

ED-BHS – Enterprise Dynamics Baggage Handling Simulation

FCD – Floating Car Data

FOD – Foreign Object Debris

GLONASS – Global Navigation Satellite System

GNSS – Global Navigation Satellite System

GPS – Global positioning system

GSE – Ground Service Equipment

GSM – Global System for Mobile Communications

GTSS – Ground Traffic Scenario Simulation

GUI – Graphical User Interface

GV – Ground Vehicle

HDSA – High-Definition Situation-Aware

HDV – Human Driven Vehicle

HMI – Human-Machine Interface

HVAC – Heating, Ventilation, and Air Conditioning

IATA – International Air Transport Association

ICAO – International Civil Aviation Organization

IMHOTEP – Integrated Multimodal Airport Operations for Efficient Passenger Flow Management

ITS – Intelligent Transportation Systems

KPI – Key Performance Indicator

LiDAR – Light Detection and Ranging

LPS – Local Positioning Systems

LVP – Low Visibility Procedures

MLAT – Multilateration

MRO – Maintenance, Repair and Overhaul

NASA – National Aeronautics and Space Administration

NavIC – NAVigation with Indian Constellation

NextGen – Next Generation Air Transportation System

OINS – Onboard Integrated Navigation System

PLC – Programmable Logic Controller

QZSS – Quazi-Zenith Satellite System

RFID – Radio-frequency Identification

RNSS – Radionavigation-Satellite Service

RTLS – Real-time LPS

RVT – Remote and Virtual Tower

RWY – Runway

SBAS – Satellite-Based Augmentation Systems

SD – System Dynamic

SDK – Software Development Kit

SMR – Surface Movement Radar

SUMO – Simulation of Urban Mobility

TAAM – Total Airspace and Airport Modeler

TCL – Taxiway Centerline

TMC – Traffic Management Center

UAV – Unmanned Aerial Vehicles

UGV – Unmanned Ground Vehicle

UWB – Ultra-wideband

VANets – Vehicular Ad Hoc Networks

VBA – Visual Basic for Applications

WiFi – Wireless Fidelity

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## 1. INTRODUCTION

### 1.1. Motivation

The development of air transportation leads to an increase in the mobility of the population and the volume of freight traffic, which is a factor in accelerating economic growth. In many regions of the world, it is air transport that has a great influence on the formation of the economic status of the region. Air transport at the beginning of the 21st century is acquiring more and more new functions and capabilities that could not even have been imagined 20-25 years ago. Being the safest mode of transport, air transport has become the main world communication, connecting the territories of different countries into a single network. According to the World Bank, in 1980-2017, air freight turnover increased 7.9 times and amounted to 212.8 billion t-km, and the number of passengers carried increased 6.4 times, to 4.1 billion passengers per year (World Bank, URL). The International Air Transport Association (IATA) expects 7.2 billion passengers to travel in 2035, nearly double the 3.8 billion air passengers in 2016 (IATA, URL).

The main element of the air transport infrastructure is the airport, the capacity of which depends primarily on the organization of its transport process, which can be defined as the process of moving passengers, cargo, aircraft (AC) and ground vehicles (GV) in the air and ground spaces of the airport. The factors affecting the stability of the flow of transport processes at the airport are the degree of automation and the capacity of the following airport zones:

- Airspace;
- Airside area;
- Landside area;
- Terminal area.

The most difficult and important from the point of view of ensuring the safety of the airport operation are Airspace and Airside area. Airspace processes are subject to strict international rules and are precisely defined for each specific airport. The greatest variety of options for organizing processes refers to the Airside area, where the ground movement of AC and GV is carried out. In the ground handling of one AC, located in the outer parking lot, more than 10 GV participate, which travel in the airside zone of the airport. More than 1000 AC are handled at the largest airports in the world during the day. This means that the number of GV trips reaches several tens of thousands per day.

These days, centralized ground movement control is provided by either conventional airport controllers or dedicated ground movement controllers. With an increase in the intensity of

flights, the workload of controllers increases, which leads to an increase in the likelihood of erroneous actions on their part. It is quite natural that there is a tendency aimed at reducing or completely eliminating the influence of the human factor on the processes both in Airspace and Airside areas of the airport. In a document called “Vision 2050”, published by the IATA organization in 2011 (IATA, 2011), it is noted that in the future it is expected to introduce automated and automatic centralized control systems of the processes of GV and AC movement on the airport territory. There is every reason to assert that such systems will be more reliable and more efficient than manual control systems for the very reason that they will be able to perceive and interpret such volumes of information that are many times greater than the capabilities of a human controller (Augustyn and Znojek, 2015).

This work is focused on the development of predicted IATA systems for automatic ground movement control at airports. The complexity of this task is so great that for its complete solution it will take many more years of work of specialists of the most diverse profile. The author of this work belongs to those specialists who began to take the first steps in the indicated direction. The author's interest in this topic is also based on his personal experience, which he received while working for several years as an airport controller.

## **1.2. Scope, relevance and novelty**

The most important document that defines the direction of development of ground movement guidance systems at airports is (EUROCONTROL, 2020), which describes the services provided by the Advanced-Surface Movement Guidance and Control System (A-SMGCS). A-SMGCS significantly expands the functionality of the controller compared to the option when it has only surface movement radar (SMR), which remains today the main technical tool to assist the controller in his work. However, the evolution of A-SMGCS services does not necessarily imply a transition to fully automatic ground traffic management. Moreover, EUROCONTROL documents are non-binding, and each airport makes its own decision regarding the timing and scope of the A-SMGCS. It can be argued that the creation of automatic ground traffic control systems is one of the development goals for systems similar to A-SMGCS, and this goal will certainly be achieved someday, but due to the great complexity of the tasks arising on this path, no one is trying to set a deadline yet to which these tasks can be solved. There is no information yet that prototypes of such systems are already being tested at airports, but there is no doubt that specialists have already begun developing them.

The tasks of automatic control of ground traffic can be conditionally divided into the areas of hardware and software, similar to how it is done in the world of computers. The main task in

the field of hardware is to create “ideal” systems for determining the location of moving objects. “Ideal” refers to systems that transfer coordinates (x, y, z) of all moving objects to the computer of the centralized control system, and they can work:

- in any weather conditions;
- for any number of controlled AC and GV;
- with an error not exceeding 1 meter;
- with a data update frequency sufficient for controlling objects.

There has been continuous progress in the art (Saifutdinov and Tolujevs, 2020a) and there is no doubt that “ideal” object positioning systems will be created. It is quite clear that only systems in which different methods and technologies of position determination are applied simultaneously will be able to fulfill all the requirements listed above. For airport services, the range of tools ranges from conventional SMR to Intelligent Cameras (Dimitropoulos et al., 2005) and related Video Analytics techniques. New types of satellite and inertial navigation systems, as well as LiDAR devices, will be installed on board mobile objects (Lee et al., 2020). An important aspect of hardware development is also progress in the field of the Unmanned Ground Vehicle (UGV), which in the foreseeable future will replace the Human Driven Vehicle (HDV), which performs the functions of ground vehicles at airports.

This work is related to the tasks that need to be solved in the field of software. The basic functions of the new generation of software become clear when one imagines that in a system of the A-SMGCS type, all the functions of a human controller will be performed by a controller computer program. Such a program can be considered “ideal” if it:

- constantly monitors the location and status of all ground movement participants;
- predicts the possibility of a critical situation (dangerous approach of objects, etc.) and identifies already existing critical situations;
- identifies ground movement participants who may be impacted by a critical situation and sends them specific traffic control commands or re-routing data.

This **work is based on the assertion** that any control system for a complex technical object cannot be put into operation without testing it using one or several types of mathematical modeling. The ground transportation system at the airport belongs to a class of systems for the study of which it is necessary to apply computer simulation. The ultimate goal of using computer simulation is to implement the interaction mode of a real control program with a model of AC and GV movement in the airport transport network. This mode of using simulation models is called emulation (Xcelgo, URL). This work does not concern the development of control

programs themselves, but it proposes a tool for their training and testing, focused on the use of simulation models in emulation mode.

The control system must receive complete and accurate information about the state of the control object, for the collection and storage of which Digital Twin (in the following sometimes also as DT) can be used (Madni et al., 2019). To train the control system to recognize critical situations in the airport transport system, it is necessary to have a “collection” of such situations and provide the ability to demonstrate them to the control system in real time. Thus, the primary purpose of using DT is to create a “collection of situations” by accumulating information about processes in the airport transport network. In this case, a simulation model can be used as a source of information, which was specially created to simulate given critical situations. At the stage of application of the control system, a DT similar in structure should collect information about real processes in the airport transport network and provide it to the control system.

Thus, **the novelty of this study** lies in the development and experimental verification of concepts for the application of computer simulation and emulation methods to create a DT, which can be used as a source of information for a real-time control system both in its training mode and in normal operation.

The concepts proposed and investigated in this work can be applied in the development of a process control system not only in the airport transport network, but also in any other in-house transport network, where the required performance and safety are provided by centralized control functions.

### **1.3. Problem statement and research objectives**

The problem of building a fully automatic ground movement control system at airports has not yet reached the stage of real design and therefore belongs to the group of purely research tasks. To implement the first steps in solving this problem, it is necessary to find answers to the following **research questions**:

- What features of the current state and development trends of navigation and ground movement control systems at airports are prerequisites for solving in the future the task of fully automating the management of this process?
- What methods and tools of computer simulation are most suitable for simulating given scenarios in the airport transport network and using simulation models in emulation mode in conjunction with the tested control programs?
- What functions can be supported by Digital Twin at the stages of creation and application of a ground movement control system at an airport and what should be the

content and form of the information accumulated in it about traffic participants in the airport transport network?

**The research goals** of this work are both in determining the methods of obtaining answers to the posed research questions, and in the formulation and verification of the answers themselves obtained as a result of the work. To achieve these goals, it is necessary to solve the following **tasks**:

- to review modern methods and control systems for both transport systems at airports in general and ground movement systems in particular;
- to consider new trends in the organization of transport processes at airports and prospects for improving the accuracy of systems for determining the location of mobile objects;
- to evaluate the possibilities and practice of using various classes of software products for simulation modeling of transport processes at airports;
- to study the practice of using simulation models in emulation mode and the prospects for using the Digital Twin concept for real-time process control;
- to develop the structure and concept of the Digital Twin application in the management of the airport transport system;
- to substantiate the choice of the simulation modeling paradigm, which should be applied to simulate given situations in the airport transport network, and apply this paradigm when developing a universal computer program designed to simulate such situations;
- to conduct computer experiments to simulate scenarios for the development of processes in the transport network of the airport, which lead to the need for the intervention of the centralized control system;
- to save debugged scenarios by recording location and status data streams of moving objects in Digital Twin form, which can be used as a source of dynamic data when training and testing algorithms for centralized ground movement control at an airport.

As the **object** of this study, the processes in the ground transport network of the airport are postulated, where the movement of aircraft (AC) and ground vehicles (GV) takes place. On the other hand, the **subject** of research is computer simulation methods designed to simulate given scenarios and save streams of data on the location and state of moving objects in the form of Digital Twin (DT).

The following **statements** are put forward for defense:

- The developed concept of the Digital Twin application, together with the simulation model, applies to all stages of the life cycle of an airport ground traffic control system. At the training stage, the control system can use the data on the decisions made by the controller, accumulated in the Digital Twin. During the testing phase, Digital Twin can offer the control system scenarios of typical critical situations in which it is necessary to make control decisions. During normal operation of the control system, Digital Twin performs the functions of converting and storing data on the location and status of objects that are traffic participants in the airport transport network.
- When applying the concept of Digital Twin in the management of the airport transport system, the original meaning of this concept as a dynamic storage of data on processes in the airport transport network should be preserved. The interpretation functions of the data stored in the Digital Twin should be conceptually and programmatically separated from the Digital Twin itself, which creates conditions for the development of an unlimited number of applications using this data both for controlling processes in real time and for retrospective analysis or forecasting their development in the near future.

#### **1.4. Methodology and methods**

In this study, the methodology of computer simulation and dynamic databases in the form of Digital Twin is used as the main one. Many of the concepts proposed in this work are based on broad engineering knowledge in the field of Positioning and Navigation, as well as the principles of managing all types of transport processes at airports. In the field of computer simulation, a special paradigm is used, which is most similar to the “continuous” paradigm. The prototype of a universal program for simulating scenarios in the airport transport network was created using the VBA programming language and is intended for use in the MS Excel environment. The source code of the program contains about 2300 lines.

#### **1.5. Approbation**

The preliminary results, inferences and findings of the research were presented at the following conferences in Latvia and Germany:

- International Conference “Reliability and Statistics in Transportation and Communication”, Riga, Latvia, 2019, 2020.
- International Doctoral Student Workshop on Logistics, Magdeburg, Germany, 2019.
- The 34th International ECMS Conference on Modelling and Simulation (ECMS 2020), Wildau, Germany, 2020.

- International Scientific and Practical Conference “Rīgas Aviācijas Forums”, Riga, Latvia, 2020.
- The 61th International Scientific Conference on Information Technology and Management Science (ITMS’2020), Riga, Latvia, 2020.

The results of the research were published in the following journals and conference proceedings:

- Saifutdinov, F., Tolujev, J. (2019) Transport Processes in Airports – Current Status and Problems. In: Proceedings of 12th International Doctoral Student Workshop on Logistics, June 6, 2019, Magdeburg, Germany, pp. 131-135. ISBN 978-3-944722-83-2
- Saifutdinov, F., Tolujevs, J. (2020) Analysis of Navigation Systems for Landside Transport Processes Control. In: Reliability and Statistics in Transportation and Communication. Lecture Notes in Network and Systems 117, Springer, pp. 552-561. doi.org/10.1007/978-3-030-44610-9 (Scopus)
- Saifutdinov, F., Tolujevs, J. (2020) A Model for Ground Transportation Systems Simulation at Airports under Centralized Control. In: ECMS 2020 Proceedings. European Council for Modeling and Simulation, pp. 5-10. doi.org/10.7148/2020-0005 (Scopus)
- Saifutdinov, F., Jackson, I., Tolujevs, J., Zmanovska, T. (2020) Digital Twin as a Decision Support Tool for Airport Traffic Control. In: 61st International Scientific Conference on Information Technology and Management Science of Riga Technical University (ITMS 2020), Piscataway: IEEE, pp. 1-5. doi: 10.1109/ITMS51158.2020.9259294 (Scopus)
- Saifutdinov, F., Jackson, I., Tolujevs, J. (2020) Modelling Data Streams of Object Positioning in Airport Ground Transportation Systems. In: International Scientific and Practical Conference “Rīgas Aviācijas Forums”, Riga: Dienasbizness, pp. 40-43. ISSN 2661-5738
- Saifutdinov, F., Jackson, I., Tolujevs, J. (2021) Scenario Modeling in a Centralized Airport Ground Traffic Control System. In: Reliability and Statistics in Transportation and Communication. RelStat 2020. Lecture Notes in Networks and Systems, vol 195. Springer, Cham, pp. 184-193. https://doi.org/10.1007/978-3-030-68476-1\_17 (Scopus)
- Saifutdinov, F., Tolujevs, J. (2021) Time and Space Discretization in the Digital Twin of the Airport Transport Network. Transport and Telecommunication Journal, vol.22, no.3, 2021, pp. 257-265. https://doi.org/10.2478/ttj-2021-0019 (Scopus)

- Saifutdinov, F., Jackson, I., Tolujevs, J. (2022) An Emulation Oriented Method and Tool for Test of Ground Traffic Control Systems at Airports. *Aviation*, Vol. 3, 2022. (paper accepted for publication) (Scopus)

### **1.6. Structure of the thesis**

The thesis consists of 5 chapters including the introduction and conclusions. Besides, it contains one appendix. It contains 135 pages, 52 figures, and 2 tables. The list of references contains 163 titles.

Chapter 1 begins with a brief description of the problem that this paper addresses and introduces a potential reader to the motivation behind the research. In addition, the scope is specified, and relevance is highlighted along with novelty. The main research questions are stated, and tasks are formulated. At the end of the chapter, a definition of the subject and object of research is given, and theses are formulated that are submitted for defense.

Chapter 2 provides an overview of the current state and prospects for improving the management of transport processes at airports. The chapter begins with a brief description of the types of transport processes, which include Aircraft Traffic, Airside Traffic, Passenger Flow, and Baggage Handling. Special attention is paid to the processes of ground movement of the vehicles and aircraft, which takes place in the Airside Area of the airport. Airport Collaborative Decision Making (A-CDM) is considered as a frequently used management system, which is a complex multi-level and multifunctional system that controls all the above-mentioned transport processes at the airport. The use of artificial intelligence technologies, unmanned vehicles, as well as Remote and Virtual Tower are considered as modern trends in the organization of transport processes. Since the very first problem of automation of traffic control in the airside area is to increase the accuracy of determining the coordinates of moving objects, part of the review is devoted to modern methods for solving this particular problem. The chapter concludes by looking at the principles of the Advanced-Surface Movement Guidance and Control System (A-SMGCS), which can be seen as a starting point towards solving the problem of fully automating ground movement control at airports.

Chapter 3 analyzes the practice of applying various methods and tools for simulation modeling of transport processes at airports. The ultimate goal of such an analysis is the choice of a method and tool with which it will be possible to solve the problem of modeling scenarios in the airport transport network in the most rational way. Particular attention is paid to the rather rare practice of using simulation models in emulation mode, but it is this mode that can be used to debug traffic control programs at a particular airport. The chapter offers a critical analysis of

the interpretation options for the concept of Digital Twin (DT) and discusses the relationship of this concept with the techniques “real-time simulation” and “online simulation” that appeared more than 20 years ago. After analyzing the problems of modeling the spatial arrangement of objects, the decision on the choice of a paradigm and a software method for modeling scenarios in the airport transport network is substantiated.

Chapter 4 describes the experience of developing and using a software tool for modeling scenarios in the airport transport network. The first part of the chapter contains a description of the conceptual solutions, on the basis of which the universal simulation program GTSS was developed. The presentation of concepts begins with an explanation of how models created with this or a similar programme can be applied to the various stages of the development of an automatic control system. The following describes the general concept of using DT both at the development stage and during normal operation of the airport transport network management system. The advantages of discrete time and discrete space solutions that were implemented during the development of the GTSS program are described in detail. When creating a digital twin associated with the GTSS program, the concept of two types of protocols, Event Protocol and State Protocol, was implemented, the latter of which is a carrier of measurement information about objects such as AC and GV, which traveled in the network in accordance with specified scenarios. The second part of the chapter describes the process of developing and verifying a demonstration model of the transport network for a specific airport. The chapter ends with a detailed description of a simulation experiment, which shows the development and correction of a critical situation in the airport transport network.

The conclusions list the main results of the study and highlight the most important findings. It is shown that the statements put forward for defence have been confirmed. Finally, recommendations for further research are given.

## **2. TRANSPORT PROCESSES AT AIRPORTS**

This chapter is devoted to the description of the research object, which is defined as the ground transportation system of a modern airport. When solving the set research task, it is necessary to imagine the real conditions in which the transport processes at the airport are taking place today and will occur both in the near and distant future. Aviation is undoubtedly the most complex and most highly automated transport sector of the national economy. At first glance, the day-to-day operation of a modern airport may seem like a simple routine, but in reality it is based on thousands of technical solutions, hundreds of regulatory documents and dozens of specialists who manage the processes at the airport in real time. This chapter sets out facts and ideas, without taking into account which it would be impossible to carry out the main actions aimed at achieving the objectives of the study.

### **2.1. Current state and problems of transport processes at airports**

#### **2.1.1. Types of transport processes at airports**

The main element of the air transport infrastructure is the airport, the capacity of which depends primarily on the organization of its transport process as a whole. Such a process can be defined as the process of moving passengers, cargo, aircraft and ground vehicles in the air and ground spaces of an airport.

The main transport processes at the airport, which can be studied both separately and in interaction with each other, include the following:

- Aircraft Traffic;
- Airside Traffic;
- Passenger Flow;
- Baggage Handling.

**Aircraft Traffic** represents the movement of AC both within the Airspace of an airport and beyond. From the side of control Aircraft Traffic is divided into controlled and uncontrolled. Controlled Aircraft Traffic means the movement of all aircraft that are under the control of one or more air traffic controllers operating within strictly established horizontal and vertical boundaries. The main task of the controller is to control the observance of the established intervals between the AC flying within his/her zone. In the event of a non-standard situation with a specific AC, the controller assists it by transmitting the necessary information to both the pilot and other parties who must participate in resolving this situation. The controller informs the nearby AC and ground services about the situation with this AC, and also clears the airspace on

the flight path and provides priority when landing. AC movement in Airspace is carried out along pre-agreed trajectories, deviation from which is allowed only with the permission of the controller. Uncontrolled Aircraft Traffic includes the movement of aircraft, in which control over the flight, maintaining safe heights and intervals between aircraft is carried out by pilots, and in the case of Unmanned Aerial Vehicles (UAV) flights – by UAV operators.

**Airside Traffic** represents all ground traffic within the Airside area of an airport intended for take-off, landing, taxiing, parking, and servicing of AC (aircraft, helicopters and gliders). The airport is traditionally divided into Airside area and Landside area. The airside area includes runways, taxiways, apron, aircraft stands, de-icing facilities and dedicated maintenance areas. Access to the Airside area is strictly controlled and the Landside area is open to the public. The Landside area includes passenger and cargo terminal buildings, as well as the airport transport access system, which includes access roads, parking, public transport facilities, and freight transport service areas.

Although the main facilities in the Airside area are AC, the number of GV in the Airside area at the same time is multiplied by the number of aircraft. GV carry out the ground handling of AC, airport infrastructure and security services. The main participants of Airside Traffic in addition to AC are: Pushback tugs, Catering trucks, De-icing vehicles, Snow-plowing, Sweeping and -blowing vehicles, Airstairs, “Follow me” cars, Apron or Shuttle buses, Belt loaders, Container loader and transporters, Water trucks, Lavatory-service vehicles, Refueling, Ground power units, Air start unit, Fire trucks etc. It is important to note that in the absence of AC at the airport, the traffic intensity of the GV decreases, but it does not stop completely, which is associated with the constant maintenance of the airport's operational state. Air traffic controllers are responsible for the separation of flows and the efficiency of AC and GV movement in the Airside area.

**Passenger Flow** is the movement and service of departing and arriving passengers in airport buildings. The main factors affecting the smoothness of Passenger Flow are (URL1):

- Ground transportation and parking;
- Trolley availability;
- Check-in;
- Passport and Security;
- Facilities and comfort.

The organization and redistribution of Passenger Flow is carried out using a management system that collects and processes data on the Passenger Flow of the airport. Information from

surveillance cameras, Wi-Fi, Bluetooth, 3D sensors, scanned boarding passes and other data sources allows a real-time picture of people's movements to be built. Analysis of these data related to flight data provides real information to identify problem areas (congestion of passengers at check-in counters, baggage claim counters, passport control, etc.). This data also allows predicting the impact of unexpected changes on passenger flow and recommending Passenger Flow reallocation actions to ensure better throughput.

**Baggage Handling** plays a critical role in an airport's ability to not only ensure smooth handling of passenger baggage flows, but also to attract or retain the function of a major aviation hub (an airport with flights to lots of different places, where people can arrive from one city or country and get flights to other cities or countries) (URL2).

Baggage Handling includes the following features:

- moving baggage from the check-in area for loading on board;
- moving baggage from board to board for transit passengers;
- moving baggage from board to baggage claim counter.

The speed of handling and moving baggage should be sufficient so that any passenger receives his baggage on time, without missing his flight or waiting for it for a long time, thereby creating additional difficulties for airport services related to servicing other departing or arriving passengers. Each airport has its own requirements for handling baggage. They depend, for example, on the time allotted for the transportation of baggage from the check-in area to loading on board. This time depends on how quickly the passenger can make the same journey. At some airports it may only be a short walk for the passenger, while at other airports passengers may need to use a special train.

### **2.1.2. Main features of ground movement at airports**

Ground movement in the airside area of the airport is performed by two types of vehicles: AC and GV. The main movement is carried out along the paths marked on the ground surface. Altogether, these paths form two transport networks that have intersection points. Some AC and GV movements over relatively short distances are carried out in free space without being bound to marked paths.

After landing, the AC is taxiing from the runway to the stand. In small airports, the AC can use only one taxiway for taxiing onto the apron. At large airports, the route can include up to 10 taxiways and their intersections, making taxiing very difficult. After the completion of taxiing to the apron, the further movement of the AC can be either independent or with the help of a tow tractor, depending on the standard procedures of the aerodrome and the specific conditions

observed at the current time. In the case of using a tow tractor, the AC will wait for some time at the designated place of arrival of the tow tractor, and after docking with it, the AC will be towed to the stand. When the AV takes off, taxiing out of the parking place can also be carried out both independently and with the help of a towing vehicle. The tractor tows the aircraft, as a rule, to the taxiway or other place designated for this purpose and goes further to its parking place or to the place of towing of another AC. Only after disconnecting the tow tractor and removing it to a safe distance is the alternate start of the AC engines carried out under the supervision of ground personnel. All this time, the aircraft is an obstacle for other AC and GV, and the space close to it is used either with great restrictions or is not used at all by other participants of the traffic movement. After a successful start of the engines, the AC starts taxiing for take-off from the runway. AC in motion have exclusive priority in relation to the GV, and starting AC have priority in relation to those AC that follow to the stand.

The movement of GV in the airside area is characterized by a much greater complexity, since the number of ground vehicles participating in this movement can be 10-20 times more than the number of serviced AC. In addition, the routes of the GV are very diverse, which must solve a variety of tasks of servicing the AC. In the ground handling of one AC in the parking lot, several GV take part, which travel to the airside area of the airport from the starting points to the AC parking area, after which they set off on their return journey along their individual routes. Very often, several GV move simultaneously to serve one AC in the airside area. In addition to servicing the AC, the movement of the GV can be conditioned by the current tasks to ensure the normal functioning of the airport. For example, the security service periodically makes a detour of the territory in order to inspect the perimeter; the aerodrome service inspects the condition of the ground surfaces of taxi routes, monitors the area of ongoing work, etc. At the largest airports in the world, the peak values of the number of AC serviced during the day have long exceeded 1000 AC. This means that the number of GV trips already today reaches several tens of thousands per day. According to SITA, the number of AC in operation will reach 43 thousand by 2034 (URL3), and the number of passengers, according to IATA forecasts, will reach 8.2 billion by 2037 (URL4). In such conditions, the traffic intensity of the GV will significantly increase, and the task of ensuring the required airport capacity will become more acute.

Nowadays, the direct control of vehicles in the airside area is carried out by AC pilots and GV drivers. Also, the general management of the transport process is carried out by controllers. All this means that the human factor has a strong influence on the processes in the airport transport system. The problem of ensuring safety, both in the air and on the ground, is one of the most important in aviation. Analysis of the causes of aviation accidents shows that in 5-15% of

cases they are not identified, in 15-20% of cases they are associated with equipment failure, including as a result of external factors, and in 70-75% of cases – with a human factor (Osman et al., 2020). Reducing the influence of the human factor on processes at airports is the goal of many programs of international organizations working in the field of aviation.

### **2.1.3. Applying the Airport CDM concept**

Airport Collaborative Decision Making (A-CDM) (URL5) is one of the airport optimization programs adopted and implemented by IATA, ICAO and Eurocontrol. A-CDM is a fundamentally new approach to the interaction of participants in the process of operating flights at an airport: the airport operator, airlines, ATC unit (Air Traffic Control = Air Traffic Management (ATM)), service companies, planning and coordination of the use of airspace and air traffic flow management bodies. The A-CDM program is essentially one of the steps in the NextGen (URL6) and SESAR (URL7-9) projects. A-CDM is a concept aimed at improving air flow and capacity management at airports by reducing delays, increasing predictability of events and optimizing resource use. The implementation of A-CDM allows each partner to optimize their solutions in cooperation with other partners participating in the program, taking into account their preferences and constraints, as well as the actual and projected situation. Decision making by A-CDM partners is achieved through the exchange of accurate and timely information, as well as adapted procedures, mechanisms and tools. This is made possible through the phased implementation of the six key elements of A-CDM:

- Information Sharing;
- Milestone Approach;
- Variable Taxi Time;
- Pre-departure Sequencing;
- Adverse Conditions;
- Collaborative Management of Flight Updates.

Each of the listed elements plays an important role in achieving the result, while the process of implementing these elements requires the consolidation of the efforts of all its participants: The Airport Operator, Aircraft Operators, Ground Handlers, De-icing companies, The Air Navigation Service Provider, The Network Manager and Support services (Police, Customs and Immigration etc.).

Figure 2.1 shows the results achieved through the implementation of A-CDM at several major airports in Europe. For example, at the Brussels airport, this helped to reduce the delay time of AC in the parking lot and runway, as well as to reduce the taxiing time of departing AC

by an average of 3 minutes. In turn, this had a positive effect on the aircraft's annual fuel economy, which amounted to 5400 tons. At Munich Airport, the implementation of A-CDM allowed achieving 93% efficiency in maintaining the time allocated to airlines for take-off and landing, while reducing AC taxi times by an average of 10%. All of this ultimately helped to save airlines 2.65 million euros per year. After the introduction of A-CDM at the Paris airport, the average taxiing time of the AC decreased by 2 minutes, and in unfavorable conditions by 4 minutes, which helped to reduce the aircraft's daily fuel consumption by 14 tons. At Frankfurt airport, with the introduction of A-CDM, the efficiency of the runway use for the outgoing flow of AC increased, the delays of arriving aircraft decreased, which ultimately had a positive effect on all ground handling processes.

SAVINGS	BENEFICIARIES
<b>Brussels</b>	
<ul style="list-style-type: none"> <li>■ Absorption of delay at the gate and no longer at the runway resulted in annual savings of:               <ul style="list-style-type: none"> <li>- 17022 tonnes of CO<sub>2</sub></li> <li>- 22 tonnes of NOx</li> <li>- 5400 tonnes of fuel</li> <li>- 2.7M €/year in fuel saving</li> </ul> </li> <li>■ Average reduction of taxi time outbound: 3 minutes</li> </ul>	Aircraft Operator, Airport Community Aircraft Operator, Airport Community Aircraft Operator Aircraft Operator Aircraft Operator, Airport Operator, Air Navigation Service Provider
<b>Munich</b>	
<ul style="list-style-type: none"> <li>■ Average ATFM slot adherence 93% in 2011</li> <li>■ 10% average reduction in taxi time</li> <li>■ 2.65M €/year in fuel saving</li> </ul>	Aircraft Operator, Airport Operator, Air Navigation Service Provider Aircraft Operator, Airport Operator Aircraft Operator
<b>Paris Charles De Gaulle</b>	
<ul style="list-style-type: none"> <li>■ Average taxi out time reduction by 2 minutes and 4 minutes in Adverse Conditions</li> <li>■ Reduced fuel consumption: 14 t /day</li> <li>■ Reduced emissions: 44 t CO<sub>2</sub> /day</li> </ul>	Aircraft Operator, Airport Operator Aircraft Operator Aircraft Operator, Airport Community
<b>Frankfurt</b>	
<ul style="list-style-type: none"> <li>■ Improved runway usage and take off flow</li> <li>■ Reduction of the impact of arrival delay leading to a more punctual departure and stable TOBT process</li> </ul>	Aircraft Operator, Airport Operator, Air Navigation Service Provider Aircraft Operator, Airport Operator, Air Navigation Service Provider

Figure 2.1. An example of the results achieved from the implementation of A-CDM (URL10)

The important thing is that A-CDM implementation cannot and does not follow a pattern. It should be based on an assessment of the characteristics, current constraints of each specific airport and the available resources of the participants in the process (see Figure 2.2).

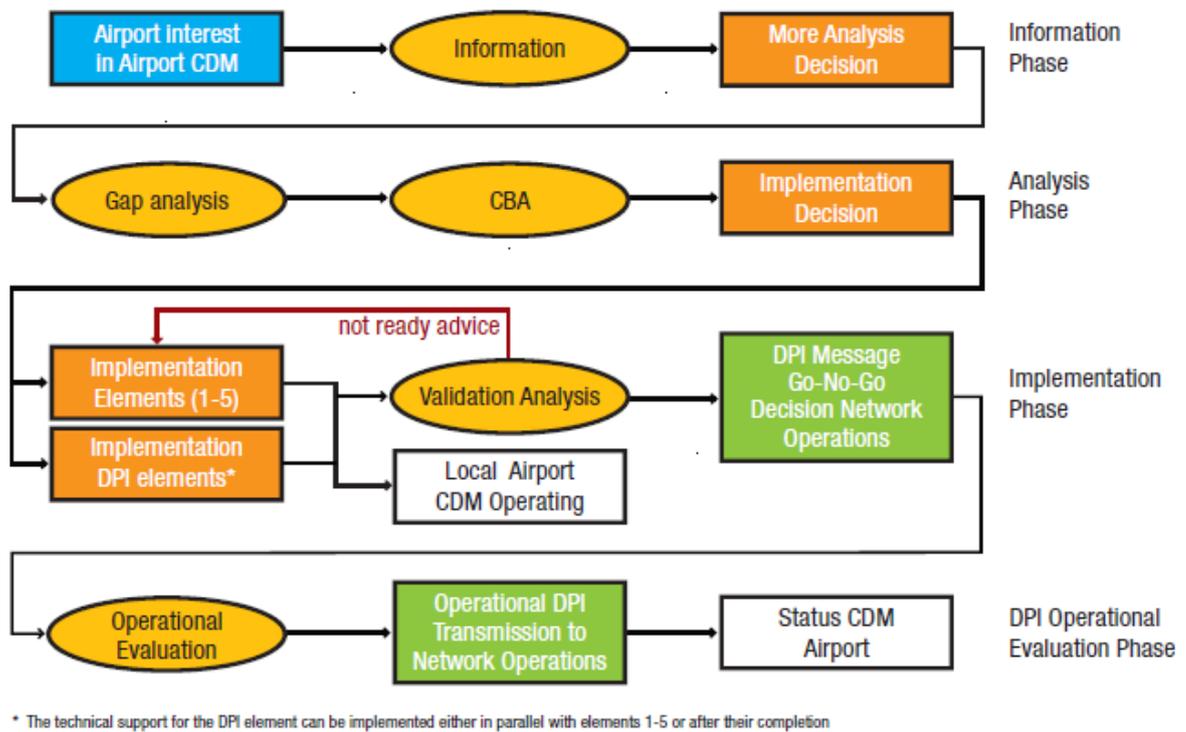


Figure 2.2. General process for Airport CDM implementation

The A-CDM implementation is an ongoing airport performance improvement process that monitors process performance using KPIs for each element being implemented. Analyzing the monitoring results allows partners not only to track the benefits of implementing A-CDM, but also helps them to identify the true reasons for deviations from the design parameters of specific flights. Based on the analysis results, corrective measures should be taken to improve the efficiency of the A-CDM system and the airport as a whole. A-CDM has already been deployed at 49 airports worldwide (30 in Europe, 18 in Asia and 1 in the USA).

## 2.2. New trends in the organization of transport processes at airports

The use of modern technologies makes it possible to increase the efficiency and safety of transport processes at airports.

### 2.2.1. Application of artificial intelligence technologies

Artificial intelligence technologies are designed to radically change the approach to organizing transport processes at the airport as a whole. Since such technologies are designed to replace human labor and reduce the cost of operating processes, the economic effect of their implementation is almost obvious. However, the real benefit of implementing such technologies depends on the completeness and quality of the underlying data. For this reason, implementation

efficiency can vary greatly, sometimes discrediting both projects and the technology itself (Li and Xu, 2015). For example, (URL11) offers a line of products using artificial intelligence implemented at 30 airports and 5 airlines. Product Offered Assaia's ApronAI optimizes daily operations and helps employees to be more efficient by providing them with highly accurate and relevant data. Assaia's ApronAI consists of three products Turnaround Control, Safety Manager and Stand Manager, which generate and collect data, create alerts, facilitate decision support and provide process automation to achieve results such as:

- reduced costs associated with poor on-time performance and delays;
- optimized service-level agreements and accurate and verifiable billing;
- reduced operational costs enabled by remote operations management and task automation;
- increased utilization of AC and GV;
- less early boarding calls and increased commercial dwell time in the terminal;
- airport data commercialization;
- reduced fuel expenses and CO<sub>2</sub> footprint.

Assaia's ApronAI uses a video surveillance system as a source of information, and the system itself is built on the basis of several well-known technologies adapted for solving applied problems. Machine vision (see Figure 2.3) can recognise events occurring on the apron, and machine learning helps to answer “if-then” questions. Having accumulated a huge array of information about flight service processes, the system will be able to reliably predict the end time of a particular operation, instantly evaluating a large amount of incoming variable data. In turn, multidimensional optimization is faster and more efficient than a human to cope with solving certain problems.

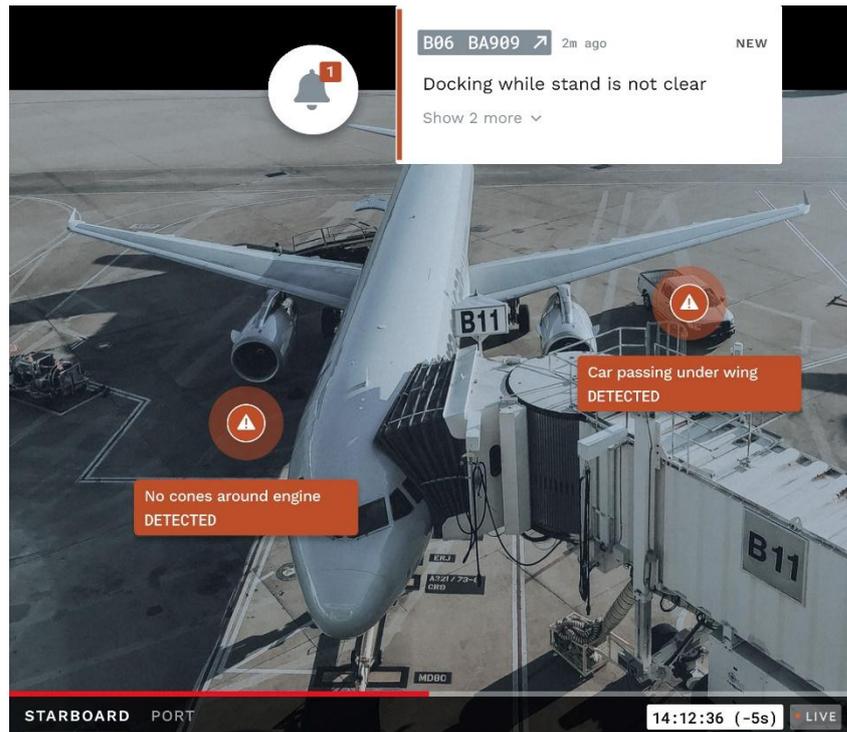


Figure 2.3. Implementation of machine vision in Assaia's ApronAI product (URL11)

Each Assaia's ApronAI product solves a specific task and can be used both separately and in combination. In the process of aircraft maintenance, Turnaround Control monitors at a given time the processes associated with aircraft ground handling and records the beginning and end of each process up to a second. Thus, Turnaround Control allows control and optimisation of the processes associated with aircraft ground handling. Safety Manager provides monitoring of safety on the apron. The system can detect many objects on the aircraft bench and determine if the bench is free for the aircraft to enter. It can also support the foreign object debris (FOD) check process and determine if it was done correctly. Stand Manager, solves the problem of allocating aircraft to parking areas using optimization algorithms.

The data saved by Assaia's ApronAI products in the form of a Log file can be easily transferred and used by all interested subscribers. The implementation process is associated with solving technical issues: which cameras will be used, new or existing, where the data will be stored and processed. After calibrating the installed system, artificial intelligence is ready to participate in the management of flight ground handling processes, reducing losses, minimizing risks and increasing the profitability of airport operators. The developers' plans already include plans to expand the functionality of the system, for example, to launch queuing systems for departure and de-icing.

### **2.2.2. Implementing of unmanned vehicles**

The implementation of unmanned vehicles can be attributed to the current and promising trends in the development of transport processes at the airport. Such vehicles are equipped with an on-board computer with a system for influencing controls using data from various sensors (Posokhova, 2016). For aircraft, such sensors are: heading (GPS), roll, pitch, altitude, speed sensors, other aircraft systems, ground station data, and much more. For cars, such sensors are: video cameras, LIDAR sensor, radars, GPS (Samà et al., 2017). Separately, it should be noted that from the first days of transport automation, the focus has been on traffic safety. The autopilot always has the ability to quickly turn off so that the operator of the unmanned vehicle, monitoring the flight, can intervene in its work. It is envisioned that unmanned vehicles at the airport will first be used to scare off birds (Kim et al., 2012) or cargo transportation. In the future, they can also be used to transport passengers in the landside area of the airport.

An equally promising direction in the development of transport processes at the airport is the local automation of processes through the introduction of robotization. For example, it is already possible to transmit from the AC to ground services information about the stocks of aviation kerosene in the tanks and calculate the volume of future refueling while still in flight. The loading of the required volumes of fuel into the tankers can be taken over by robots, and the tankers themselves can be, as mentioned above, unmanned. For example, in the fall of 2018, at the Sheremetyevo international airport, “Gazprom Neft” showed the concept of a robotic system for loading petroleum products into an aerodrome refueler. The process of filling aviation fuel was carried out automatically using a robotic arm without the participation of personnel. Planning and control of AC ground handling in the future will be carried out by an electronic system that is responsible for managing AC refueling on the ramp of the airport. Having received an application from the airline, the system processes data from the airport dispatch service about the flight number, parking lot, and refueling start time and displays all the necessary information on the fuel tanker driver's tablet (URL12).

### **2.2.3. Remote and Virtual Tower application**

The ATS (Air Traffic Service) procedures used at airports depend on the technical capabilities of the surveillance equipment. One of the areas of modernization is the implementation of the Remote and Virtual Tower (RVT). RVTs enable safe and cost-effective ATS to be implemented from a remote location close to one or more aerodromes in rural areas where dedicated local ATS systems are exhausted or not cost effective, but where aviation provides local economic and social benefits. These features can also be used to provide

contingency services at medium to large airports. Thus, RVT technology is applicable for aerodromes with low flight intensity or as an emergency control system in case of emergencies (fire, destruction of a control tower, etc.). Providing an ATS remotely to a single aerodrome offers some cost savings, however, maximum benefits are expected from providing a remote ATS to multiple aerodromes. The rich capabilities of digital technology can be used to maintain airport capacity in low visibility conditions.

Several states are already implementing programs for the introduction of RVT, but the number of functioning systems is not so great. The costs associated with setting up an RVT will only be offset in the long term. The effect of the introduction of RVT will be achieved through a reduction in personnel, as well as due to a decrease in operating costs for control rooms. Studies have shown the possibility of reducing personnel costs from 10 to 35%, depending on the scenario. The issue of RVT implementation remains relevant. Although the RVT concept was described in 2011, the technology was first tested in 2015 in Sweden (URL13). Gradually, RVT began to be introduced in other countries (URL14), (URL15). Thus, the Norwegian company Avinor Air Navigation Services, together with Kongsberg Defense & Aerospace and Indra, implemented an RVT solution on the Arctic island of Røst on October 19, 2019. The world's largest center, Remote Towers, will also manage 15 more airports. To the implemented four airports in 2019-2020, 6 more airports will be added in 2021 and 5 in 2022. A second phase is also envisaged to increase the number of airports operated from the Remote Towers Center in Bodø. Thanks to large screens, the center staff can observe every movement and operation at the airport, as well as communicate directly with the pilots and ground crew. The airport has cameras, microphones and other equipment that provide detailed information on weather and airport activities at any time of the day or night.

For pilots using these airports, there are no practical differences in the procedures performed. For example, the conversation with the ATC Tower is carried out over the radio, as in conventional airfields. Passengers will also not notice that the airport has a Remote Tower unless they see that the airport is now equipped with a camera mast instead of the regular Tower (see Figure 2.4). An airport camera takes a 360-degree image of the airport, which contains more detail than the human eye can detect. Cameras can magnify small details, show movements in images (such as birds or drones), and have infrared settings that allows seeing in the dark. Each airport is connected to the Remote Tower Center via redundant networks. These networks are high speed networks that use both fiber cables and radio links.



Figure 2.4. RVT camera mast in Norway (URL 15)

The purpose of the implementation of Remote Towers is to improve the quality and efficiency of airports. Many control towers in Norway need to be refurbished or completely replaced. Using Remote Towers will save some of these costs. In the future, one person will be able to control traffic at several airports from one workplace. This offers great opportunities to reduce costs while maintaining high quality air traffic services.

### **2.3. Determining the spatial location of objects**

Various systems for determining the location of objects are used today in a wide variety of areas of human activity. With their help, it is possible to organize the work of people and technology, to ensure the safety and smooth flow of production processes, which together allows to increase the efficiency of the business as a whole. One of the main areas of use for positioning techniques is transportation systems in general and Intelligent Transportation Systems (ITS) in particular. Systems are based on positioning techniques that support accident search and rescue, vehicle routing, towing, and cargo tracking (URL16). Positioning is the process of determining the location of a particular object in relation to objects whose location is already known. The choice and application of one or another type of positioning is the prerogative of the user and depends on the specifics of his activities and specific tasks. Methods for determining the location of objects can be divided into three large groups:

1. Global and regional positioning.
2. Local positioning.
3. Hybrid positioning.

### **2.3.1. Global and regional positioning**

Both global (GNSS) and regional positioning (RNSS) systems are based on the use of satellite technology. In global positioning systems, coordinates, direction of movement and speed are determined using GPS and GLONASS systems, or satellites of other navigation systems (Galileo, BeiDou). The accuracy of determining the location of objects varies from 2 to 6 meters. If the positioning system uses signals from several orbital constellations, then the error does not exceed 2-3 meters. In the future, as technology develops, the accuracy is planned to be increased to several tens of centimeters. For many applications, this accuracy is sufficient. However, higher accuracy in determining the location of objects is often required. Examples are such tasks as navigation in straits, canals, port waters, automatic instrumental landing of AC, and geodetic referencing of various objects (Ablameyko, 2011).

Global positioning systems operating in line of sight of satellites, such as GPS and GLONASS, have many advantages, the main of which are large coverage and sufficiently high positioning accuracy outdoors. The implementation of satellite control systems does not require much effort and expense, since for their operation it is enough to equip objects with tracking devices and implement traffic control software in the company. However, the disadvantages of such technologies include high energy consumption, dependence on weather conditions and the inability to use in closed rooms due to the large amount of interference from various equipment inside the building, as well as the shielding effect of the building itself. Thus, with all its advantages, global positioning will be effective only in open areas, that is, with confident reception of the satellite signal. Therefore, the scope of application of global systems is limited: it is exclusively transport and, in some cases, mobile workers.

To ensure high accuracy of navigation, more advanced navigation systems are required than GNSS. For example, to improve the accuracy and possibilities of using GNSS as a means of landing AC, differential correction systems are used, which belong to the GNSS Augmentation group. Such a system is based on the integration of external and satellite data in the calculation process. The system improves the accuracy of GNSS signals by correcting the pseudo-ranges measured by the receiver to the satellites with corrections to them, received from the outside, from a reliable meter (base or reference station). This compensates for both atmospheric distortion and ephemeris errors. Depending on the amount of data transmitted in the DGPS (Differential Global Positioning System) correction signal, the positioning accuracy can reach values less than 10 cm. A common problem with all DGPS methods is that almost all of the compensated errors vary with distance. For this reason, DGPS accuracy decreases with increasing distance from the reference station. The problem can be compounded when the user

and stations cannot see the same satellites. Within the airport, the distance is measured in several kilometers, so that errors in determining the location of the object become insignificant and can be neglected. At the same time, the question of positioning outside open spaces remains open, since DGPS, although it is a more accurate variation of GNSS, retains all the disadvantages of GNSS.

In the case of regional navigation systems (QZSS, NavIC), the same principles and approaches are used in determining object data as in global positioning systems. The difference lies only in the part of the globe that the system covers. Thus, the NavIC (NAVigation with Indian Constellation) system provides only regional coverage of India and parts of neighboring states. QZSS (Quazi-Zenith Satellite System) is designed to serve consumers in the Asia Pacific region (Figure 2.5). Due to the coverage of a limited area by the QZSS system, the accuracy of determining the coordinates of objects in such a system can be both higher and equal to the accuracy of global navigation systems. The QZSS system operates in two modes: autonomous – positioning accuracy up to 7-10 m, and differential – accuracy up to several centimeters (URL17).

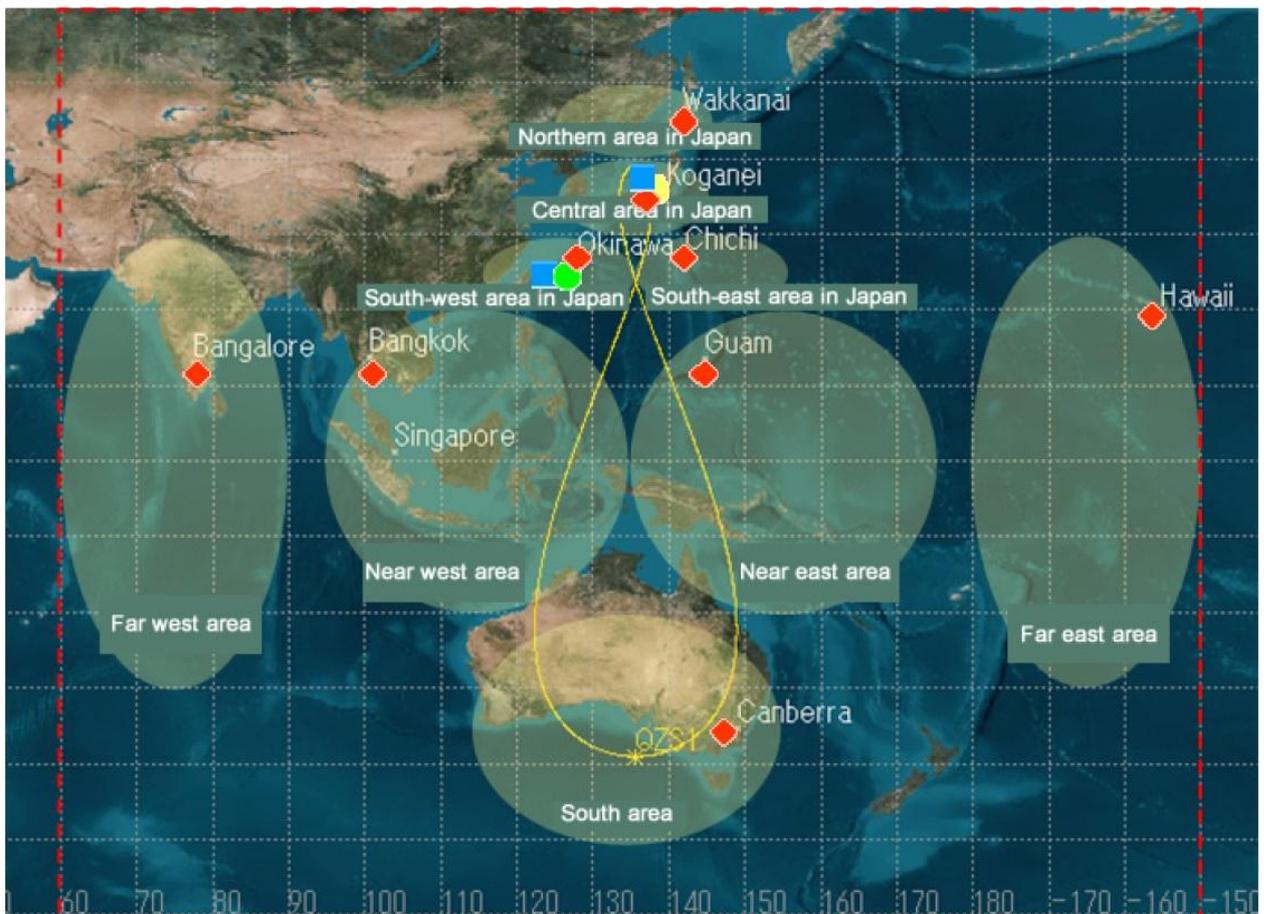


Figure 2.5. QZSS coverage area (URL17)

The development of GNSS and RNSS systems has led to the emergence of Multi-GNSS receivers that can simultaneously process signals from satellite stations of different systems, thereby increasing both accuracy and redundancy of signal acquisition. For example, FURUNO receivers can simultaneously process GPS, SBAS, QZSS, GLONASS, Galileo (URL18) signals. In addition, signal processing algorithms are also being improved (Dong et al., 2017), which also positively affects both the speed of information processing and the accuracy of object positioning.

### **2.3.2. Local and hybrid positioning**

The main purpose of LPS (Local Positioning Systems) is to quickly position and monitor situations within strictly defined boundaries. Despite the widespread use of GNSS systems, the use of local positioning systems within an airport may be advisable in at least two cases. Firstly, it is the segmentation of the received signals from local and other systems, which allows more efficient control of the ongoing processes. Secondly, local positioning can be organized in places where other types of positioning cannot be available for a number of reasons (inaccessibility of GNSS signals, a large amount of interference, high density of objects, etc.). These can be office and industrial premises, warehouses and logistics complexes, medical organizations, underground structures, mines, etc. The set of technologies used for this type of positioning is quite wide: they can be used as wireless and radio-frequency technologies (Wi-Fi, Bluetooth, RFID, ZigBee, nanoLOC, UWB) and infrared, ultrasonic, optical, inertial, etc. (Lee et al., 2007), (Kabir and Khan, 2016), (Sahib Hasan et al., 2018), (Naidu et al., 2019). Depending on the technologies used, local positioning is subdivided into zonal (up to 20 meters) and precise (from 0.1 to 3 meters). A special type of LPS is the Real-time LPS (RTLS) (Villarrubia et al., 2013), which allows real-time tracking of an object or person in an enclosed space, such as an airport building. RTLS is based on determining the current location of the user's mobile terminal (Kim et al., 2012a). RTLS based on ultrasonic transducers works on a source-receiver principle (see Figure 2.6).

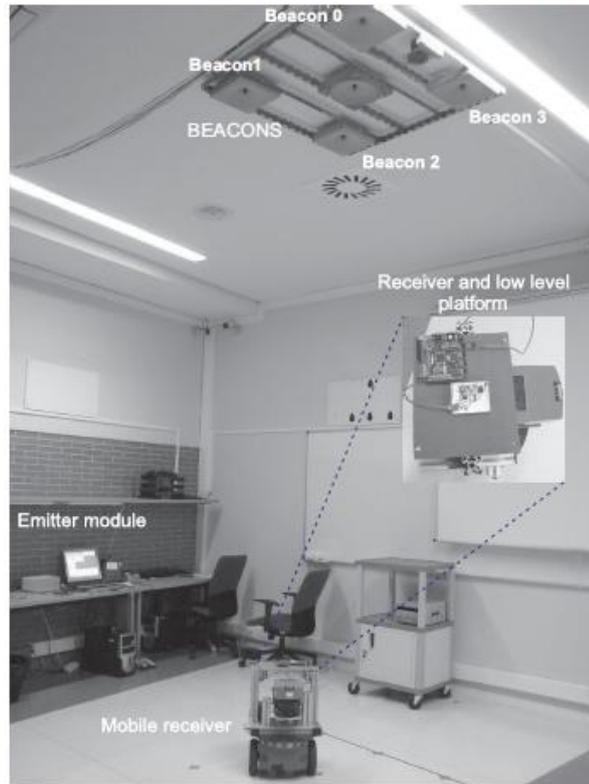


Figure 2.6. Ultrasonic RTLS (Peréz Rubio et al., 2012)

The source of ultrasonic waves is installed on the object, and the receivers are placed in the room in a certain order. To calculate coordinates on a plane, it is enough to receive data from three receivers. To determine the position in space, including elevation, it is necessary to have at least four wave receivers. The measurement accuracy under ideal conditions reaches about 3-5 cm. The disadvantage of this method is the need for strict planning of the placement of sensors that are receivers of ultrasonic waves.

Another version of RTLS is Bluetooth LE (BLE), built on the basis of wireless technology and based on distance measurement by radio signal level (Kim, 2017), (Huang et al., 2021). The main advantages of this technology are the compact size of the device and ultra-low power consumption. The sensors are compact Bluetooth transmitters, the coordinates of which are constant and known. The transmitters broadcast their own ID at a predetermined frequency. The object receives this data and based on the signal strength, determines its location, taking into account the data on the distance from each of the sensors.

Positioning using Wi-Fi signals, like BLE technology, measures distance by signal strength (Kostyk et al., 2015). RTLS based on this technology is the most affordable method due to the developed infrastructure of networks based on Wi-Fi access points and does not require additional expensive equipment. Almost all wireless transceivers measure the level of the

incoming signal, from which the coordinates are calculated. With a weak signal near the Wi-Fi access point, it cannot be argued that the object is far away, which is a significant disadvantage of the implementation. A weak signal can be caused by external factors: obstacle, attenuation, and others (Kirichek and Koucheryavy, 2016). Access points can be moved; therefore, compiling a database of access points with the ability to dynamically update is one of the requirements that must be considered when implementing navigation based on Wi-Fi technology.

The use of systems such as HDSA (High-Definition Situation-Aware), capable of operating in difficult conditions of signal propagation in the environment, is also a rather promising type of positioning. They are effective where GNSS and RNSS cannot be used, for example, inside buildings and underground rooms. HDSA systems require the use of UWB (Ultra-wideband) technologies (Liu et al., 2007). UWB is one of the radio frequency technologies that make it possible to create a real-time positioning system indoors. A practical implementation is a transmitter attached to an object and three or more fixed points that are signal receivers. The location of the object is calculated from the known coordinates of the receivers and the time of receiving the signal from the transmitter. In difficult conditions of radio wave propagation, UWB is a promising means of obtaining high-precision information about the location of objects (Win and Scholtz, 1998, 2000, 2002), (Suwansantisuk and Win, 2007), (Cassioli et al., 2002). By accurately measuring signal latency, UWB provides high-resolution range estimation during the measurement phase and reliable communication during the position update phase (Gezici et al., 2005).

Another type of positioning that takes advantage of the above systems is hybrid positioning. This type of positioning helps to control objects both inside closed spaces and outside their redistributions in open areas within the same control system. This is due to the fact that hybrid positioning combines the technologies described above for global, regional and local positioning. So, for example, GNSS and LPS technologies can be combined in one device. In such a system, it becomes possible to switch to different modes for determining the coordinates of an object, thereby providing comprehensive control, both indoors and in an open area. For example, if an object moving through an open area enters an enclosed space, it will transmit information about the fact of entering the building and switch to local positioning devices. In the absence of a satellite or radio signal, the information will be stored in the internal memory of the facility and will be transmitted to the server when communication is restored. One example of a hybrid positioning method is A-GPS (Assisted GPS), which uses GPS in conjunction with GSM. This implementation option is quite difficult to implement and requires certain costs. The disadvantages of this method include sensitivity to interference from sunlight and low relative

accuracy. The use of an infrared laser in such a system can increase the measurement accuracy up to 10 cm, but will cause its rise in price.

## 2.4. Organization of ground traffic control based on A-SMGCS

ICAO and EUROCONTROL have defined the Advanced-Surface Movement Guidance and Control System (A-SMGCS) to ensure the safety and efficiency of ground movement in airport traffic areas (runways, taxiways, and apron areas) (ICAO, 2020). The A-SMGCS provides observation and issuance of warnings about the movement of both AC and GV on the territory of the aerodrome. The A-SMGCS is applicable to any airport, to all types of AC and GV, and its implementation should be based on requirements arising from estimates of operational needs and costs, as well as individual benefits of a particular airport.

### 2.4.1. Operating principles of A-SMGCS

The A-SMGCS is a system that supports ground movement operations at an aerodrome in any weather conditions based on defined operating procedures. It consists of a surveillance service that provides location, identification and tracking of mobile objects, and may include a combination of other services as well. A-SMGCS improves access to those parts of the GV and AC maneuvering zone that are hidden from the airfield control tower's view, creating the same opportunities for managing traffic objects regardless of their location on the aerodrome. The A-SMGCS provides sustainable levels of aerodrome capacity with lower minima than would be observed without such a system. A-SMGCS detects and reduces runway incursions, thereby reducing runway collisions. The system provides the ability to take more effective responses to unsafe situations. Figure 2.7 shows the main features and users of A-SMGCS.

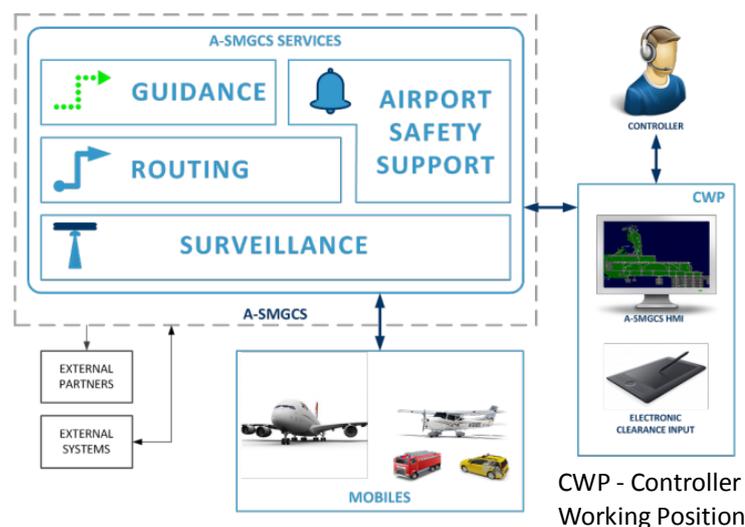


Figure 2.7. Functions and users of A-SMGCS

ICAO published the A-SMGCS Regulation in 2004. The document introduced the concept of system implementation levels. Since 2020, EUROCONTROL has been using a slightly different approach to defining A-SMGCS categories from ICAO (ICAO, 2020). Instead of levels, the system functions are highlighted:

- Surveillance Service (concentrates on supporting Controllers only).
- Airport Safety Support Service (concentrates on supporting Controllers only).
- Routing Service (supports to Flight Crew and Vehicle Drivers).
- Guidance Service (support to Flight Crew and Vehicle Drivers).

### **Surveillance Service**

The Surveillance Service is a key and paramount element of the system, as it is the source of information for the rest of the A-SMGCS components and objects. The Surveillance Service provides aerodrome traffic situational awareness by identifying, locating and tracking aircraft and vehicles within a specified coverage. The Surveillance Service is based on sources with varying degrees of sensor information content: Cooperative and Non-cooperative. The Cooperative Facility is equipped with the means to automatically and continuously provide information within the A-SMGCS. A non-cooperative facility is not equipped with such facilities. In addition, the Surveillance Service receives information from external systems such as Actual Landing Time (ALDT) or A-CDM Platform (see section 2.1.3).

### **Airport Safety Support Service**

The Airport Safety Support Service facilitates controlled area operations to improve safety by enabling controllers to prevent hazards or incidents resulting from operational errors or errors by the controller, crew or vehicle driver.

Here are four types of support that the security system provides to the airport controller:

- Anticipating potential conflicts (e.g. hazardous situations between aircraft or aircraft and vehicles).
- Detecting conflicts and incursions.
- Detecting mobiles that are not following given Clearances.
- Providing alerts.

### **Routing Service**

The Routing Service generates a route for each facility based on known aerodrome parameters and restrictions or after interacting with the Controller, and is the activator of the

Guidance Service and some elements of the Airport Safety Support Service. An accurate taxi time is then generated from the route and can be used by the A-CDM system.

The Routing Service should allow the controller to create or change the route of the vehicle and enter into the system a number of maneuvers that are widely used at aerodromes, for example push/pull manoeuvres, deep or long pushback, Alternative Parallel Taxi Routing (APTR).

The Controller should be able to observe the displayed routes for individual objects and not all routes at the same time. To improve the situational awareness of the controller, the status of various sections of the routes (for example, Planned, Cleared and Pending) is displayed by means of the HMI (human-machine interface) using a different color or format (for example, solid/dashed line). Various statuses allow Controllers, especially at large airports where there are several Tower and Runways, to know in real time whether an object has started moving and to what point it has received the clearance.

### **Guidance Service**

The Guidance Service is a service that improves the movement of objects in the movement area by the means of visual aids in conjunction with the Routing Services and Surveillance Service, and clearances issued by the Controller. The Guidance Service is based on one or more of the following three functions, which can only be partially introduced depending on local requirements:

- Automatic switching of taxiway centerline lights (Taxiway Centerline = TCL) is currently used in some airports with manual TCL switching. The function provides individual escort of any object with a cleared route. It links the cleared route with the Controller's clearance and automatically turns on the TCL a specified distance ahead of the object. The Guidance Service takes into account other road users by assigning priority to traffic based on local operating rules, allowing the traffic to move along its cleared route. The Controller has the ability to quickly make changes to the assigned Guidance Service priority.
- Automatic switching of stop bars provides the ability to turn off and turn on the stop bars in accordance with the clearances issued by the Controller. They can be placed either at the RWY Holding Position (RWY = runway) or across the taxiway. In the latter case, they can maintain the distance between intersecting or converging ground paths, clearly indicating where to stop, for example, to streamline traffic at taxiway

intersections. In addition, stop bars can be used to maintain distance in low visibility conditions (LVP = low visibility procedures).

- Automatic activation of the Advanced Visual Docking Guidance System (A-VDGS) provides docking guidance to obtain the correct docking position for each AC. During the docking process, the AC type is also checked. Integration of A-VDGS with Surveillance Service provides a more accurate initiation process and continuous control from the taxiway/apron to the final stop position at the designated stand. In addition, A-VDGS can provide external systems such as A-CDM with accurate event times such as Actual In/Off-Block Time (AIBT/AOBT).

The specific set of services and functions implemented at a particular airport is determined as a result of decision making after discussion between the local ANSP (Air Navigation Service Provider), airport operators and regulatory authorities.

#### **2.4.2. Prospects for the development of A-SMGCS**

Since A-SMGCS is a general concept in which the requirements for the system as a whole are spelled out, the researchers of this issue offer their own versions of this kind of systems. Its capabilities, characteristics and features (composition of the system, existing limitations, etc.) directly depend on the tasks assigned to a particular system. Of course, the use of radars within an aerodrome is a cheap and proven method of obtaining information about the location of objects, but this method is known to have significant limitations in accuracy.

The abbreviation ADS-B stands for Automatic Dependent Surveillance-Broadcast. Automatic dependent surveillance (ADS) is a process by which an AC automatically transmits data received from airborne navigation systems. MLAT (Multilateration) is a technology that allows to determine the location of AC or other objects using the equipment available on board without the use of ground-based radars. Since one of the key elements of A-SMGCS is ADS-B, an interesting solution to expand navigation capabilities is the joint use of ADS-B and active MLAT, already available on the market (URL22, URL23).

The study of such a configuration in the framework of (Hicok and Lee, 1998) showed that the demonstrated accuracy of the A-SMGCS is 10 meters for the longitudinal and lateral accuracy of the position of the object in the movement area. Unfortunately, within the framework of the study, the accuracy requirement in the apron area of 3 meters was not achieved. Problems were also identified with signal transmission between GV, AC and ground stations. Therefore, when investigating the use of an active MLAT based on ADS-B sources, the number of transmit and receive antennas, as well as their location, need to be studied.

So, in (Loth et al., 2009), the authors propose the CARMA (Car Management on Aprons) system, which expands the capabilities of A-SMGCS due to the effective organization of GV management (see Figure 2.8). The solution proposed by the authors increases the circle of users who own information about the operations performed by the STC in the A-SMGCS system, thereby reducing non-operational time of both GV and AC. However, due to the increase in the functionality of the system, difficulties arise in its implementation.

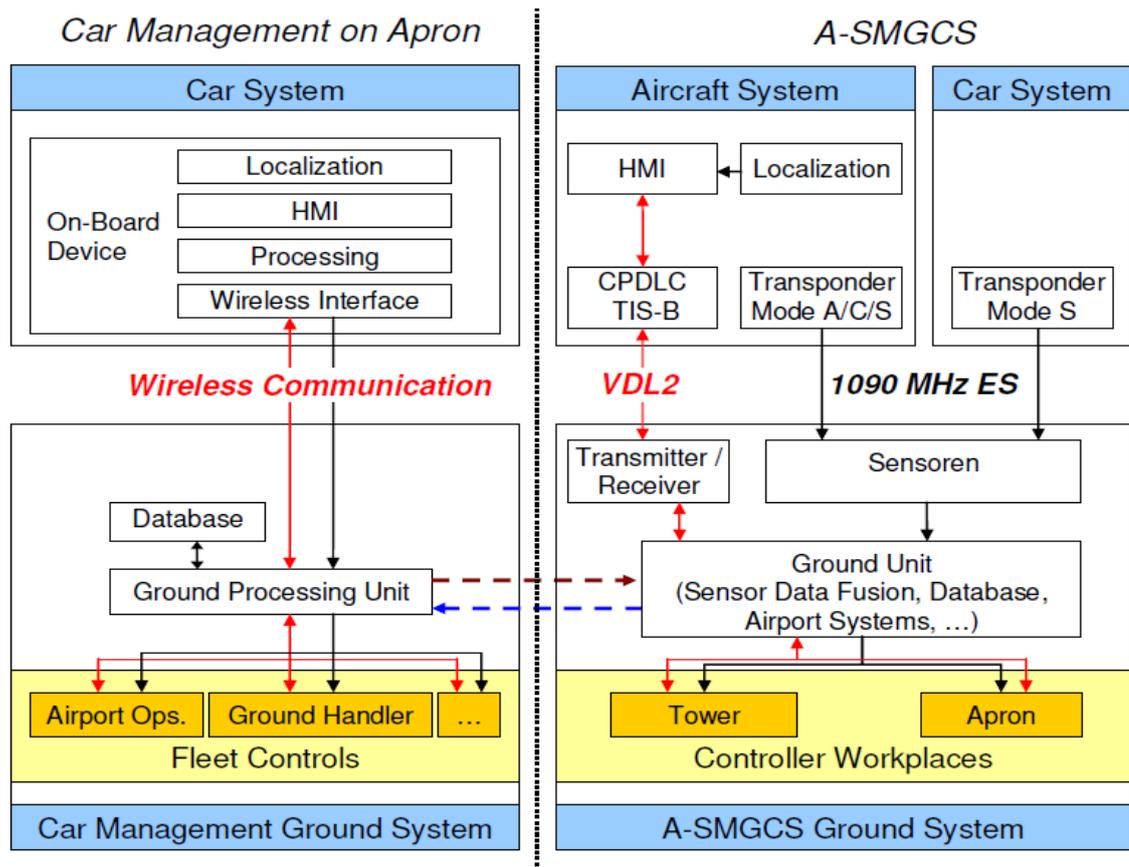


Figure 2.8. Architecture of CARMA Ground System and A-SMGCS (Loth et al., 2009)

One of the most interesting versions of the A-SMGCS is the system described in (Antonov et al., 2015). The innovation of the system lies in the possibility of using unmanned vehicles in it. Structurally, the system consists of a ground segment and an airborne segment (see Figure 2.9). The ground segment includes a control center and a radio center. The airborne segment includes all airborne equipment of vehicles operating at the aerodrome. The radio center provides reception and processing of satellite navigation signals and signals received from pseudo-satellites. It generates differential corrections and provides communication of all traffic participants with controllers and among themselves. A key feature of this system is the use of the onboard integrated navigation system (OINS). Incorporated into the airport's transport

management system, OINS becomes a mandatory component for all vehicles. The main components of such an onboard complex are usually a satellite navigation receiver, a micromechanical inertial navigation system, an odometer and/or a relative speed sensor (Antonov et al., 2015). Such a set of subsystems allows solving the problems facing airport vehicles with the required accuracy, continuity, and integrity of the navigation solution.

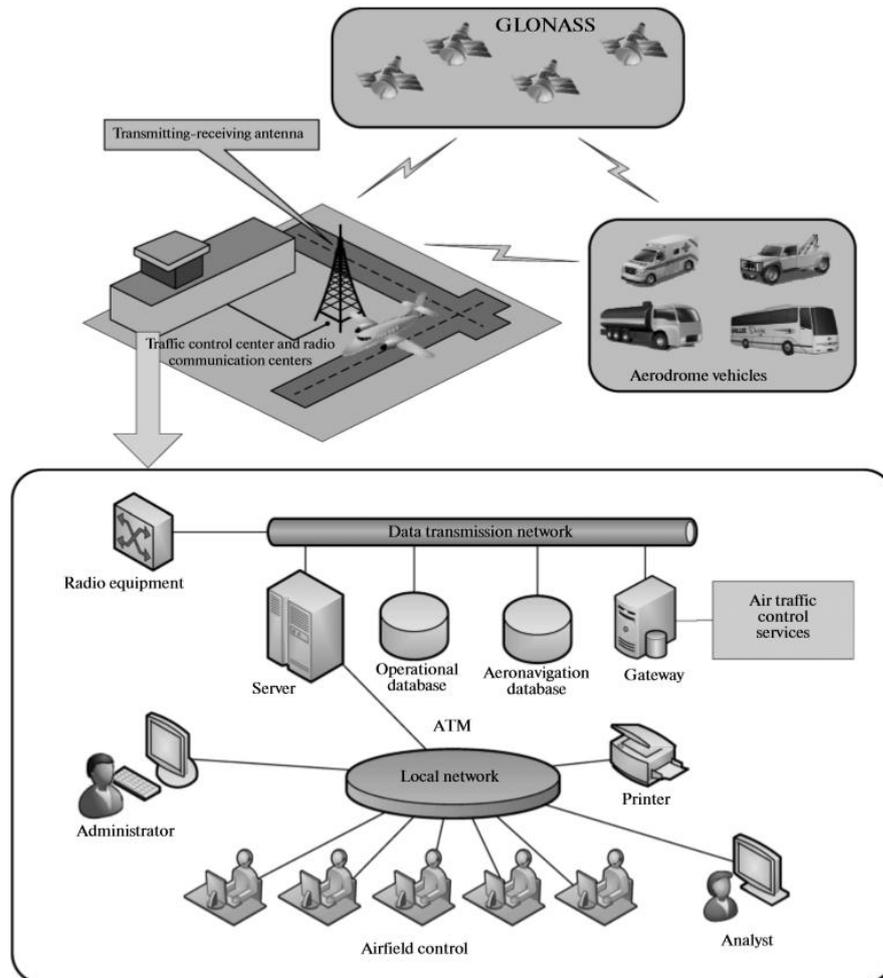


Figure 2.9. The structure of the prospective system A-SMGCS

The main and significant disadvantage of the system is the only source of information about the location of objects – ADS-B in tandem with GNSS. Since the use of the system is envisaged within the framework of aerodrome traffic, such a solution cannot ensure the integrity, reliability and availability of the system in all conditions.

Since the A-SMGCS concept implies obtaining information about the movement of objects from additional sources to eliminate dead zones of the airport, it will be advisable to use data that can be obtained from optical sensors that are part of the Light Detection and Ranging (LiDAR) system and are adapted for various types use (Liu, 2018), (Zhao et al., 2019). A positive property

of such sensors is the possibility of their placement both in transport and stationary. Installed on a vehicle moving within an aerodrome, such a sensor could inform about the presence of obstacles and foreign objects along the route. The study indicates that the range of some sensors reaches 300 m at a sufficiently high resolution. A significant disadvantage of these types of sensors is their cost, which currently makes them economically poorly competitive.

A more cost-effective use case is “a network of intelligent cameras” (Dimitropoulos et al., 2005). The capabilities of such a system as part of the A-SMGCS studied in real conditions showed that the system had a satisfactory performance for objects with speeds from 0 to 100 km/h, which is quite enough for solving problems within the airfield. The advantages of such a system are the absence of radiation, lower cost and the provision of video information. Lots and tracks created with VSDF (Video Sensor Data Fusion) can be used by any A-SMGCS to fill in blind spots and improve track reliability. While cost effective and innovative, the system is not without its drawbacks. Poor detection in heavy fog conditions and false detection due to occlusions are issues that will need to be considered when introducing such a system. An alternative for this sensor system would be to use thermal cameras.

A. Savvaris, M. Melega, and A. Tsourdos considered such a system installed at Cranfield Airport as part of the A-SMGCS (Savvaris et al., 2015). Thermal information was used to detect and classify threats. When the distance between objects is 100-200 m, special indicators lit up. In the study, objects were divided into three main categories based on temperature range: people, vehicles, and airplanes. Based on temperature differences between groups, objects can be easily identified. In this way, various types of objects can be identified at the airport, including all types of aircraft, helicopters, trucks and cars, as well as people.

The authors (Geng et al., 2011) considered the possibility of using such an A-SMGCS in complex and busy airports, which is capable not only of detecting and predicting road conflicts, but also generating proposals and solutions for their elimination. The authors also presented their vision of the structure and composition of the system (Figure 2.10).

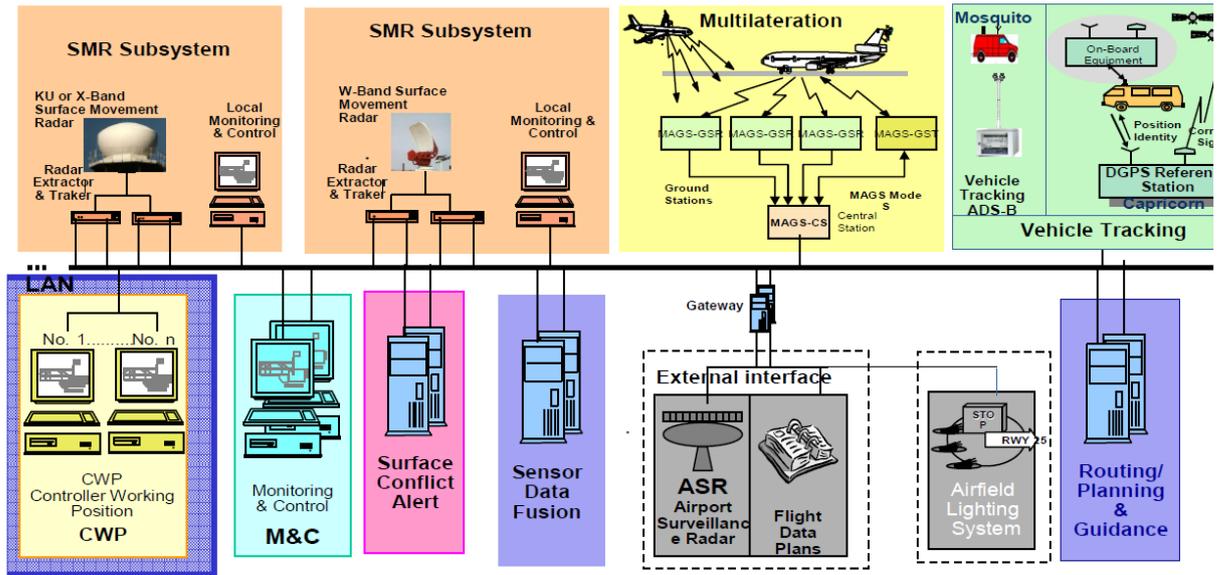


Figure 2.10. The structure of A-SMGCS (Geng et al., 2011)

Summing up, it can be noted that the main trend in the development of navigation aids on the territory of the airport is the deployment and application of joint surveillance systems, for example, ADS-B and active MLAT. The role of primary surveillance radars in the used systems will gradually decrease and become a means of backup or emergency use.

## 2.5. Conclusions

Based on the analysis of the material discussed in this chapter, the following conclusions can be drawn:

- Airport Collaborative Decision Making (A-CDM) is a complex multi-level and multifunctional information system that controls the movement of aircraft in the Airspace, the movement of aircraft and ground vehicles in the Airside area, as well as the movement of baggage and passengers in the Terminal and Landside areas.
- Ground Traffic of aircraft and ground vehicles is a very complex and important process on which the capacity and safety of the airport depends.
- The main control functions of Ground Traffic today are performed by airport controllers or special ground traffic controllers.
- The most advanced functions of automated control of Ground Traffic are included in the Advanced-Surface Movement Guidance and Control System (A-SMGCS), but the role of the controller remains the leading.
- As a long-term task, ICAO described the concept of fully automatic control of Ground Traffic.

- Prerequisites for solving the problem of automatic control of Ground Traffic are progress in the field of Artificial Intelligence and Unmanned Vehicles, as well as an increase in the accuracy of determining coordinates in Positioning and Navigation Systems.
- A-SMGCS can be seen as a starting point towards solving the problem of fully automating ground movement control at airports.

### **3. METHODS AND TOOLS FOR MODELING AND EMULATION OF TRANSPORT PROCESSES AT AIRPORTS**

As mentioned in the Introduction, the main practical goal of this work is to build a simulation model that can be used as a tool for training and testing software for centralized ground movement control systems at airports. The result of this chapter is a decision on how to build such a model, but this decision is based on studying a large number of examples of using various methods and tools for building models that have at least some common properties with the model being designed in this work. Among the examples considered, there are no models that are largely similar to the projected model, since the very problem of building software for automating ground movement control at airports was formulated relatively recently and only at the conceptual level (IATA, 2011).

To prepare an informed decision on how to build a model, both quite common examples of using simulation modeling and very special methods and technologies that are almost impossible to find in textbooks on modeling were considered. Since the designed model is intended for testing and debugging control software, this chapter details the principles and practical experience of using simulation models in emulation mode. Real-time, dynamic data on the state of physical objects is called the Digital Twin today. It can be argued that the information base of the centralized ground movement control system at the airport will operate in the Digital Twin mode. This chapter examines in detail the modern understanding of this type of information models and shows their relationship with models such as “real-time simulation” and “online simulation”. A feature of the projected model is to take into account the interaction in the 2D space of the airport of mobile objects, which include aircraft (AC) and ground vehicles (GV). The experience of solving this problem in the field of using Automated Guided Vehicles (AGVs) is also briefly reflected in this chapter. As mentioned above, in the last part of the chapter, a rationale is given for the decision on how to build a projected model of processes in the airport transport network.

#### **3.1. Application of various classes of software products for simulation of transport processes at airports**

In order to justify the choice of tool for solving the airport transport simulation problem, the following is a review of model building experience using software products belonging to four classes:

- airport simulation software (e.g., TAAM, AirTOP, SIMMOD and CAST);
- road traffic simulation software (e.g., VISSIM, SUMO and Aimsun);

- general-purpose simulation software (e.g., AnyLogic and Simio);
- general-purpose programming languages (e.g., C#, C++, Java, JavaScript, Python, and Visual Basic).

### **3.1.1. Airport Simulation Software application**

The best known products in the airport simulation software group include TAAM, SIMMOD, AirTOP and CAST packages. All of them have been on the market for over 10 years. All of these packages are focused on modeling processes in such airport areas as airspace, airside, landside, apron and terminal, but in the following review, first of all, such properties of these packages will be noted, which are related to modeling ground transport processes. It should be noted that all these packages are expensive commercial products, and they are relatively rarely used for solving research problems. Additional difficulties for researchers arise due to the fact that the source code of such packages is closed and there is no possibility for flexible changes in the rules of behavior of individual participants in ground movement. Most often, such packages are used in large projects developed for specific airports. Due to the factors noted above, publications related to the use of products from the airport simulation software group are quite rare.

The TAAM (Total Airspace and Airport Modeler) package defines the following position types for AC locations: Gates, Deice Stations, Long Term Parking Positions, and Standoffs (TAAM URL). To simulate AC movement, such path types as Taxiways, Runways, and Pushback Paths are used. The ground vehicle modeling capabilities are related to the Aprons concept. The developers of the package call it a virtual laboratory in which any operational environment can be simulated and the results of simulation experiments can be analyzed.

The work (Bazargan et al., 2002) reports on the use of the TAAM package to select the number and location of new runways during the reconstruction of Philadelphia International Airport. The airport's capacity was used as the main criterion for evaluating each of the possible reconstruction options. The authors (Sood and Wieland, 2003) solve the purely technical problem of speeding up the TAAM package by defining model fragments that can be processed in parallel.

Simmod PRO package! (SIMMOD URL) has been on the market since 1997. In (Bertino et al., 2011) it is noted that the package allows efficient simulation in interactive mode, when at certain points in time, the model stops and waits for instructions from the user, which are the result of his decisions. Such instructions are used to control the processing steps of each individual AC, taking into account the specific conditions that develop in both the airspace and

the aerodrome. The dissertation (Lee, 2014) solves the problem of optimizing surface movement control at Detroit airport. Using the SIMMOD package, the author simulates the real timetable for the arrival and departure of AC at the airport.

The authors of the work (Long et al., 2001) assess the feasibility of connecting the LMINET package to the TAAM and SIMMOD packages. The LMINET package is a large queuing network model that displays processes throughout the US National Airspace System (NAS). The use of the LMINET package will lead to an increase in the accuracy of air traffic statistics at the airport, which is investigated using the TAAM or SIMMOD packages. Several short reports on the properties and application examples of the TAAM and SIMMOD packages can be found in the report of the conference, which is held annually by the Transportation Research Board (TRB, 2001).

The AirTOP package allows simulating the movement of aircraft and ground vehicles on the territory of an airport (AirTOP URL). In the AirTOP Airside Vehicle module, a significant place is given to the standard rules of interaction between aircraft and ground vehicles, which allows the user to display a process very close to real in the model. Simulation accuracy is improved if this module interacts with the AirTOP Airside Aircraft module. AirTOP modules are often used today to carry out not only applied projects, but also research work. For example, in (Kageyama and Nakamura, 2018) and (Sekine et al., 2021), the authors use AirTOP modules to study new principles of aircraft separation. In (Sidiropoulos et al., 2018), using the AirTOP modules, the authors evaluate a new operational scenario that should be applied for the entire New York MAS, consisting of the airports of John F. Kennedy (JFK), LaGuardia (LGA), Newark Liberty International Airport (EWR) and Teterboro (TEB).

It should be noted that the TAAM, SIMMOD and AirTOP packages discussed above focus on the AC motion processes, while the ground vehicle motion processes is modeled almost automatically. Only in the CAST package there is a special CAST Vehicle Ground Handling module, which makes it possible to set the GV motion control strategies. The choice of a specific strategy is made by specifying special input parameters of the model (CAST URL). In Master Thesis (Sanz de Vicente, 2010), the author studies the processes of ground handling of aircraft using the CAST package. In the work (Metzner, 2019), the tasks of analyzing the influence of the design parameters of the terminal on its stability are solved. The author models passenger flows using the “agent based” concept offered within the CAST package.

All the packages mentioned above allow displaying aircraft and ground vehicle movement processes on the airport territory with a high degree of adequacy, including in the form of photorealistic 3D animation. The purpose of using such packages can be to solve both tactical

and strategic tasks. Tactical tasks include training and training of air and ground traffic controllers. Strategic objectives include comparing alternative management strategies and even options for airport transport network plans by analyzing the most important process quality indicators that are assessed using simulation. The packages implement a high level of automation of the process of building models. This means that after entering the basic initial data, for example, about the sequence of AC that must be processed before the next flight, the package programs automatically simulate the movement of the corresponding GV in strict accordance with the specified rules and regulations. Due to the inaccessibility of the program code, the researcher has only very limited possibilities for describing and analyzing non-standard scenarios that can be observed in the airport ground transport system. The idea of creating an open source package was implemented as a CATS package (Alliot et al., 1997), but this package has not been supported by its developers for a long time.

### **3.1.2. Road Traffic Simulation Software application**

Packages from the Traffic Simulation Software group allow a high degree of adequacy to simulate the processes in traffic systems. It is generally accepted that each model can be attributed to the class of micro-, meso-, or macromodels. In the context of this work, only micromodels are of interest, in which the movement of each individual vehicle or pedestrian is displayed. In the models of this group, it is possible to accurately describe the characteristics of all road users, as well as the characteristics of the infrastructure, which includes both the road itself and the technical means and algorithms for controlling the flow of vehicles and pedestrians. There are many commercial packages and programs in the public domain that belong to the Traffic Simulation Software group, but in one of the latest reviews of this group, the Vissim, SUMO and Aimsun packages are noted as the most advanced (Ejercito et al., 2017). The characteristics of these packages and examples of their application to airport transport modelling will be briefly discussed below.

The development of the PTV Vissim package was started back in 1992 at PTV Planung Transport Verkehr AG in Karlsruhe (Vissim URL). Today this package is a multimodal system for road traffic microsimulation. Multimodality means the ability to simulate all types of road users: cars and trucks, trams and buses, pedestrians, cyclists and even rickshaws. The PTV Vissim package is the most used traffic simulation package in the world.

In (Zhang, 2020) the use of the PTV Vissim package for modeling and forecasting traffic in the Los Angeles International Airport Road Network is reported. The webinar (Ortiz, 2020) shows the possibilities of modeling not only traffic flows in the Landside area, but also the

processes of servicing passenger flows, for which the “Terminal Operation” and “Security Check Points & Queueing” sections were created in the model. Bandaru (2017) describes a model in which Vissim was used to simulate movement in both the landside area and the airside area, where vehicles are classified as Ground Service Equipment (GSE). Using a simulation, the author estimated the required GSE resources to service the projected terminal at Bengaluru Airport.

The SUMO (Simulation of Urban MObility) package, like the Vissim package, is intended for microsimulation of transport processes. A feature of the package is that it belongs to the group of open-source simulation package. The SUMO package is mainly developed by the German Aerospace Center and has been freely available since 2001 (Lopez et al., 2018).

In (Jung et al., 2017) and (Noyer et al., 2018), within the framework of the multi-airport region models, the SUMO package was used to simulate ground public transport, including buses and trains, which are used for transfers between airports in the region. The experience of using SUMO for modeling data transfer processes between cars in the study of the concept of Virtual Traffic Lights is important (Tonguz, 2018). It should be noted that although the SUMO package qualifies as a research tool, there are practically no reports of its use for modeling processes in the airside of airports.

Aimsun Next is a relatively new package that supports microsimulation and mesoscopic simulation concepts as well as macroscopic functionalities (Aimsun URL). Experts consider this package to be the fastest in the field of microsimulation. A feature of the package is the fact that it is the most advanced in the field of Connected and Autonomous Vehicles (CAV) modeling (Figure 3.1).

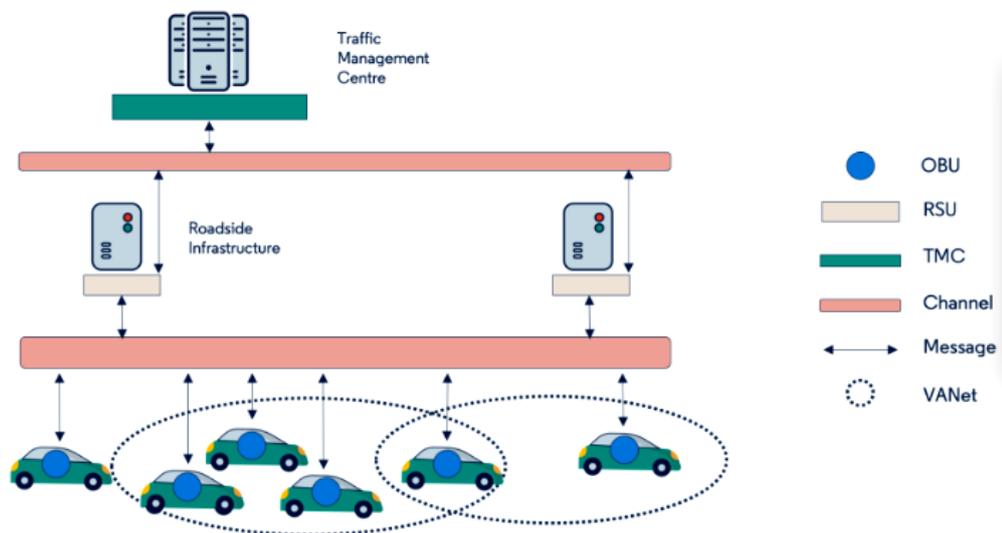


Figure 3.1. Modeling of Connected and Autonomous Vehicles (Aimsun URL)

V2X Software Development Kit (SDK) is designed to display communication systems such as VANets (Vehicular Ad Hoc Networks) to simulate the exchange of messages between vehicles and a roadside device. In Figure 3.1, OBU stands for On-Board Units, and RSU stands for Roadside Units. In the light of this work, this property of the Aimsun Next package is very important, since it gives the researcher the ability to model his own centralized management algorithms used in the Traffic Management Center (TMC). Additional flexibility and extensibility of the package is provided by the ability to connect your own user programs written in Python or C++.

The website (IMHOTEP URL) of the Aimsun company informs about the international project “Integrated Multimodal Airport Operations for Efficient Passenger Flow Management” (IMHOTEP), which should be completed in the time period 2020-2022. As part of its work package, Aimsun is to create tools to simulate airport inbound and outbound passenger flows, as well as “Door-to-Kerb” and “Kerb-to-Door” travel routes.

The work (Pashkevich et al., 2021) describes the experience of using the Aimsun Next package for assessing the runway capacity at Krakow-Balice International Airport. At the same time, the authors criticize the package manufacturers from the Traffic Simulation group, which, with a focus on airports, created support tools only for simulating passenger flows at terminals.

### **3.1.3. General-Purpose Simulation Software application**

The General-Purpose Simulation Software group includes commercial products that are designed to simulate processes in systems that, at an abstract level, can be represented as network structures through which streams of moving objects are passed. It is generally accepted that three types of paradigms can be used to build process models (Borshchev, 2013): “continuous”, “discrete event” and “agent based”.

The “continuous” paradigm can be used to model any processes described using differential equations, but in the field of modeling production and transport processes, it is most often used in the form of Systems Dynamics models. Models based on the principle of System Dynamics will not be considered in the overview below, since they belong to the class of macromodels, which do not display the behavior of individual objects. It should be noted that the  $\Delta t$  principle for representing time in a model, which is characteristic of System Dynamics models, is also often used to model the continuous movement of objects in transport models. Although these models do not use differential equations or the System Dynamics categories, they should be classified as “continuous”.

The “discrete event” paradigm is most often used to model processes at the logistic level, when aircraft, ground vehicles, cargo units or individual passengers are displayed as moving objects in models. All changes in the model occur at specific points in time, which form an arbitrary sequence of events on the time axis of the model.

Since about 2000, the “agent based” paradigm has been used to solve practical problems in which active or simply movable elements of the model have the properties of a subject with his personal goals and the ability to interact with other elements informationally. In terms of computer program principles, “agent based” models do not differ significantly from “continuous” or “discrete event” models, since they use the same timing and event scheduling mechanisms.

The following packages are most often used for modeling transport, manufacturing and logistics systems: AnyLogic, Arena, AutoMod, Delmia Quest, Enterprise Dynamics, ExtendSim, Flexsim, GPSS, Plant Simulation, ProModel, Simio, Simul8 and Witness. Most of these packages support the “discrete event” paradigm, but some of them allow the simulation of continuous processes based on the  $\Delta t$  principle. The “agent based” paradigm is most easily implemented in the AnyLogic package. Below examples of General-Purpose Simulation Software application for simulation of processes in airports will be discussed.

The developers of the universal **Simio** package have created a separate section of the Airport Simulation Software (Simio URL) on their website. They offer airports to solve the problems of analyzing processes in terminal, landside and airside sectors. The company's website describes an example of using the **Simio** package to simulate the operation of AECOM de-icing facilities at Edmonton International Airport (Canada). In (Koeners and Rademaker, 2011), using the **Simio** package, methods of organizing taxi flow control in the vicinity of Amsterdam airport are investigated.

In (Scala et al., 2015), the Terminal Manoeuvring Area of Lelystad airport (The Netherlands) is modeled using **Simio**. The model takes into account, for example, such restrictions as separation minima between aircraft and weather restrictions as crosswind. In (Scala et al., 2019), the authors summarize their experience of using the **Simio** package and write about the development of a general approach to modeling processes at the airport. They believe that based on their approach, it is possible to create effective models of such complex systems as airspace-airside operations or multi-airport systems. A model of Paris Charles de Gaulle airport is given as a case study.

**FlexSim** only supports the “discrete event” paradigm (Beaverstock et al., 2018). A feature of the package is the intensive use of 3D animation already at the stage of model building. The

**FlexSim** developers have also created a separate Airport Simulation section (FlexSim Airport URL) on their website. There one can see information about the completed project “TSA Screening Process”. The abbreviation TSA stands for Transportation Security Administration. The main task of the simulation was to estimate the required number of Travel Document Checker (TDC) stations different times of the day when the airport is open.

In (Olaru and Emery, 2007), the **Extend** V.6 package is used to simulate all operations related to servicing departing passengers. The process begins with the arrival of passengers at the airport building by car and ends with their boarding the plane. In (Savrasovs et al., 2009), a newer version of this package called **ExtendSim** is used to study the baggage handling system at the Riga airport. Using the model, it was shown that bottlenecks can occur at those points in the baggage handling system where operations are performed manually by airport personnel.

In (Takakuwa and Oyama, 2003), the authors use the well-known **Arena** package and focus on modeling the flow of departing passengers at Kansai International Airport. The authors (Confessore et al., 2005) use the **Arena** package to study the processes in the apron of Rome-Fiumicino airport. As a result of the simulation, options were proposed for changing the apron configuration in order to reduce the number of aircraft simultaneously located there.

In (Appelt et al., 2007), the **Arena** package is used to analyze processes in the passenger check-in zone. The authors obtain statistics on the waiting time and passenger service for different types of check-in modes. The authors (Ju et al., 2007) use the **Arena** package to study the processes of movement and waiting of passengers in the airport premises. In (Fayez et al., 2008), the **Arena** package is used to simulate the flow of passengers in all areas of the airport. With the help of the model, various indicators of passenger service are assessed, of which level of service (LoS) is the main one. In (Guizzi et al., 2009), the **Arena** package is used to solve a similar problem of analyzing the flow of passengers in an airport terminal building. In (Lopez et al., 2019), it is reported about the use of the **Arena** package to build a model, with the help of which the bus fleet size dimensioning was performed at the airport.

The developer site for the popular **Enterprise Dynamics** suite specifically shows the Baggage Handling Simulation (BHS) (ED-BHS URL) and Airport Passenger Flows (ED-APF URL) sections. The first package allows for simulation experiments that can be used to make informed decisions about creating, expanding or upgrading the Baggage Handling System. The second package is based on the Pedestrian Dynamics simulation software. It is assumed that the main purpose of the models will be to assess the airport infrastructure designed to serve passenger flows. For example, it will be possible to find out whether the number of stairs,

escalators and elevators is sufficient. The authors (Joustra and Van Dijk, 2001) use **Enterprise Dynamics** to explore alternative airport check-in methods to optimize staff utilization schedules.

The authors of (Fonseca i Casas et al. 2014) argue that airport passenger flow models should include landside processes where passengers use conventional ground transportation. The authors used the **Witness** package to simulate the processes at Barcelona International Airport.

The authors of (Verbraeck and Valentin, 2002), solve the problem of developing so-called Building Blocks, that is, unified software modules that can be used to simulate various processes at the airport. The authors chose the **eM-Plant** commercial package as a tool for building such modules. This package is object oriented and supports only one paradigm, “discrete event”. The current commercial name of this package is **Plant Simulation**. The authors (Brandau and Tolujevs, 2013) used the same package to study the processes of handling cargo flows at the airport. The process is based on the principle of cross-docking, according to which incoming and outgoing cargo flows are distributed among several geographic locations.

On the (**AnyLogic** Cloud URL) collection of demo models, the following models can be seen, for example:

- *Airport with Two Terminals*. A model of an airport with two terminals. Includes flight schedule, check-in, security check, shuttle train between the terminals, boarding, unboarding, and baggage claim.
- *Airport*. This is a simulation of the international flight’s departure of Koltsovo airport, Yekaterinburg, Russia. The simulation duration is one day and night. Passengers arrive; pass security control, customs control, check-in, passport control and gate control.
- *Aircraft Boarding Simulation*. The model simulates a single-aisle aircraft boarding using various boarding policies. Available parameter settings include priority queues, companies of passengers, distribution of carry-on luggage, and late or early boarding passengers.

In (Hafner, 2008) solves the optimization problem of the runway slot assignment strategy. The timelines created as a result of the optimization algorithm were evaluated by the authors using a simulation model implemented in **AnyLogic**. In (Iyigunlu et al., 2014), the authors compare different aircraft boarding strategies using the “agent based” paradigm in the **AnyLogic** package. The authors (Cheng et al., 2014) investigate the airport check-in and evacuation process under the assumption that passengers can exhibit not only individual but also group behavior. When building their model, the authors applied the “agent based” paradigm in the **AnyLogic** package. In (Tomasella et al., 2019), using simheuristics, the task of coordinating aircraft turnaround operations, which are carried out by various stakeholders, is solved. All movements

of objects on the airfield are modeled using the **Anylogic** package using the “agent based” and “discrete event” paradigms.

The author (Metzner, 2019) describes statistical experiments with airport passenger flow models. For the model based on the “agent based” paradigm, the author uses the CAST Terminal package, and for the model based on the “discrete event” paradigm, the **Anylogic** package. The work (Sinha et al., 2019), investigates the influence of passenger flows in the terminal building on energy consumption in HVAC (heating, ventilation, and air conditioning) installations. Using the model implemented on the basis of the “agent based” paradigm in the **Anylogic** package, the authors reproduce the passenger flows in the terminal building necessary for research. The authors (Zhao et al., 2020), investigate the impact of the differentiated security strategy on the overall safety performance of an airport. To assess these indicators, a model was developed based on the “agent based” paradigm in the **Anylogic** package.

The authors of the work (Rauch and Kljajić, 2006), study the processes of servicing passenger flows at Ljubljana Airport in a situation where it was necessary to separate flows into Schengen and non-Schengen. The **GPSS/H** package is used as a simulation tool. It should be noted that the **GPSS/H** package is the only product in the General-Purpose Simulation Software group that does not have a Graphical User Interface (GUI), and the models are created only as texts in the GPSS language.

#### **3.1.4. General-Purpose Programming Languages application**

General-Purpose Programming Languages are used to designate simulation models for airport processes when none of the commercial packages from the three groups described above are used. Authors often do not indicate the specific programming language used, since this aspect of the model development process is clearly secondary. An important fact is that for solving many research problems, specialists develop models based on their own program code. The main advantage of such models is the absence of restrictions both with respect to the logic of the development of the modeled processes and with respect to the input and output data of the model. If a software product turns out to be rather complex or it is also used by other researchers, then its developers sometimes assign it a unique name, as, for example, in the case of the STROBOSCOPE and VTASIM programs considered below.

The works (Martinez et al., 2001) and (Khoury et al., 2007) show how the STROBOSCOPE package, developed in 1996 within the framework of J. C. Martinez's thesis, can be effectively used to simulate the real situation in the airside zone of an airport during construction work there.

In (Dzikus et al., 2010), the authors analyzed the movement of vehicles in the airport transport network. The limitation of the model is that it only displays aircraft movement. To create the model, the authors used the VTASIM research package, in which, simultaneously with the “discrete event” paradigm, the “continuous” paradigm is used to simulate the continuous motion of objects.

The work (Bevilacqua and Ciarapica, 2010) investigates the waiting and service processes in the airport check-in area. The method of microsimulation of processes is used, for the software implementation of which one of the usual programming languages is used. A similar microsimulation-based approach is described in (van Boekhold et al., 2014). Security screening checkpoints are subject to research. The model is used to assess the impact of screening methods on such classic performance indicators of systems with queues as average wait time, average service time, average queue length, and average throughput rate.

The authors (Koener and Rademaker, 2011) deal with the problem of automatically generating of taxi routes. To solve these problems, they developed their own simulation environment, since the standard simulation tools did not make it possible to study all the effects of the introduction of new planning algorithms of taxi routes.

The authors (Mas et al., 2013) study in detail the ways of organizing the aircraft boarding process. They compare different strategies for getting passengers on board based on their seating arrangements. The authors created the model using the Visual Basic for Applications (VBA) programming language within MS Excel.

The authors (Gök et al., 2020) have developed their own Petri-Net-based discrete-event simulator to analyze aircraft turnaround operations. The created model can be automatically improved by interpreting the obtained simulation results. The authors note that if such an approach was implemented using well-known commercial simulation packages, the time required would be much greater.

### **3.2. Application of simulation models in emulation mode for debugging control software**

The main goal of this work is to develop this type of simulation models that can be used as a tool for developing and testing software in centralized traffic control systems in the apron airport zone. An effective method for debugging and testing control software is based on the use of simulation models in emulation mode (Xcelgo URL). Since there is practically no information on the application of this method in the field of aviation, below will be considered examples of testing programs for centralized control of transport processes in areas where there is already a

useful experience in solving such problems. The first group of examples relates to the field of Automated Guided Vehicles (AGVs), and the second to the use of the Floating Car Data (FCD) concept for road traffic control.

The concept of emulation is well known to specialists involved in the development and testing of software designed for automatic control of technical systems. The essence of emulation is that the control object is replaced by a simulation model that interacts with real control programs (Xcelgo URL). The model includes a sensor part, from where signals are sent from various “sensors and counters” corresponding to the devices of the real system. Control programs process these signals and generate control commands that are perceived by the executive part of the model. The model responds adequately to control commands, that is, the same changes and events occur in it as should occur in a real system. Most often, the simulation model is processed on a separate computer, which must be hardwired to the computer on which the control programs are installed. A special type of emulation is the “Hardware in the Loop” technology, when the control system is a specific electronic device (hardware) designed to be installed on a technical object, for example, on a car.

Emulation can be used both for testing new control programs and for adapting standard programs before connecting them to a new object. The main effect of the use of emulation is that the time for debugging and commissioning complex control programs is significantly reduced. Naturally, this effect is achieved provided that the processes in the simulation model proceed much faster than in the real system. A large economic effect is achieved, for example, in the case of using emulation when commissioning a management system for a large, automated warehouse (Spieckermann et al., 2012). Without the use of emulation, the process of debugging programs can take several months, during which high costs arise due to the need to constantly keep the warehouse equipment in working order. Figure 3.2 shows two ways to use emulation, one for debugging programs in the Programmable Logic Controller (PLC) and the other in the Materialflow Controller. Virtual Conveyors module is a simulation model running in emulation mode.

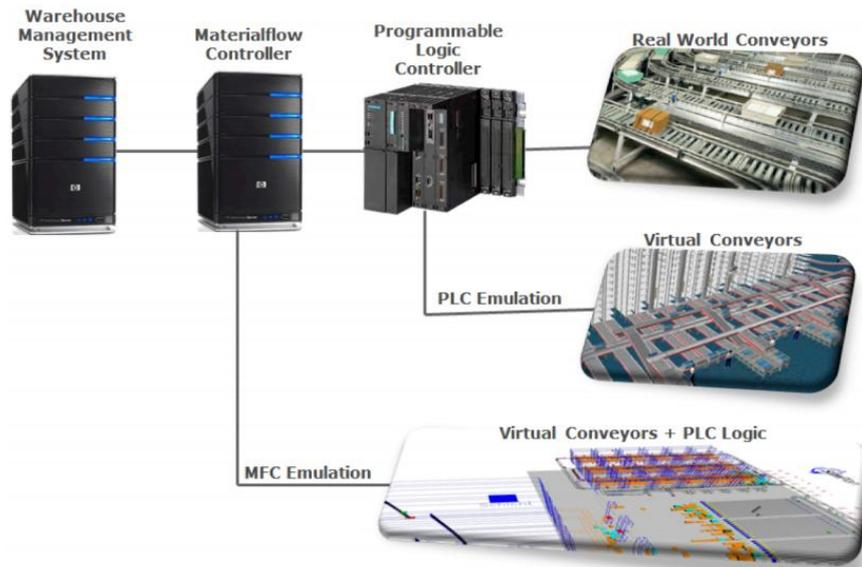


Figure 3.2. Schema of different emulation approaches (Spieckermann et al., 2012)

Emulation as a type of simulation is described on the FlexSim developer site (FlexSim PLC URL). This type of emulation is focused on debugging PLC-type control systems. First, the control logic is programmed and tested inside the simulation model in FlexSim. In the next step, the tested logic is programmed on a real controller. Then the controller is connected to the FlexSim model, with which the final adjustment of the control algorithms is made.

The work (Helleboogh et al., 2006) discusses the issues of testing software for controlling a group of Automated Guided Vehicles (AGV) in a large warehouse. Each AGV has onboard software that, for example, prevents the AGV from colliding with each other or with other obstacles. But in the transport network, conflict situations can arise that can only be resolved by activating centralized control programs. The system has a central server that schedules the AGV movement, sends AGV commands and constantly polls their status. The authors of the work report on the use of a warehouse simulation model for testing both onboard and central software, which together provide reliable AGV motion control.

A special kind of AGV is Automated Rail-Mounted Gantry Cranes (ARMG), which are often used at container terminals in seaports. Such cranes serve container storage areas and operate in automatic mode. In large ports, as a rule, several dozen ARMG-type cranes are used. Rintanen and Thomas (2021) reported on the experience of using simulation and emulation when debugging ARMG crane control software in ports such as CTA and CTB in Hamburg, APM Terminal Virginia, Antwerp Gateway, London Gateway, Khalifa Container Terminal and others. The simulation model was used as a substitute for a real crane. Emulation allows debugging the

control software simultaneously with the production and installation of equipment and creates a new environment for controlling the quality of the software product.

Floating Car Data (FCD) is a method of collecting data on the current state in road traffic. The data comes from the so-called “connected vehicles” in the form of records, the main content of which is the time stamp and coordinates of the vehicle location. In (Astarita et al., 2020), not only the experience of the practical application of a traffic management system based on the FCD method is reported, but also the process of developing and debugging the corresponding software, in which simulation and emulation was used, is described in detail. At all stages of this project, experiments were carried out on the basis of the TRITONE software platform, specially designed for the purposes of simulation and emulation.

The authors of the article (Astarita et al., 2012) solved the problem of choosing software for developing models operating in emulation mode. As a result of comparing all the product classes described above, it was decided to develop its own TRITONE package using General-Purpose Programming Languages. Although the competing open-source SUMO package has been available since 2001, solving research problems in traffic management at the micro level needed to develop a tool that provides even more opportunities for creating scripts that determine the behavior of each individual vehicle. In addition, the option was taken into account when the simulation and control programs must be executed on separate computers.

### **3.3. Digital Twin as a result of the development of the Online Simulation concept**

It is generally accepted that the concept of Digital Twin (DT) was first formulated in (Grieves, 2005). The essence of DT should be a dynamic virtual copy of a real system or process, which leads a kind of “parallel life” in relation to the original. The terms “physical asset” and “physical twin” are often used to refer to the original. DT itself is also sometimes called “device shadow” or “digital avatar”. Since the concept of DT is relatively new, authors of articles and developers of relevant applications understand a variety of models as a virtual copy. For example, NASA experts (Glaessgen and Stargel, 2012) believe that the term DT can be used to refer to almost any complex simulation model of a real object that serves to represent its life cycle. In (Madni et al., 2019), provides a definition of four types of models that the authors associate with the concept of DT:

- Pre-Digital Twin is a conventional simulation model of an object that does not even exist yet;
- Digital Twin is a simulation model, which regularly, but not in real time, receives data from a real object;

- Adaptive Digital Twin is a simulation model that receives data from a real object in real time;
- Intelligent Digital Twin is an extension of the previous type, which adds machine learning functions.

The first ideas for the implementation of DT were associated with virtual modeling of purely technical objects, for example, from a single ship engine to the scale of the entire technical support of the ship. The main feature of the DT was its direct connection with the physical system, which was carried out through one-way data transmission from numerous sensors installed in the system. The main function of DT was to store data about the current state of the system, which could be used, for example, to predict failures of specific system nodes. Later, a discussion began on the possibilities of using the DT concept for virtual modeling of technological processes and even complex business processes of enterprises.

Only the third DT variant shown in (Madni et al., 2019) is consistent with the original concept, while the remaining variants show examples of blurring this concept. For example, conventional or well-parameterized simulations have been around for decades and it doesn't make sense to call them DT today. Figure 3.3 shows the difference between a “real” DT and a “fake” one. The DT concept begins with the acquisition of real-time data from a physical object. Any digital models that do not work in this mode are not related to the DT, but if they are connected to an object, they become part of the DT.

Typical applications for DT are as follows (Figure 3.3a):

- the operation of the facility in normal operation mode;
- the operation of the facility on the test bench.

The term DT is often misapplied to models of the following type (Figure 3.3b):

- conventional mathematical models and Finite Element Method;
- conventional discrete event or continuous simulation models;
- CAD models including dynamic 3D models and models for virtual tests.

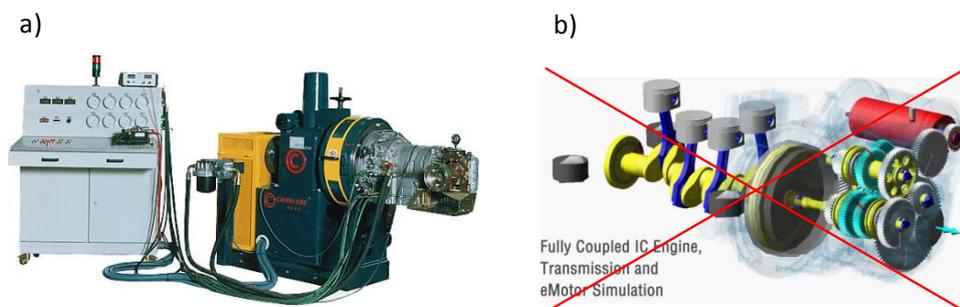


Figure 3.3. True and fake Digital Twins

In the aviation field, the focus was also initially on purely technical systems. For example, the DT display the status of an airframe (Tuegel, 2012) or an aircraft engine (Zaccaria et al., 2018).

Rolls-Royce is developing virtual replicas of aircraft engines under a concept called IntelligentEngine (Rolls-Royce\_1 URL). This concept assumes that the engine collects complete information about its condition and has continuous two-way communication with the service system. Engine Health Monitoring (EHM) systems can record information from thousands of sensors. Such systems not only monitor the status of various parts in real time, but also predict when they should be replaced.

Rolls-Royce has built the Testbed 80, which assembles the world's largest aircraft engine, the UltraFan (Rolls-Royce\_2 URL). Each fan blade of this engine has a digital twin that stores data about all tests performed. This information is used to predict the behavior of engine parts under real operating conditions. When testing an engine on the Testbed 80 stand, specialists can register 10 thousand parameters at a speed of up to 200 thousand polls per second.

Figure 3.4 shows that TEST-FUCHS has developed a broad application program for the DT concept in all areas of aircraft design, manufacture, testing and operation (TEST-FUCHS URL). One of the goals of such a program is to use it to provide data on the technical condition of the aircraft in real time. Based on this data, aircraft owners can timely perform aircraft maintenance in their MRO stands. Using Cloud IFS technology, the company accumulates lifecycle data of many aircraft in order to obtain a digital DT landscape around each of them.

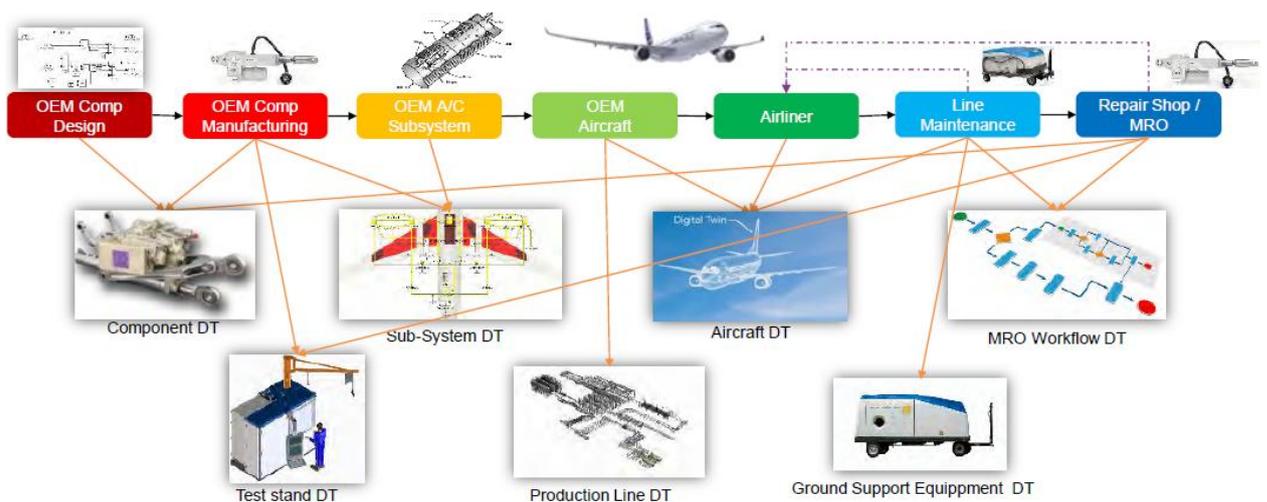


Figure 3.4. Multiple Digital Twins concept from TEST-FUCHS (TEST-FUCHS URL)

Numerous statements by specialists concerning the prospects of applying the DT concept for monitoring and controlling processes at airports are beginning to appear. It should be

emphasized that such statements refer exactly to the prospects, as there are no ready-made comprehensive solutions yet.

For example, (DT1 URL) reports that SITA Lab is developing a project to create a DT for an airport in the United States. Such a DT must control the processes on the airfield, in the traffic areas in front of the airport building, as well as in the security check areas. Experts note that the main problem lies in creating a data collection system, and if it is successfully solved, it will take from 5 to 10 years to complete the project. (DT2 URL) reports on a broad implementation program for the DT concept at Copenhagen Airport. As the first, the tasks of monitoring the condition of the airport premises, for example, the degree of their congestion and air quality, will be solved. In the future, it is planned to create other DTs and connect them to systems such as A-CDM (Airport Collaborative Decision Making). The (DT3 URL) reports that Hong Kong International Airport is planning to become a smart airport. At the first stage, DT will be used mainly for 3D visualization of processes at the airport, but then it is planned to develop analytical applications capable of solving forecasting problems. In (DT4 URL), it is reported that 51WORLD, a well-known IT company, and the China Academy of Civil Aviation Science and Technology have begun work on a smart airport project, of which the DT concept is a part. In 2020, 23 demonstration projects have already been implemented in the cities of Beijing, Guangzhou, and Shenzhen. It is noted that big problems arise due to the need to integrate previously developed and independently operating process control systems at the airport.

It should be noted that long before the appearance of the term “digital twin”, “real-time simulation” and “online simulation” techniques were used in the field of simulation modelling, in which the simulation model exchanges data with a real physical object.

The “real-time simulation” technique is often used to simulate processes in electrical systems (Bélanger et al., 2010). In general, the term “real-time simulation” refers to such models in which the internal time runs at the same rate as the actual “wall clock” time. Most often, such models are launched at specific moments of discrete time, for which the step  $\Delta t$  is specified, that is, at times:  $t$ ,  $t + \Delta t$ ,  $t + 2\Delta t$ , etc. Figure 3.5 shows that the model is run at times  $t_{n-1}$  and  $t_n$ . The model is considered correct if it produces the corresponding results no later than the moments  $t_n$  and  $t_{n+1}$ . At each moment of discrete time  $t_{n-1}$ ,  $t_n$  and  $t_{n+1}$ , data is exchanged between the model and the real object, i.e., the simulation results are transmitted to the object at the previous step, and the input data is received from the object, with which the modeling will begin at the new step. It should be noted that the moments of time  $t_{n-1}$ ,  $t_n$  and  $t_{n+1}$  serve only to synchronize the processes in the model and the real system, while every time the model  $f(t)$  is started, its own time flows inside it. Most often, the  $f(t)$  process is modeled using analytical models, but

conventional simulation models based on the “continuous”, “discrete event” or “agent based” paradigms can be used. Since in the “real-time simulation” mode, the simulation results are transferred to the real object at each step, the model in this case becomes part of the feedback control system.

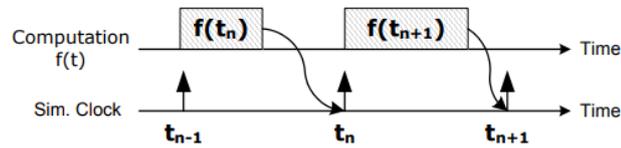


Figure 3.5. Synchronized real-time simulation (Bélanger et al., 2010)

The concept of “real-time simulation” was considered even more broadly in works (Hanisch et al., 2003) and (Hanisch et al., 2005), for which the term “online simulation” was used at that time. Here, the time step  $\Delta t$  is also used for the next model run at the moment  $t_{n-1}$ , but the simulation results do not refer to the next moment of discrete time  $t_n$ , but show the possible development of the state of the real system for a longer time. Thus, “online simulation” can be viewed as a kind of “real-time simulation”, which uses incomplete synchronization of processes in the model and the real system. It remains mandatory to transfer data from the real system to the model at times  $t_{n-1}$ ,  $t_n$  and  $t_{n+1}$ . Simulation results should also appear in the interval  $\Delta t$  before the next moment  $t_n$ , but these results do not have to be immediately transmitted to the real system but can be interpreted by a person or appropriate software.

In (Hanisch et al., 2003), an example is considered when online simulation is used for short-term forecasting of the number of passengers in specific airport premises. The model receives initial data from a real system and runs with a time interval of  $\Delta t=5$  minutes. As a result of each run, the model produces a forecast of the development of the “Pedestrians in Storage j” indicator for the next 30 minutes (Figure 3.6). The “threshold” line denotes the critical number of passengers in room j. If there is a danger of reaching this value, then the system must take specific measures to prevent this from happening. It is quite clear that the real model produces results for all controlled areas of the airport.

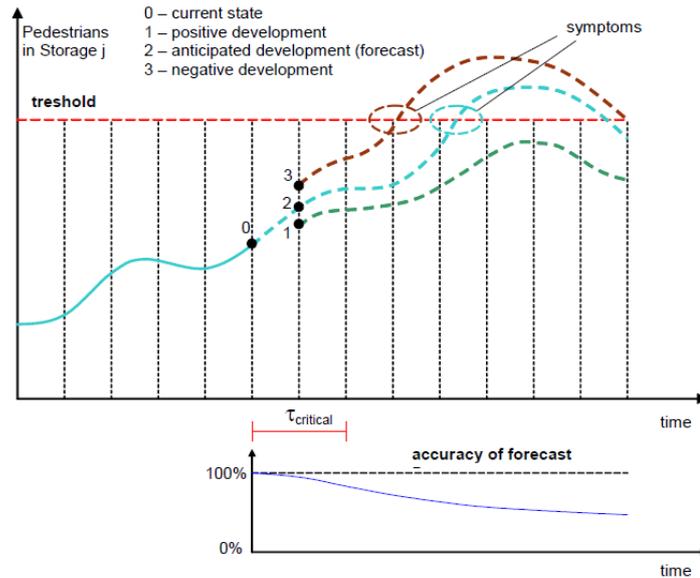


Figure 3.6. Process forecasting in online simulation (Hanisch et al., 2003)

The fully developed idea of using online simulation to predict and eliminate dangerous situations is illustrated in Figure 3.7. Cycle refers to the  $\Delta t$  step described above. During this time, information is updated in the four drives shown in Figure 3.7. The concept shown here emerged during the development of a project to build an early warning system to control passenger flows at a major airport in Germany, so communication with existing airport information systems was used to update the information in the accumulators.

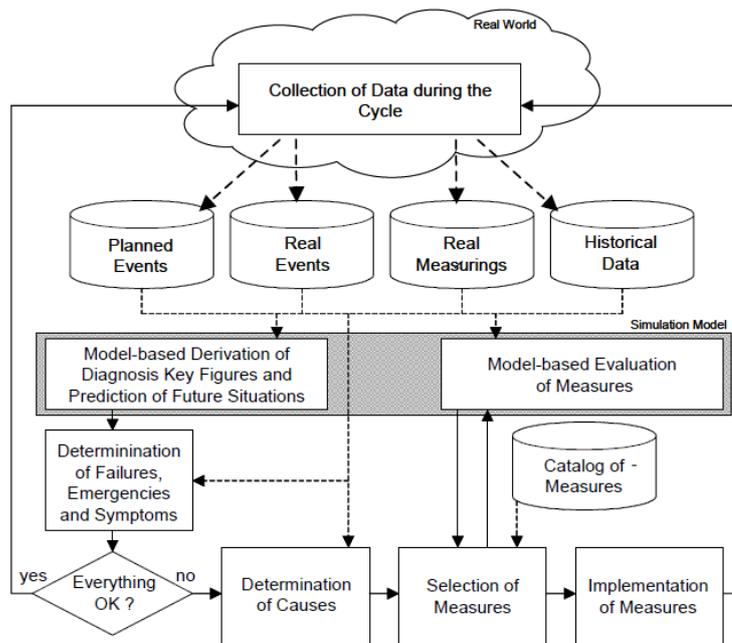


Figure 3.7. Online simulation based Decision Support System (Hanisch et al., 2003)

The Planed Events drive receives information about all the nearest arrivals and departures of the aircraft, indicating the number of passengers. Information about the arrival of the aircraft may arrive approximately 0.5 hours before this event, and information about the departure of the aircraft arrives much earlier, since passengers can arrive at the airport 2-3 hours before departure. The Real Events drive receives information about the arrivals or departures of the aircraft. In the first case, it becomes known how many passengers will appear in the arrival area a few minutes after the aircraft has landed. In the second case, it becomes known that the waiting area in front of the corresponding boarding gate has been completely vacated. The Real Measurements drive receives information from the automatic passenger flow control system in the airport premises. The system uses various optical sensors to count passengers crossing measurement lines near doors and escalators. With the help of TV cameras and image processing programs, the number of passengers simultaneously present in the controlled premises is estimated. The data in the Historical Data accumulator can be updated relatively infrequently, that is, not even every day. They are based on the results of processing statistics on passenger flows for the previous weeks. For example, the accumulator may have hourly statistics available for the current day of the week that were obtained for the same day, but a week earlier. Statistics for the previous day, as a rule, are of no value since the flight schedule is tied to the days of the week.

The simulation model can perform two functions in the system shown in Figure 3.7. The first function is to run the model regularly (for example, every 5 minutes) and produce short-term forecast results, as shown in Figure 3.6. If the Decision Support System (DSS) detects no hazards, then the model “rests” until the next cycle begins. Otherwise, the DSS must decide on measures to improve the situation. This can happen both without using a model, and with its use. In the second case, a fast-working model will allow to evaluate and compare several options for the development of the process, which correspond to the options for the decisions made.

The online simulation-based system considered above deserves special attention, since in fact it is an example of a digital twin (DT), which not only collects information from a real object, but also implements the use of this information to regularly run a simulation model. Moreover, the simulation results are applied to control the object using DSS. This example once again shows the feasibility of separating the functions of the “real” DT from the functions associated with the use of the data it provides. In fact, the “real” DT in the considered system is what is shown in the upper part of Figure 3.7, that is, the “Collection of Data” block and four types of accumulators, which together form a dynamic database.

As the examples discussed above suggest, the main uses of the information provided by the DT are as follows:

- passive monitoring of the state of the object, when information is recorded on electronic media or provided to the user in the form of text messages, tables, diagrams and static graphics;
- passive monitoring of the state of the object, when information is provided to the user in the form of 2D or 3D animation;
- direct use of information in a closed-loop real-time control system;
- use of information within the framework of DSS, when a person makes decisions on managing an object;
- using information as initial data of a simulation model, with the help of which a short-term forecast of the object's behavior is carried out.

Of course, combinations are possible when information from DT is simultaneously used in different ways.

### 3.4. Modeling the spatial location of moving objects

The main feature of the motion model of objects is the need to take into account their relative position in 2D-space. In this case, the real shape and size of each object must be taken into account, since one of the main tasks of the controller is to prevent collisions of both moving objects with each other and moving objects with fixed obstacles. A direct way to solve this problem is to represent the shape of a moving or stationary object in the form of a polygon (Figure 3.8). Then it becomes necessary to check the condition of intersection of all polygons displaying moving objects with their neighboring objects or nearby obstacles. Such a check in the model should be carried out with a time interval of the order of 0.1 seconds, since at a speed of 30-40 km/h during this time the object can travel a distance of about 1 meter. The problem of checking the condition of intersection of two polygons can be solved by geometric modeling methods, but this problem will have to be solved 600 times during each minute of model time, which, with dozens of interacting objects, will lead to a noticeable slowdown in the operation of the modeling program.

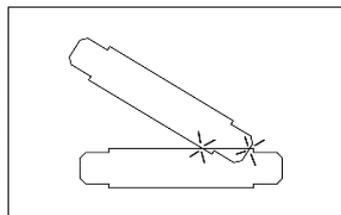


Figure 3.8. Objects collision detection represented by polygons

The second feature of the model of the movement of objects is the need to take into account the accelerations and associated changes in the speed of movement of objects. It is quite understandable that the processes of acceleration and deceleration of aircraft will differ from those observed in land vehicles. It is important to note that such processes can arise both at the initiative of drivers and in response to commands from an automatic controller. Figure 3.9 shows the results of measuring the speed of 10 aircraft on one specific taxiway for 180 seconds (Mazur and Schreckenberg, 2018). It can be seen that speeds vary over a wide range, e.g., from 6 to 10 m/s.

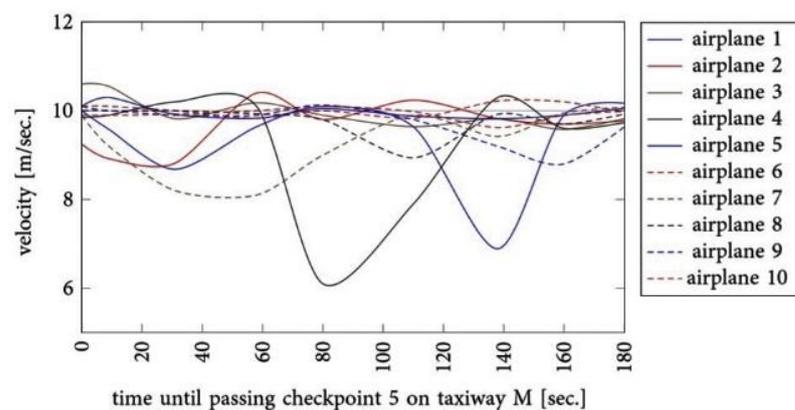


Figure 3.9. Speed-time plot of 10 airplanes taxiing on taxiway (Mazur and Schreckenberg, 2018)

In commercial road traffic simulation software, for example, in the PTV Vissim package, the movement of objects is carried out mainly along dedicated lanes, that is, in mathematical terms, the models are one-dimensional, since they only take into account the distance between the following other cars. Models based on Cellular Automata are also one-dimensional (Mazur and Schreckenberg, 2018). Models of traffic flows use the principles of local control, when for each car at the step “delta T” a new speed value is determined depending on the speed of the vehicle in front and the distance to it. Since the standard methods of modeling traffic flows do not allow solving the problem of modeling in 2D space, it becomes necessary to consider other areas of application of modeling to study the interaction of controlled moving objects.

Since the beginning of the 90s, transport systems based on Automated Guided Vehicles (AGVs) have been used in production and logistics. Most often, such systems are modeled under the assumption that individual vehicles move along fixed sections of the path that together make up the transport network. The central control system usually assigns to each vehicle only the route and then does not control its position during the trip. Conflicts that may arise between vehicles are resolved by means of local control systems that are installed on the vehicles

themselves. A typical example of a model created with the Plant Simulation package based on the “discrete event” paradigm can be found in (Selmair et al., 2019).

For this work, of interest are examples in which systems with multiple free navigating AGVs are modeled. A serious study is master thesis (de Groot, 1997), in which moving objects and obstacles are described using polygons, and the “delta T” principle is used to display the dynamics of the process. To predict collisions of objects, the above geometric model is used (see Figure 3.8). The simulation model is implemented using the Python programming language. An example of simulating a scenario involving 10 AGVs is shown in Figure 3.10.

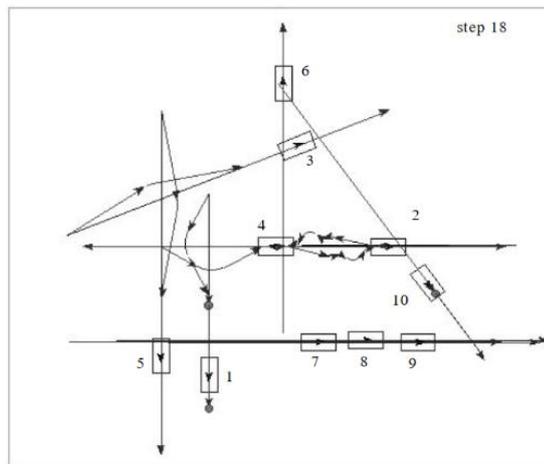


Figure 3.10. A simulation test with 10 AGVs (de Groot, 1997)

A simulation model of a system with free navigating AGVs can also be found in (Berman et al., 2003). It focuses on the local management of individual AGVs in order to avoid collisions between AGVs and obstacles (Figure 3.11). The simulation model is implemented using the Visual C++ programming language.

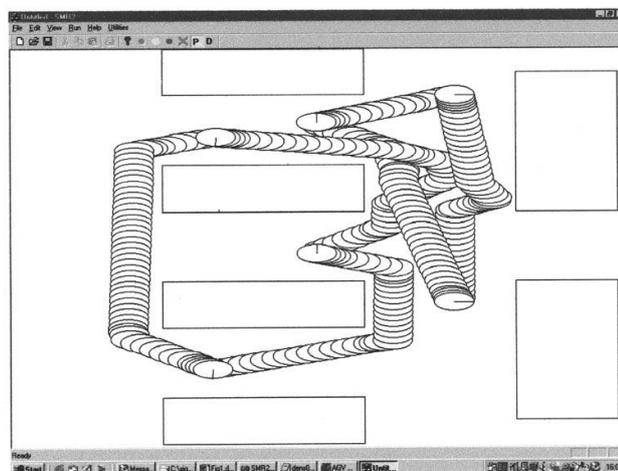


Figure 3.11. A simulation test with 6 AGVs (Berman et al., 2003)

From the examples considered, it follows that the interaction of objects of the AGV type in free 2D space is modeled by specialists using General-Purpose Programming Language.

### **3.5. Stating of requirements for the model of transport processes at the airport and the choice of a modeling method**

The main requirements for the developed model follow from the immediate and future goals of its application for training and testing programs for centralized ground movement control at airports. The model should be universal, that is, it should provide opportunities for mapping the topology of the transport network of any airport. As the first, the problem of modeling the continuous movement of aircraft and ground vehicles in accordance with user-defined scenarios should be solved. The model should provide the user with means for describing such scenarios and means for visual control of their implementation in the form of computer animation. The main result of the first stage of applying the model should be data streams with coordinates of moving objects that are participants in the simulated scenarios. The data streams generated by the model should be similar in content and format to those that can come from real measuring equipment installed at the airport or on board vehicles.

The choice of a method for modeling processes in the ground transport network of an airport consists in solving the following problems:

- it is necessary to analyze the options based on a discrete and continuous approach to displaying the time of the model and the state of its elements, and decide on the type of paradigm for modeling processes;
- in connection with the difficulties of analyzing the relative position of moving objects in continuous 2D space, it is necessary to formulate the principle of double representation of space, in which, in parallel with the coordinates  $(x, y)$ , the coordinates of the cells  $[i, j]$  of a grid space can be used;
- it is necessary to formulate the fundamental features of the created model, which should be taken into account by the programmer who implements the model on a computer, and on this basis make a decision about a specific tool that will be used at the stage of programming the model.

#### **3.5.1. Choice of airport transportation process modeling paradigm**

The task of choice and correctly denoting the modeling paradigm is far from trivial. As will be shown below, it is almost impossible to uniquely choose one of the process modeling paradigms from the list of “continuous”, “discrete event” and “agent based” (Borshchev, 2013) to solve the problem posed.

After the work of G.W.F. Hegel “Science of Logic” (German: “Wissenschaft der Logik”), which was published between 1812 and 1816, almost no one wrote serious papers about the very concept of “discrete quantity” or about the inextricable connection between the concepts of “discrete quantity” and “continuous value”. Of course, in mathematics there is a clear definition of a **discrete variable** that can only take on certain values. For example, a variable that can only take integer values is discrete because it cannot take fractional values. But the concepts of **discrete and continuous time** are much less definite. Time is considered discrete if a discrete variable is used to display it in the model. The processes taking place in discrete time conditions are described by finite-difference equations. Unlike models with discrete time, in models where time is considered a continuous variable, the processes are described by differential equations. It follows from these definitions that when solving differential equations, continuous time can be observed only in analog computers, and in models on digital computers, only discrete time is used.

A lot of chaos is still observed when defining the concepts of **discrete and continuous modeling**. Many authors and practitioners believe that “discrete event” modeling has this name because the events in the model occur at “discrete time moments”. It should be noted that this concept does not make sense at all, since any fixed (recorded) moment in time can be considered discrete. The concept of “discrete event” is not based on the way time is displayed in the model, but on the way changes in the state variables of the model are displayed. The main thing here is the fact that at certain points in time the values of the state variables change instantly, which is called an event in models of this type. In models of the “discrete event” type, events most often can occur at any moment in time, and therefore such a time should be called **continuous**, since no precisely defined values are predetermined for it. Of course, discrete event models can also use **discrete** time, when its values are calculated using a given step “delta T”. In this case, it would be correct to say that the events in the model occur at “moments of discrete time”.

The behavior of the variables  $t$  (model time) and  $S$  (state variable) should be clearly defined for each model. Both variables can be either continuous or discrete. As a result, four basic combinations are formed (Figure 3.12). In the case of continuous time, the  $t$  axis shows only random times  $t_1, t_2$ , etc., when events occur in the model. In the case of discrete time, all time stamps are shown in “delta T” steps. An indication that the variable  $S$  is discrete is the marks on the coordinate axis  $S(t)$ . In their absence, the variable  $S$  is continuous, that is, it can take any unlimited values.

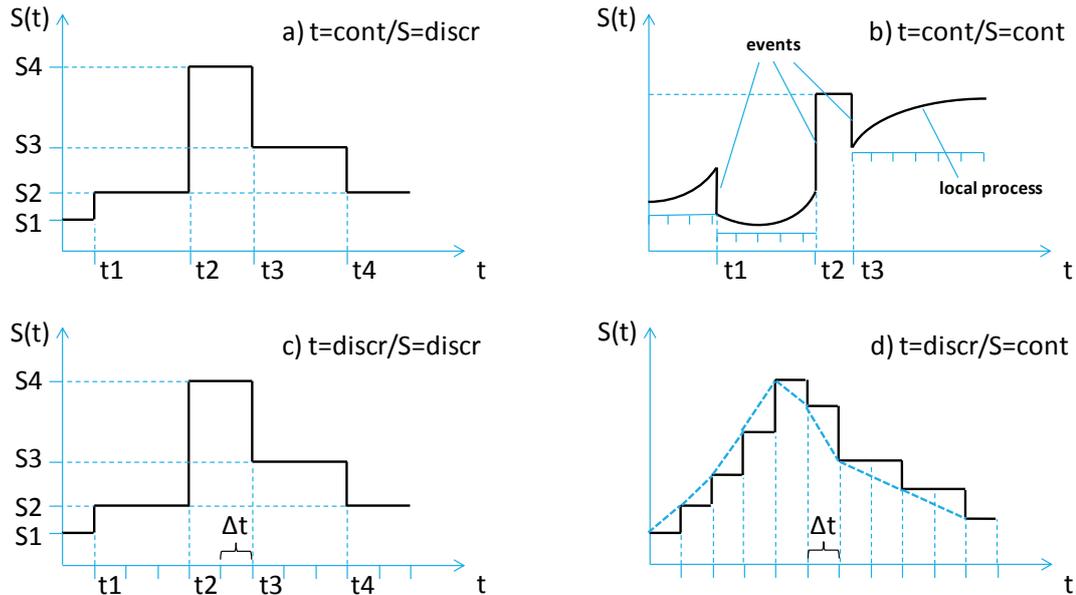


Figure 3.12. Four types of processes based on a combination of “time/state” features

- a) ***t is continuous, S is discrete***. Most often, this scheme appears when using the “discrete event” paradigm for modeling queuing systems. For a service station, the states “free” and “busy” are displayed in the model. The number of occupied seats in the queue is displayed as a non-negative integer.
- b) ***t is continuous, S is continuous***. This scheme is found in hybrid models, when the main process is modeled on the basis of the “discrete event” paradigm, but in some time periods it is modeled as continuous. For example, the number of passengers in a certain waiting lounge changes abruptly upon arrival or departure of an aircraft, but then it slowly changes over time. If there are no continuous processes in the model, this scheme becomes similar to scheme *a*, that is, it corresponds to the “discrete event” paradigm, when as a result of an event the variable  $S(t)$  can change in an arbitrary way. An example is the receipt or dispatch of a batch of bulk cargo, the quantity of which is measured in tons.
- c) ***t is discrete, S is discrete***. Scheme *a* obtains this form if events in the model can occur only at moments of discrete time. The model can be of the queuing system type, but events in the system must occur strictly regularly. An example is the operation of a warehouse area where vehicles unload or pick up a certain number of pallets only at even hour. At small values of “delta T” on the basis of this principle, it is possible to build time management mechanisms in any models using the “discrete event” paradigm.
- d) ***t is discrete, S is continuous***. All changes in such models occur at discrete time instants. This diagram is basic for models using the System Dynamics concept. When modeling

business processes, the step size “delta T” is chosen such that the dynamics of the modeled process is displayed in accordance with the goals of the simulation study. Typical values for “delta T” are day, week, month, or year. When simulating physical processes, the “delta T” value directly affects the accuracy of solving the corresponding difference equations. At small values of “delta T” the accuracy of the solution increases, but the number of steps in modeling a specific process should be limited by the allowable time of the computer.

The geometrical problems of modeling the movement of objects in 2D space were noted above, as well as the nature of the change in speed of the aircraft when they move on taxiway (Figure 3.9). Already these two factors indicate the need to frequently repeat the calculation of the instantaneous velocity and coordinates (x, y) of moving objects, i.e, to use discrete time with a small value of “delta T” in the model. The need for such a solution is also associated with the fact that in the future a real automatic controller will have to receive information about the current state of all traffic participants also several times per second. Thus, in relation to the time of the model, the decision is made: *t is discrete*. Since the coordinates (x, y) of moving objects will most often be displayed as state variables, the decision is made with respect to the state variable *S*: *S is continuous*.

Although the chosen paradigm of modeling processes in the airport transport network refers to type *d* (see Figure 3.12d), the term System Dynamics cannot be applied to it, because such an important category of System Dynamics as Causal Loop Diagram (Sterman, 2000) will not be used when developing models of transport processes at the physical level. Thus, the standard terms “continuous”, “System Dynamics”, “discrete event” and “agent based” cannot be used to unambiguously define the chosen paradigm of process modeling. Only a couple of signs “*t is discrete, S is continuous*” forms such a definition.

### **3.5.2. Application of 2D grid space**

In all the models described above, a continuous 2D space was used, the position of each point in which is described by a pair of coordinates (x, y). It was in such a space that, in particular, the rather difficult task of identifying the intersection of graphic images of objects described using polygons was solved. This space can be additionally divided into cells with coordinates [i, j], where i and j are row and column numbers, respectively. For example, in MS Excel worksheets, the x direction is the j direction, and the y direction is the i direction. If the dimensions are assigned to a cell, e.g. 2x2 meters, then the following transformation of

coordinates is trivial:  $(10.7; 15.3) \rightarrow [8; 6]$ . Since for each point with coordinates  $(x, y)$  the coordinates of the cell  $[i, j]$ , in which it is located, are known, many tasks of controlling the movement of objects can be reduced to checking the belonging of the points of the object to the corresponding cells. For example, two polygons are not in a state of intersection if they have no common cell. The accuracy of taking into account the real distances between points depends on the size of the cell  $d$ . Figure 3.13 shows that two points  $p_1$  and  $p_2$  will be in different cells both in the case of  $\{p_1^1, p_2^1\}$ , and in the case of  $\{p_1^2, p_2^2\}$ . Since the distance between the centers of the cells is equal to  $d\sqrt{2}$ , in both cases the maximum error in interpreting the position of the points will be equal to this value. For example, with  $d=2$  meters, this error will be 2.83 meters. Since the accuracy of technical systems for determining the location of mobile objects rarely exceeds this value, such accuracy can be considered sufficient, for example, when simulating the movement of vehicles on an airfield field. In the case of a higher accuracy of determining the coordinates of objects, the value of  $d$  can be reduced, for example, to 1 meter.

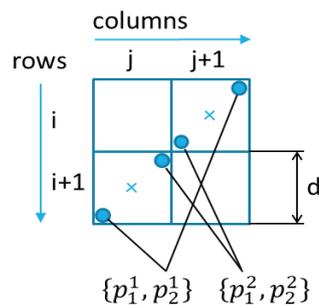


Figure 3.13. Limit variations on the location of points in neighbouring cells

In (Szlapczynski, 2006) describes the use of 2D grid space, which the author calls “raster grids”. The model reflects the process of maneuvering ships in the port water area, where there is a danger of their collision with each other or with port facilities. It should be noted that the concept of grid-based space is widely used in modeling processes occurring in certain geographic areas. Most often, such processes belong to the class of very slow ones, for example, the processes of development of urban areas. There are models that have been created to investigate relatively fast processes such as floods or fires. In (Mazzoleni et al., 2006) reported on the development of a general-purpose software package that created ecological models such as animal distribution, fire propagation, seed dispersal, different models for simulation of vegetation dynamics. The bulk of the package has been implemented in Visual Basic (VB6) using ActiveX and COM components. The article by (Taillandier et al., 2016) discusses how to improve the accuracy of raster models by adding objects represented using vector models to them.

The efficiency of the decision to represent the location of moving objects in two ways simultaneously based on continuous coordinates  $(x, y)$  and cell coordinates  $[i, j]$  should be checked in the model of the airport transport network being created.

### 3.5.3. Selected method of model implementation

The examples of modeling considered above, which have at least some properties that are like the properties of the formulated problem of modeling transport processes on the airfield, indicate that such problems can be solved only with the help of general-purpose programming languages. All types of commercial simulation software (airport simulation software, road traffic simulation software and general-purpose simulation software) considered in this chapter, for various reasons, do not provide the conditions for the implementation of all the formulated requirements for the model. The following describes fundamental solutions for modelling the movement of objects with a focus on the use of general-purpose programming languages.

1. Moving objects and obstacles are in 2D space, which uses both continuous coordinates  $(x, y)$  and cell coordinates  $[i, j]$ .
2. Each moving or stationary object is described using a convex polygon, the points of which can be located in several cells of discrete space.
3. One of the points of the moving object is declared as a reference. The current position of the object is determined by the coordinates of the reference point  $(x_{ref}, y_{ref})$  and the rotation angle  $\alpha$  relative to the north direction.
4. It is agreed that there are eight discrete directions of orientation of moving objects, i. e.  $\alpha \in \{N, NE, E, SE, S, SW, W, NW\}$ .
5. For each class of movable objects, eight graphic models are created that display the location of the occupied cells at the specified coordinates  $(x_{ref}, y_{ref})$  and rotation angle  $\alpha$  (Figure 3.14).

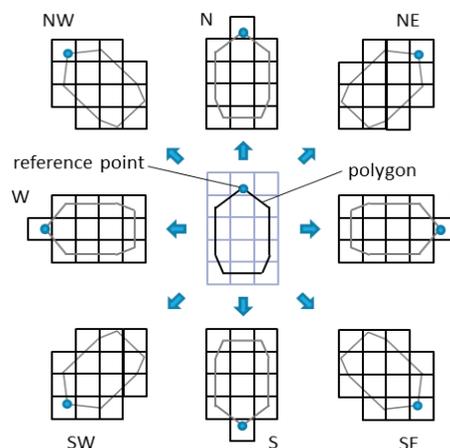


Figure 3.14. Eight graphic models of a moving object

6. The real trajectory of the  $R_{real}$  object is replaced with a sequence of cells according to Bresenham's line algorithm. The simulated path  $R_{sim}$  passes through the center points of the cells that this path is composed of (Figure 3.15). At any time, the reference point  $p_{ref}$  can be at any point on the path  $R_{sim}$ , depending on the distance traveled, and its position is determined by continuous coordinates (x, y).

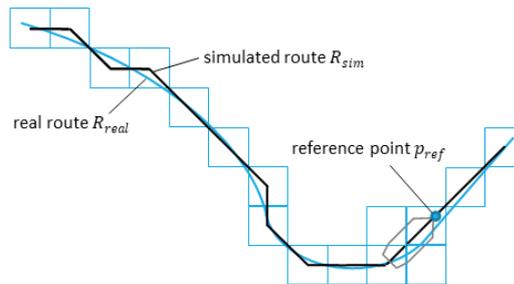


Figure 3.15. The replacement of real route with a sequence of cells

All the above-described features of the simulation model of processes in the airport transport network can be implemented using the VBA programming language in the MS Excel environment. The main advantages of this solution are as follows:

- the model will have an open-source code, which will allow the user to make any changes to it related to its functionality or information input/output operations;
- the model will have completely open data, that is, it will make it possible using MS Excel tables to control any input data, current values of model variables and simulation results;
- animation of processes in 2D space will be implemented in the model, since visual information is necessary for the user of the model to assess the simulated situations and make management decisions;
- the model will be universal, i. e. the user will be able to customize it to simulate processes at any airport without changing the program code by using only MS Excel graphical objects and tables.

The next chapter describes the stages of creating and using the GTSS (Ground Traffic Scenario Simulation) program, which implements all the properties of a model formulated above, focused on conducting experiments related to centralized control of ground transportation at airports.

### 3.6. Conclusions

Based on the analysis of the material discussed in this chapter, the following conclusions can be drawn:

- The most effective tools for modeling and researching algorithms for managing transport processes at airports are created by using general-purpose programming languages.
- An effective method of developing and testing control programs is the use of simulation models in emulation mode. In this mode, the control object is replaced by a model that interacts with a real control program. This means that the model generates measurement information, the control program processes this information and transfers control commands to the model.
- The DT concept begins with real-time data acquisition from the physical master. Any digital models that do not work in this mode are not related to the DT, but if they are connected to an object, they become part of the DT. Most modern authors ignore in their publications the fact that the DT concept is the result of the development of modeling techniques called “real-time simulation” and “online simulation”, in which a simulation model exchanges data with a real physical object.
- The established tradition of attributing the paradigm of process modeling to one of three classes named “continuous”, “discrete event” or “agent based” does not make it possible to reflect all the features of the applied modeling principle. It is necessary to separately indicate the ways of displaying both the time in the model and the state of the model elements.
- When developing our own tool for modeling processes in the airport transport network, a paradigm was formulated that is most like the “continuous” paradigm, but at the same time has specific features, the existence of which is not associated with the general idea of the “continuous” paradigm. Along with the usual concept of discrete time, it is proposed to use a dual way of representing 2D space, which takes into account both the continuous coordinates of objects  $(x, y)$  and their position in the grid space with the coordinates of the cells  $[i, j]$ .
- The second feature of the developed paradigm of process modeling is that the behavior of each object in the model is determined not only by general rules, but also by precise instructions relating only to it. This type of simulation is called a “scenario-based simulation”.

#### 4. DIGITAL TWIN APPLICATION CONCEPT DEVELOPMENT AND SCENARIO SIMULATION IN THE AIRPORT TRANSPORT NETWORK

The GTSS program was developed to simulate scenarios in the airport transport network. In fact, this program is a small universal package for simulation of processes in the transport network of the airport, but the designation “package” does not apply to it, since it is a laboratory tool that lacks some of the service functions typical of commercial simulation packages. Further, the difference between the GTSS program and the specific model that was created using this program should be clearly understood. Although the model depicts the ground transport network of a real airport, the model is called a demonstration model, since it serves to explain the principles of operation and the possibilities of using the GTSS program.

The models created with the GTSS program can be applied at various stages of software development for the centralized control of ground transport processes at the airport. The first part of this chapter identifies four stages of this process, and for each of them, the principles of applying the simulation model and the associated Digital Twin are discussed. The following describes all the major conceptual decisions that underlie the implementation of the GTSS program. These include the use of the Digital Twin, as well as time and space discretisation techniques. A separate part of the chapter is devoted to the development and verification of the demo model. The last part of the chapter describes a simulation experiment in which this model was used to simulate a user-defined scenario that leads to critical situations and the need to make management decisions. The processes occurring within the studied scenarios are recorded in the form of protocols, which together constitute the content of the Digital Twin.

##### 4.1. Ways to use simulation model and DT together

Figure 4.1 shows the four stages of the software development process for a centralized ground traffic control system at an airport. Table 4.1 explains the components of the structure shown in Figure 4.1 and the information links between them.

At the **data collection** stage, the user creates typical scenarios for the emergence of critical situations in the airport transport network, enters scenario descriptions into the model and, using animation, and observes their implementation. Debugged scenarios are recorded in the DT in the form of state protocols of the traffic participants. A set of such scenarios is prepared for use at the training stage of the automatic control system.

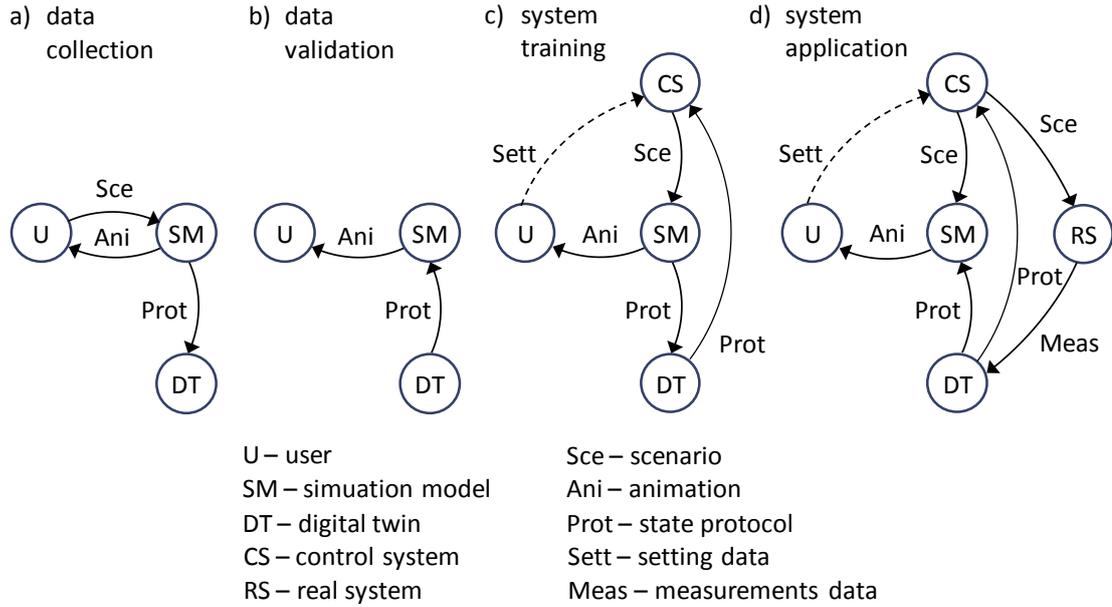


Figure 4.1. Application of the simulation model and the Digital Twin at various stages of development of the automatic control system

Table 4.1. Meaning of structure elements shown in Figure 4.1

Legend in Figure 4.1	Comment
<i>Structure components</i>	
U – user	The user of the model is an airport ground transportation expert.
SM – simulation model	A simulation model is a computer program created with GTSS or other airport ground traffic simulation tool.
DT – digital twin	DT is a dynamic database that is part of a model created with GTSS, or a stand-alone database like MS Access.
CS – control system	A control system means software that performs the functions of automatic control of ground traffic at an airport.
RS – real system	Real system refers to a managed ground transport network at a specific airport.
<i>Informational links</i>	
Sce – scenario	Scenario is a set of directions for individual traffic participants in the ground transport network with new route content.
Ani – animation	Animation refers to the dynamic visualization of processes in a model or a real transport network.
Prot – protocol	Protocol is a sequence of records about the state of participants in the movement, tied to the moments of discrete time $\Delta t$ .
Sett – settings data	Settings data is expert information from the user that is used in training or maintaining an automatic control system.
Meas – measurements data	Measurements data is a stream of information about the current location and status of traffic participants, which comes from on-board and aerodrome technical means.

At the stage of **data validation**, the ability of the model to reproduce a given process in the transport network of the airport is used not only based on a scenario, but also on the basis of a protocol of states of traffic participants. Each protocol is processed by a model, and the user has the ability to check the correctness of the reproduced process using animation.

At the stage of **system training**, work begins with a real control program. The first task of the control system is to recognize critical situations, which, in the form of previously prepared state protocols, come from the DT to the input of the control system. The control system issues commands to participants in the movement in the form of scenarios, which are processed by the model and evaluated by the user by the means animation. The user acts as a teacher and interacts with the control program by transferring expert information to it. If  $SM \rightarrow DT$  communication is used and DT receives current traffic information in the transport network, the  $CS \rightarrow SM \rightarrow DT \rightarrow CS$  system becomes closed. This means that the model and the control system interact in emulation mode (see Section 3.2).

At the **system application** stage, the control program is connected to the real transport network of the airport, which is denoted as RS in Figure 4.1d. The main closed-loop control loop is:  $RS \rightarrow DT \rightarrow CS \rightarrow RS$ . Data in the  $RS \rightarrow DT$  direction comes from the measuring equipment in the form of an unsynchronized event protocol, which is called measurements data in Figure 4.1d. This event protocol is converted into a state protocol by means of DT and is fed to the input of the control system, which generates control commands and sends them to the participants in the movement in the RS space. The simulation model can perform auxiliary functions at this stage. For example, it can serve as a means of monitoring real processes by interpreting state protocols received from DT or used for short-term forecasting of the development of processes based on scenarios proposed by the control system (see Section 3.3).

Figure 4.2 reflects the fact that during the development of the automatic control system, each of the interacting components changes according to its own lifecycle and performs specific functions at each stage. Since the main component of the study is the DT, the figure shows only the data observed at the input and output of the DT.

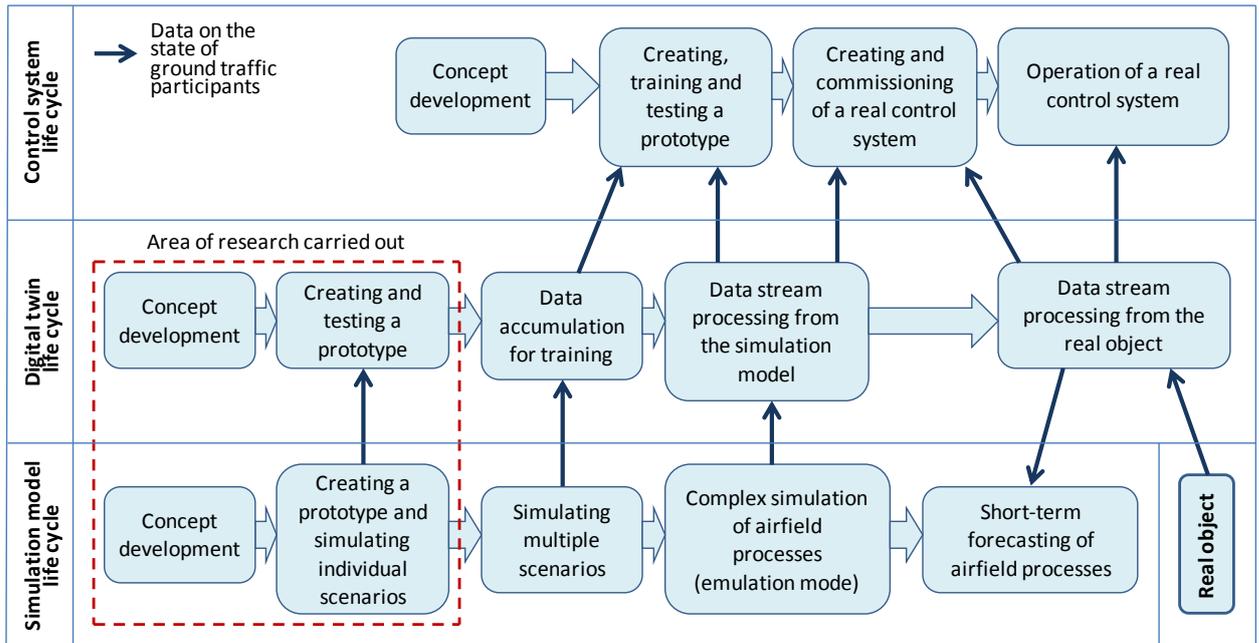


Figure 4.2. Link between the lifecycles of the control system, the digital twin and the simulation model

#### 4.2. The concept of construction and properties of the GTSS program

GTSS allows the construction of simulation models of processes in airport ground transportation systems. The transport system of the airport includes two overlapping transport networks (traffic routes for ground vehicles and aircraft), as well as the mobile objects themselves in the form of ground vehicles (GV) and aircraft (AC). All these elements of the model in the form of graphic objects can be seen in the example shown in Figure 4.3.

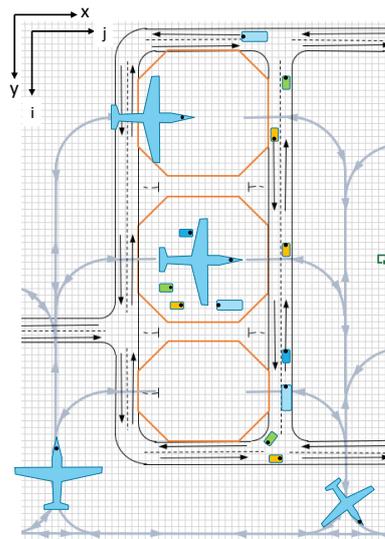


Figure 4.3. Graphical objects of the GTSS program

The main feature of the models built using GTSS is the way to control the movement of moving objects based on the interpretation of the given scenarios. An object entered into the model cannot independently select a route and speed of movement, even if the start and end points of the trip are set for it. This is how the GTSS program differs from conventional programs for modeling transport processes, but this feature of the created models allows achieving the main purpose of their application, which is to develop and debug centralized control systems for the movement of objects in the airport transport network.

#### **4.2.1. The concept of applying DT in the management of the airport transport system**

The focus is on the problem of centralized control of the movement of objects in the transport network of the airport, the essence of which is to recognize and process the so-called critical situations. It is assumed that on-board (local) control systems for mobile objects are not able to both recognize such situations in a timely manner and make such decisions on getting out of them that would be acceptable to all traffic participants. It is also assumed that the centralized control system will not take over the functions of the on-board control systems. Functions such as keeping distance between vehicles or avoiding collisions with obstacles will continue to be performed by on-board control systems.

Figure 4.4 illustrates the basic concept of using DT in a centralized airport transportation system. The main function of DT is to collect and accumulate data on the location and state of mobile objects (GV and AC), as well as provide this data to operators or software applications in a form that allows solving the problems of monitoring and analyzing processes in the airport transport system. Each message received from an object is recorded in the DT as a data record. At the beginning of such a message, there is a time stamp, followed by data on the location and status of the object. While messages from objects can arrive at any time, DT generates data for applications tied to discrete time with a given  $\Delta t$  step. The minimum step size  $\Delta t$  is determined by the speed of the data collection and processing system. The actual step size  $\Delta t$  can be greater than the minimum, but it must provide sufficient accuracy in determining the coordinates of moving objects, the speed of which almost never exceeds 40 km/h. In the experiments described below with the DT model, a step of  $\Delta t=0,2s$  was used.

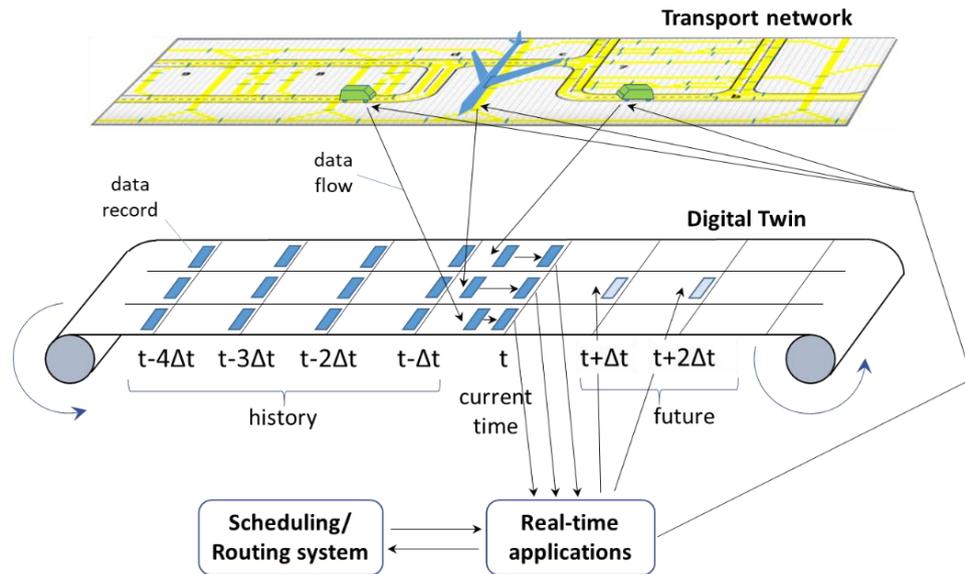


Figure 4.4. The concept of applying DT for control of objects in the transport network

In Figure 4.4, the DT is shown in the form of a dynamic database, which stores data that is related to three time periods:

- to the past time periods  $\Delta t$  (history);
- to the next observed time period  $\Delta t$ , the end of which will be marked as current time  $t$ ;
- to future periods of time (future) in cases where real-time applications include means of short-term forecasting of the behavior of individual objects.

Figure 4.4 shows an example in which messages are received from one AC type object and two GV type objects. Each object has its own “track” for data records. For the current step  $\Delta t$ , it is shown how messages are received in asynchronous mode, but then by means of DT they are brought to time  $t$ . For the AC, two data records are shown, which are the result of predicting its location in the next seconds of the observed process. When a critical situation is detected, the controller program sends commands to mobile objects that are affected by this situation. If in a small airport there are on average 30 objects in motion at the same time and each data record has a volume of 100 bytes, then with a step of  $\Delta t = 0.2s$ , 54 MB of data will be accumulated in DT per hour. If in a large airport there will be not 30, but 300 such objects, then 540 MB per hour in the scale of modern information systems is a negligible number.

#### 4.2.2. Benefits of using discrete time

The analysis of the relative position of objects in the apron zone can be performed only for certain points in time. This means that the coordinates  $(x, y)$  of each object must correspond to the time moment  $t$ , for which the corresponding calculations are performed. Already at the stage of developing the DT concept, one should proceed from the assumption that messages about the

coordinates of objects will come in asynchronous mode, that is, at random times. Synchronous mode can be imagined, for example, in the case when the data comes from surface movement radar (SMR). But even in the presence of such radars, other technical means, located both on board the objects and in the apron zone of the airport, will also be used to determine the location of mobile objects. The flow of data on the location of mobile objects should be redundant, since information loss due to radio interference or hardware failures is possible. In any case, the total data flow will be asynchronous, and the frequency of information arrival from various sources will differ. In such conditions, the binding of data with the coordinates of objects to the moments of discrete time is a prerequisite for using this data to analyze the situation in the airport transport system.

Figure 4.5 shows an example of the correction of coordinates  $(x, y)$  for moving objects Obj1 and Obj2 in the transition from real time to discrete. The calculated coordinate value is obtained by linear extrapolation of the last two measurements. Between the moments  $(t - 2\Delta t)$  and  $(t - \Delta t)$  the object Obj1 did not change its location. In the time interval between the moments  $(t - 3\Delta t)$  and  $(t - 2\Delta t)$ , the measurement data for the object Obj2 were not received and therefore its coordinates for the moment in time  $(t - 2\Delta t)$  were calculated under the assumption that the object retains its speed and direction of movement.

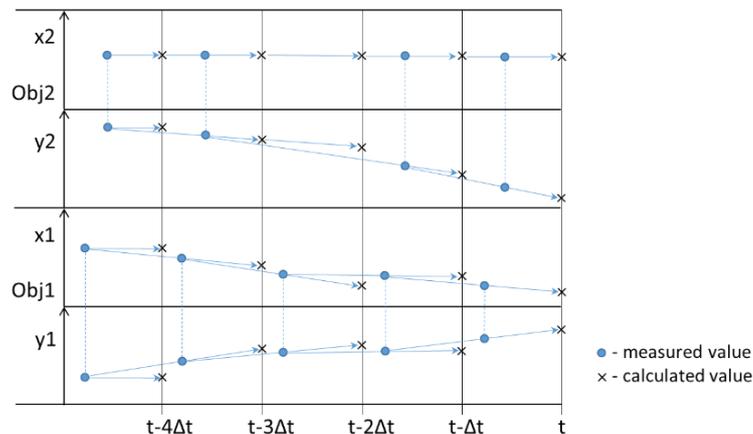


Figure 4.5. Correction of coordinates  $(x, y)$  when transition from real time to discrete

The primary data obtained from means of measuring the location of objects within the framework of this study is called the Event Protocol, and the data tied to discrete time is called the State Protocol (Saifutdinov et al., 2021). The transition from real time to discrete time within a DT means that the Event Protocol is converted into a State Protocol. Figure 4.6 shows an example of such a transformation for the case of three moving objects and three moments of discrete time with an interval  $\Delta t=0,2s$ .

Event protocol			
real-time stamp	object name	X-coordinate (m)	Y-coordinate (m)
10:45:11.82	GV2_2	573,60	315,12
10:45:11.83	AC2_1	525,60	376,68
10:45:11.85	GV2_3	679,95	377,55
10:45:12.00	GV2_2	573,60	318,54
10:45:12.03	AC2_1	525,60	375,46
10:45:12.04	GV2_3	679,46	376,30
10:45:12.23	GV2_3	679,20	372,85
10:45:12.24	AC2_1	525,60	372,24
10:45:12.25	GV2_2	573,60	320,49



State protocol								
discrete time	object name	X-coordinate (m)	Y-coordinate (m)	location	speed (m/s)	direction ID	target	priority
10:45:12.00	GV2_2	573,6	318,5	GV108	5	S	GV51	1
10:45:12.00	GV2_3	679,5	377,1	GV28	4	NW	GV51	1
10:45:12.00	AC2_1	525,6	376,0	AC197	4	N	AC218	1
10:45:12.20	GV2_2	573,6	319,5	GV108	5	S	GV51	1
10:45:12.20	GV2_3	679,2	373,0	GV29	5	N	GV51	1
10:45:12.20	AC2_1	525,6	372,4	AC197	4	N	AC218	1
10:45:12.40	GV2_2	573,6	323,3	GV108	5	S	GV51	1
10:45:12.40	GV2_3	679,2	372,0	GV29	5	N	GV51	1
10:45:12.40	AC2_1	525,6	371,6	AC197	4	N	AC218	1

Figure 4.6. Converting Event Protocol to State Protocol

The Event Protocol is shown in its most compact form when it only contains object identifiers and their coordinates (x, y). When creating a State Protocol, not only the coordinates (x, y) are corrected, but also other additional parameters are defined, for example:

- by comparing the coordinates (x, y) with the airport map, the name of the section of the transport network or other territory of the apron zone, where the moving object is located, is determined;
- by processing the results of several measurements of coordinates (x, y), the speed of the moving object and the direction of its movement are determined;
- as an option, any attributes of the moving object stored in the Scheduling/Routing system can be recorded, for example, the destination of the trip and the priority.

As mentioned above, it is the data from the State Protocol that are used both to analyze the current situation in the airport transport system and to obtain statistics or short-term forecasting of the development of processes.

#### 4.2.3. Benefits of using discrete space

The advantages that appear in the procedures for analyzing situations in a transport network as a result of space discretization are most conveniently explained by the example of solutions used in the GTSS (Ground Traffic Scenario Simulation) model described below (Saifutdinov and Tolujevs, 2020). The analyzed 2D space of the transport network is presented in the form of a grid-based space and is divided into cells with a side of 2m. Figure 4.7 explains the way of graphical representation and coding of network sections intended for the movement of AC or GV. It is assumed that objects can move in eight directions, i.e. horizontally, vertically

and at an angle of  $45^\circ$ . Section S2 starts at cell A and ends at cell B. When coding sections, the condition is that the previous section ends at the start cell of the next section associated with it. This means that cell A is the end point for section S1, and cell B is the end point for sections S2, S3 and S7. At the same time, cell B is the starting point for sections S4, S5 and S6. The serial numbers of the cells of the section correspond to the direction of movement of objects along this section.

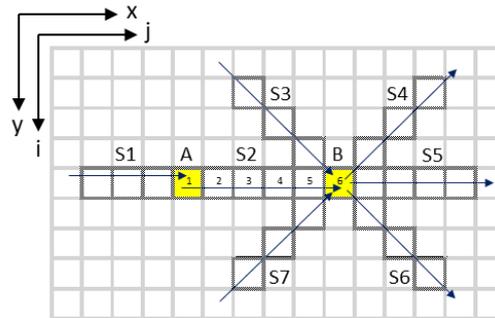


Figure 4.7. Method of graphic representation and coding of sections of the transport network

Figure 4.8 shows the result of applying this method of describing the transport network in MS Excel for a specific airport. Short strokes in the figure mark the boundaries of the sections. Each section can be of any length and shape. Sections can overlap, that is, any cell can belong to several sections. When coding a section, an arbitrary name is assigned to it. In Figure 4.6 it can be seen that in the position “location” the letters “GV” are used in the names of the sections along which the GV move, and the letters “AC” are used in the names of the sections along which the AC move. The network sections can be coded in any sequence independently of each other. To encode one section in MS Excel, it is enough to assign color and serial numbers to its cells. The corresponding program will transfer the following data about each cell to the table: its coordinates  $[i, j]$  in the Excel table, graphic coordinates  $(x, y)$  in points for the lower left corner of the cell, the transition length between the centers of neighboring cells and the code of the direction of this transition, i.e., the value of N, S, W, E, NW, NE, SW or SE.

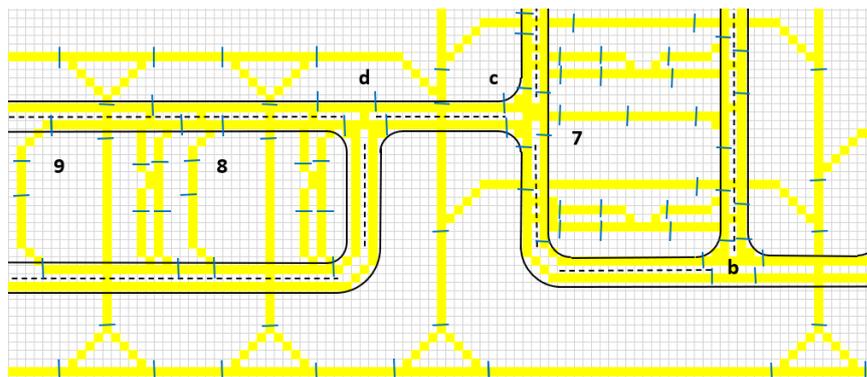


Figure 4.8. Fragment of the transport network in a grid-based space on a MS Excel worksheet

Although it may seem that this method of describing the transport network will not provide sufficient accuracy when analyzing the relative position of moving objects, the limited accuracy is compensated by the simplicity of the corresponding analysis algorithms. In addition, it should be borne in mind that the centralized control system does not analyze the kinematics of the movement of objects with an accuracy of centimeters, since this is the task of local navigation and control systems. Its main task is to obtain a picture of the location of all moving objects in the apron zone, at least with an accuracy of 3-5 meters, and to predict the occurrence of dangerous situations. Figure 4.9 shows the 2D “shadows” that follow moving objects in the same grid-based space in which the transport network model is located. Such “shadows” act as control areas, which greatly simplifies the task of analyzing the relative position of objects, for example, in comparison with the method of controlling the intersection of polygons. It should be noted that the idea of “shadows” for modeling the collision of moving objects has long been proposed in the field of marine navigation (Davis et al., 1980). The term “ship domain” has become generally accepted in this area. Most modern works on this topic, for example, (Kang et al., 2018), use complex geometric models that will be quite effective when analyzing two or three slowly moving objects. In the case when such problems will have to be solved several times per second for hundreds of objects, the use of such models will require very large computational resources.

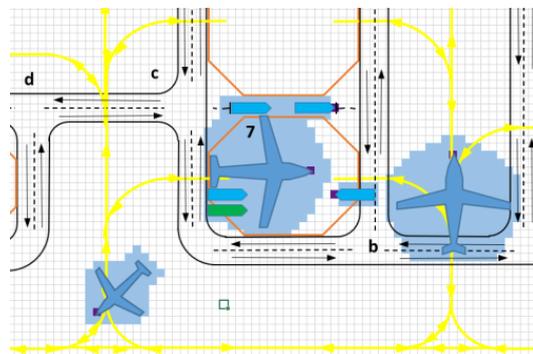


Figure 4.9. Control areas of moving objects

The control areas shown in Figure 4.9 must be manually created for all types of mobile objects that may appear in the airport transport network. It is assumed that in the protocols shown in Figure 4.6 the coordinates  $(x, y)$  refer to the so-called reference points of moving objects, which are marked as black dots in the bow of the objects. Since the State Protocol has a “direction ID” position, it becomes possible to correctly display the cells of the control area of an object when it is located on a section of a transport network or on a free site. The fact of a dangerous approach of objects can be relatively easily established by analyzing the location of the boundary cells of their control areas.

#### **4.2.4. Focused on modeling scenarios and critical situations**

The main feature of the GTSS program is its orientation towards modeling precisely described scenarios of the processes in the airport transport network. Each such scenario describes the behavior of a group of traffic participants, which includes both the GV and the AC (Saifutdinov et al., 2021). As a rule, the scenario has duration of about 5-15 minutes, and with it the user describes in detail which vehicles (AC and GV) are participants in the movement during the simulation time. For each vehicle, the moment of its appearance in the investigated area of the airport is specified, as well as the proposed route of movement with any number of intermediate stop points. The scenario is drawn up in such a way that in the process of its implementation a critical situation arises, in which it is necessary to make decisions at the level of centralized management.

A decision-making or critical situation is a situation in which it becomes necessary to activate the central control of the transport process, that is, to make decisions regarding specific vehicles and send them appropriate commands. A scenario can be called both a primary process, the result of which is the formation of such a situation, and a secondary process that develops after the moment of making decisions. The secondary process can be both positive and negative. It is believed that the secondary process will always be negative if no management commands are generated at the time of decision making. The task of the researcher working with the model is to find solutions that will lead to the development of a positive secondary process.

The procedure for using the GTSS program for modeling and analyzing a specific decision-making situation, as well as its further processing in order to train the control system, includes the following points:

1. Drawing up a verbal description of the chosen decision-making situation.
2. Getting an animated picture of the primary process of forming the required situation.
3. Development of control commands and observation of the animation picture of the secondary process.
4. Analysis of the characteristics of the secondary process. In case of negative or insufficiently positive development of the secondary process, changes are made to it by repeating paragraph 3.
5. Fixing (recording) of the finished scenario in the DT in the form of a state protocol.

The user of the model observes the process in the transport network using computer animation and stops the model at the moment when it is necessary to make decisions and send appropriate commands to the participants in the movement. The entire simulated process of the

emergence of a critical situation is recorded in the GTSS program in the form of DT. Based on the data contained in the DT, an analytical or trainable application in the future will have to automatically recognize a critical situation, as the controller-user does now. Thus, using the GTSS program, it makes no sense to simulate the routine operation of the airport transport network for several hours as a random process, since the model user wants to see only examples of the occurrence of types of critical situations known to him, among which the following can be noted:

- at one of the sections of the transport network there is an obstacle for the passage of vehicles, for example, due to the fall of cargo on the road;
- a priority vehicle appears on the network, which should arrive at its destination as soon as possible;
- a vehicle appears on the network that is out of order and must be evacuated from the place of its stop;
- an unacceptably large congestion of vehicles or even a traffic jam occurs in one or more sections of the transport network;
- the vehicle has failed brakes or steering, as a result of which it moves along a dangerous trajectory.

For the first three types of situations, the recognition problem is not relevant, since all participants in the transport process, including the controller, can learn about it based on the received information messages. Many other situations must be determined by automatic recognition.

The GTSS program makes it possible to simulate the processes that will be observed in the system after making decisions at the level of the central control system. For this, the user of the model changes or creates anew the scenarios of the behavior of traffic participants after the moment of making decisions and continues processing the model using these scenarios. It is quite clear that the continuation of the simulated process is also written in the DT form. If DT is supposed to be used not only for recognizing critical situations, but also for developing control actions, the corresponding decisions of the controller should be recorded in a separate protocol, since only the physical results of the execution of these decisions will be visible in the DT itself.

#### **4.2.5. Features of GTSS programme implementation**

The GTSS program was created in the form of a special laboratory, in which the researcher gets the maximum amount of freedom to experiment with the model of the transport network of a particular airport that he created. The GTSS program is written in the VBA programming

language and is intended for use in the MS Excel environment. The main advantage of this solution is the perfect availability of all kinds of data: model input data, current state parameters of all model elements and simulation results. GTSS implements a continuous animation of the object movement processes in 2D space (Figure 4.3). For this, lists of objects in the form of ShapeRange are created in the model, and their positions on the screen are set using the Left, Top and Rotation properties. The DoEvents function is used to slow down the program.

To provide the ability to simulate quasi-continuous motion of objects in the GTSS program, the time counting method “delta T” is used. The value of this time step can be set using a separate parameter and is usually 0.1 or 0.2 seconds. Along with the discrete way of representing time in the GTSS program, a discrete way of representing space in the form of grid-based space is used. For example, in the model shown in Figure 4.3, the width and height of each cell in the Excel spreadsheet is 2 meters. Simultaneously with continuous coordinates (x, y) in meters, the program uses discrete coordinates [i, j], meaning the numbers of the row and column of the cell. Coordinates (x, y) are used to display in the model the exact location of reference points of moving objects, which can move both along specified paths and in free 2D space. The [i, j] coordinates describe the path configurations for GV and AC. Figure 4.8 shows an example of representing paths in discrete [i, j] space with section boundaries indicated.

The left part of Figure 4.10 shows a fragment of the model created using the GTSS program, and the right part explains the possible ways of exchanging information between the model and its external environment.

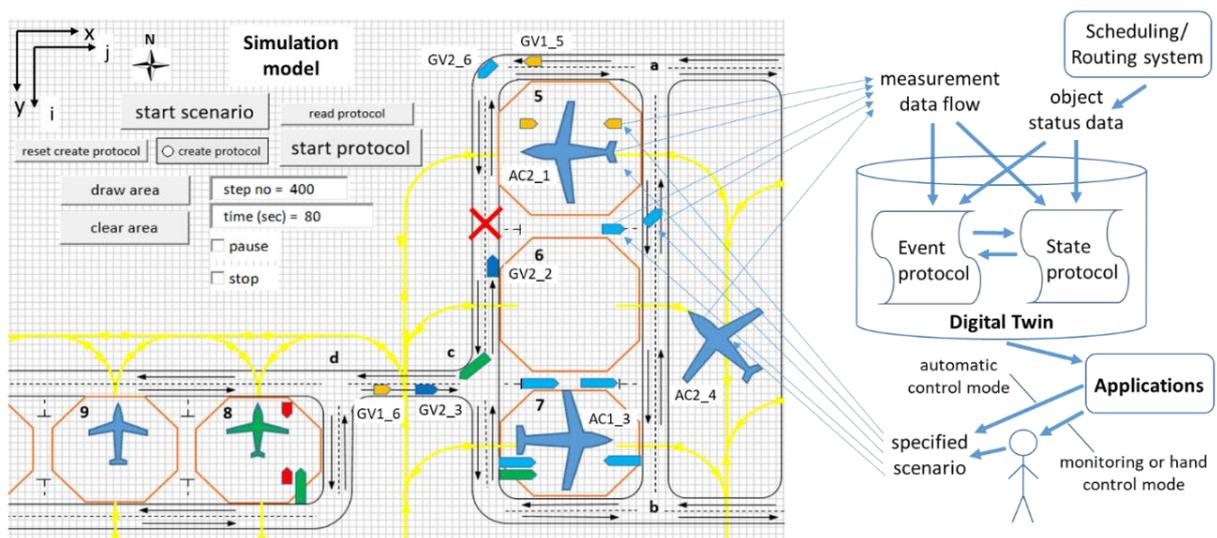


Figure 4.10. Ways of applying a model created with the GTSS program

Figure 4.10 illustrates the two main modes of applying the simulation model. In “hand control” mode, the model user manually describes the movement scenario of a specific AC or

GV. As this scenario implementation result, a planned critical situation arises in the model, which requires the intervention of centralized management. In the absence of a tested automatic traffic control program in the Applications block, the user of the model takes the role of the ground movement controller. He develops and introduces into the model a new scenario that describes the behavior of traffic participants after the moment of making control decisions. In the “automatic control” mode, the required initial scenario is also specified by the model user, but the scenario of behavior of traffic participants after a critical situation occurs is determined by the tested control program. It is this mode of application of the simulation model that is the emulation (see Section 3.2).

Other features of the GTSS program, as well as the methodology for its application to build a model of the transport network of a particular airport, will be described in the next section.

#### 4.3. Development and verification of a demonstration model of an airport transport network

The ground transportation network of a small airport was chosen as the object of modeling, a fragment of which is shown in Figure 4.11. An area is marked on the plan for which the method of encoding transport network segments in the model built using GTSS will be shown. The same area will be used to describe and simulate specific scenarios within which objects such as AC and GV will move. AC paths are shown as blue arrows, and GV paths are shown as two-way highways. The letters a, b, c and d denote four intersections on GV roads, and numbers 5 through 9 represent five parking spots for AC.

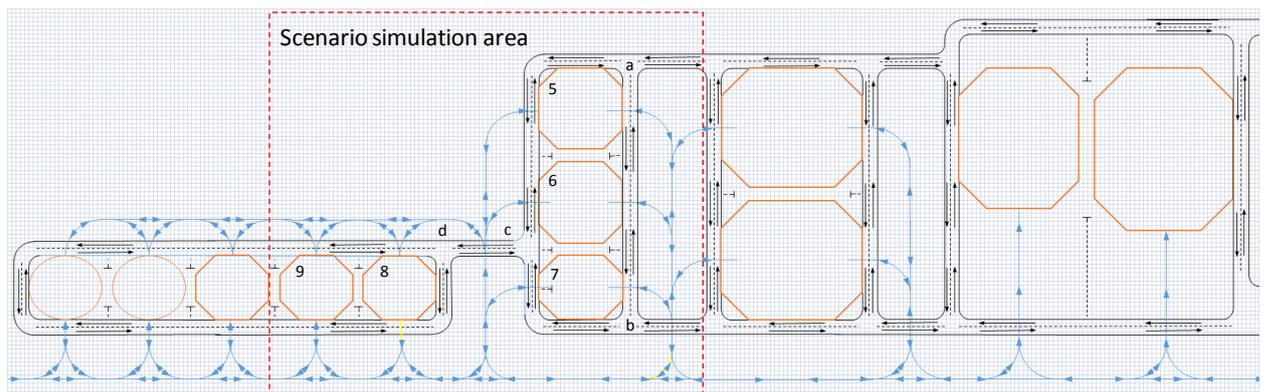


Figure 4.11. Fragment of the airport transport network plan

The plan shown in Figure 4.11 is hosted on an Excel worksheet named “transport\_network” as a set of graphical objects of type Shape. It is on this worksheet that the work with the finished model will take place and the animation of the simulated scenarios will be shown. The cell size on this worksheet corresponds to a 2x2 meter square of the airport area. The

size of the entire area shown in Figure 4.11 is 580x180 meters, and the size of the dedicated area is 192x180 meters.

The next two sections will describe the procedures for entering persistent source data that apply to the selected modeling object. Such data are the results of coding the airport transport network and the characteristics of mobile objects, both at the level of classes and individual objects. The group of source data variables includes data in the “Static positions” and “Dynamic routes” tables. The table “Static positions” describes the position of stationary objects before the start of the simulation and the processes of their movement in free 2D space. The "Dynamic routes" table describes the movement of objects along trajectories that are made up of previously defined sections of the transport network.

### 4.3.1. Transport network section coding

Figure 4.12 shows the steps involved in coding the airport transport network, which results in the completed worksheet named “network\_sections” in the GTSS program.

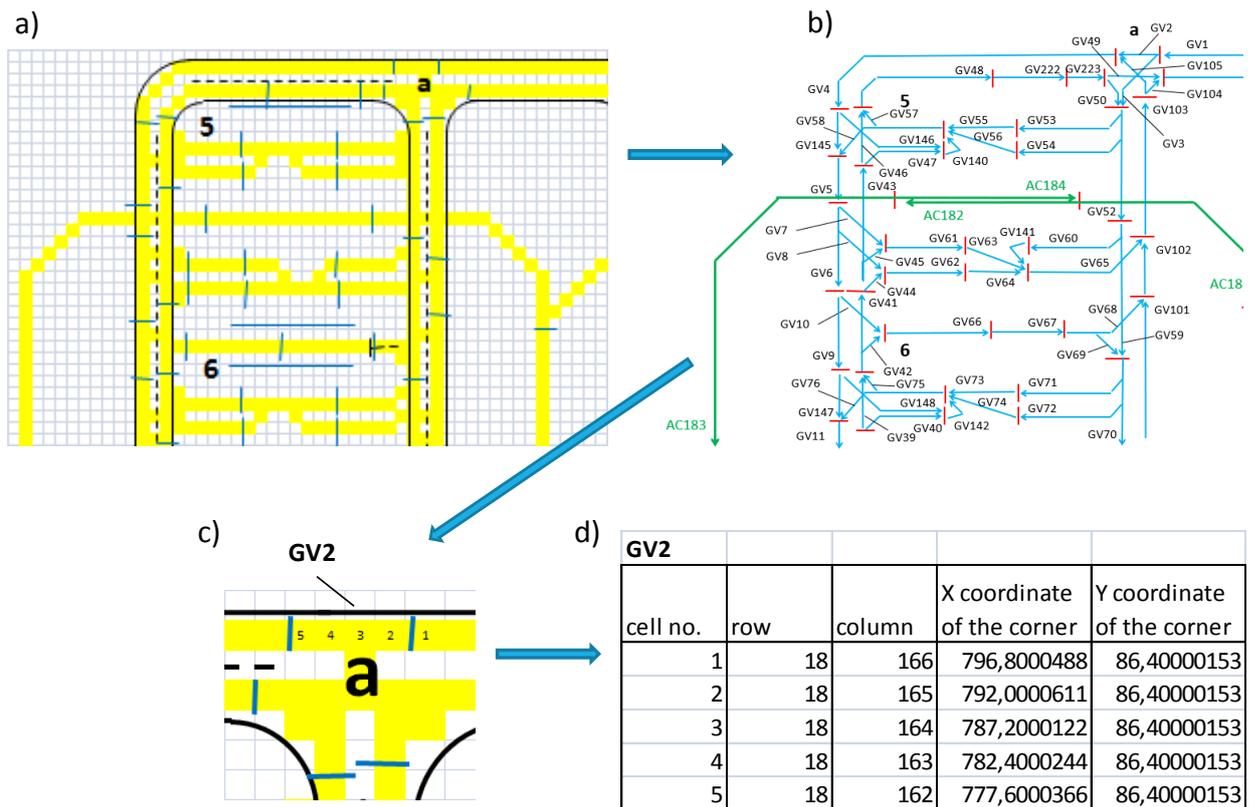


Figure 4.12. Method for coding sections of the airport transport network

At stage *a*, the network plan located on the “transport\_network” worksheet is transferred to the “transport\_ways” worksheet by copying. On the “transport\_ways” worksheet, the cells corresponding to all possible paths of AC and GV are marked in yellow. After that, these paths

are divided into separate sections, the boundaries of which are marked graphically in the form of short strokes. The allocation of sections on the “transport\_ways” worksheet is the most important step in the coding of the transport network, since the number and configuration of sections determines the possibilities that are provided to the user to describe the trajectories of vehicles in specific scenarios. Each section has a start and end cell, which determines its direction (see Figure 4.7).

At stage *b*, the user creates a topological structure in which each section is named and displayed as a unidirectional arrow. In the examples given, the tradition is that the name of the section on the path of movement AC starts with the letters “AC”, and the name of the section on the path of movement GV starts with the letters “GV”. The graphical structure shown in Figure 4.12b is part of the transport network conceptual model and is not handled by the GTSS program.

At stage *c*, the user transfers the parameters of each section of the transport network to the model created using the GTSS program. For example, in the area of intersection *a* there is a short section GV2. The user writes the numbers from 1 to 5 in the cells that make up this section and starts the VBA macro using the button found on the “transport\_ways” worksheet. The program asks for the name of the memorized section and creates the table shown in Figure 4.12d in the “network\_sections” worksheet. The program automatically finds the cells of the memorized section if they are colored yellow and have serial numbers written in them. The generated table shows the (x, y) coordinates of the bottom-left corner of the cell, expressed in points. Other columns of the table also contain the length of the transition between the centers of neighboring cells and the code of the direction of this transition, that is, the value of N, S, W, E, NW, NE, SW or SE. For each display, the *D* number used to convert coordinates from *points* to metres can be defined. The *D* number is the number of *points* corresponding to the width or height of the square cell on the “transport\_ways” worksheet. The example shown in Figure 4.12d was created using a display for which  $D = 4,8$ . Calculation of coordinates (x, y) in meters for the first cell of the GV2 section looks like this:

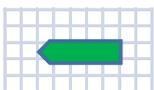
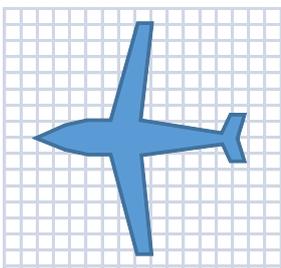
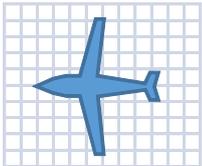
$$x = 796,8/4,8 * 2 = 332m, \quad y = 86,4/4,8 * 2 = 36m.$$

In total, the worksheet “network\_sections” contains tables for 223 sections, of which 149 refer to “GV” sections and 74 to “AC” sections. The longest section includes 52 cells. The complete structure of the transport network sections of the demonstration model as shown in Figure 4.12b can be found in Appendix 1.

### 4.3.2. Creating moving object classes

The user can create any number of moving object classes, which include GV and AC. In the described model, three classes are created for objects of the GV type and six classes for objects of the AC type. For each class, the user creates its graphic image in the form of Freeform Shape on the worksheet “drawing\_lab”. Table 4.2 shows five of the created nine classes of movable objects.

Table 4.2. Classes of moving objects in the demo model

Class no.	Graphical view of the Shape	Object class description	Object class designation	Instance designation
1		Small GV: passenger cars, tractor for dollies, dollies for loose baggage and unit load devices (ULDs), etc.	GV1	GV1_1, GV1_2, etc.
2		Medium GV: large dollies, container loaders, transporters, tugs and tractors, catering vehicles, etc.	GV2	GV2_1, GV2_2, etc.
3		Large GV: buses, tank trucks, de/anti-icing vehicles, etc.	GV3	GV3_1, GV3_2, etc.
4		Large AC.	AC1	AC1_1, AC1_2, etc.
5		Medium AC.	AC2	AC2_1, AC2_2, etc.

Since when drawing Freeform Shape, a grid-based space a 2x2 metre cell size as the background is used, the user has the ability to accurately reflect the basic shape and dimensions of the object. The user creates the maximum required number of copies of objects (instances) of each class before the start of the simulation and places them in a special basement on the “transport\_network” worksheet, where the simulation and animation will be performed. At the same time, he enters data about each object into a worksheet on the “list\_of\_objects” worksheet. In this table, he writes the length of each object in meters, so the accuracy of the geometric dimensions of the Shape itself does not really matter. When simulating movement along a given

trajectory, the program takes into account the real length of the object and does not allow collisions of the following objects.

To take into account the size of an object in 2D space, the principle is applied, which is explained in Figure 4.9. In a separate “object\_scanning” worksheet, the user must create 8 control areas for each class of movable objects. Figure 4.13 shows the output of this work for class AC1.

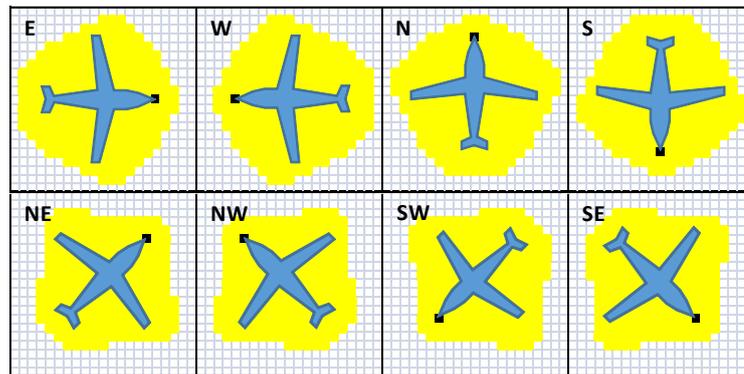


Figure 4.13. Control areas for AC1 class objects

On the “object\_scanning” worksheet, the user can run two VBA macros. The first one positions the Shape of the object of the selected class in the given direction of orientation. After that, the user manually paints the cells with yellow color, which should belong to the control area of the object and starts the second VBA macro. As a result of these actions, information about the control area for a given orientation of objects of the selected class will be recorded in the table of the GTSS program.

#### 4.3.3. Placing objects in fixed positions

In the “Static positions” table, the user describes stationary objects that should be located at certain points in the airport space already at the start of the simulation (Figure 4.14). The “positioning time” column specifies the time when the object should appear in the model. When an object is first mentioned, this time is most often 0, but using this table it is possible to describe the process when an object appears at the boundary of the simulation area at an arbitrary point in time and continues its movement in free 2D space.

The model uses discrete time with a step of  $\Delta t = 0.2 \text{ sec}$ . This condition must be taken into account when filling out the tables “Static positions” and “Dynamic routes”. Any simulation run starts at time  $t = 0 \text{ sec}$ . Typically, the duration of the scenario is within 5-15 minutes, so the maximum model time does not exceed 900 seconds.

<i>Static positions</i>								
positioning time	object name	object color	comment	row number	column number	X coordinate	Y coordinate	direction ID
0	GV1_1	red		25	157			W
0	GV1_2	red		76	116			N
0	AC1_1	standard		31	146			W
0	GV1_3	green		74	90	419.5	350	E
0.2	GV1_3			74	91	421.9	350	E
0.4	GV1_3			74	91	424.3	350	E
0.6	GV1_3			74	92	426.7	350	E

Figure 4.14. Example of filling the “Static positions” table

Figure 4.14 shows an example of filling the “Static positions” table for four objects: GV1\_1, GV1\_2, AC1\_1 and GV1\_3. The object names correspond to specific GVs or ACs that have already been previously defined in the model as Shape objects. The “row number” and “column number” columns define the position of the object's reference point in the center of the corresponding cell [i, j] on the “transport\_network” worksheet, and the “direction ID” column specifies one of eight options for object orientation along the horizon sides (N, NE, E, SE, S, SW, W, and NW). The position of the object can also be specified using the coordinates (x, y). If the user has not specified these coordinates, then they are calculated and recorded in the “Static positions” table automatically when the program is called for the first time. The user can use these coordinates when preparing the next simulation runs, for example, to simulate the continuous movement of an object.

For the further presence of a specific object in the model, three development options are possible:

- the object remains at a given position during the entire simulation time;
- at a certain moment in time, the object starts moving along the specified trajectory (see the “Dynamic routes” table in Figure 4.15);
- at a certain moment in time, the object begins to move in free 2D space, at which the trajectory is specified by the coordinates of individual points.

Objects GV1\_2 and AC1\_1 will not change their position in the model. Object GV1\_1 at time  $t = 5$  will start moving along the trajectory, which consists of five sections (see the “Dynamic routes” table in Figure 4.15). It will exit from the point with cell coordinates [25,157] and leave the model at the end of section GV51. The GV1\_3 object will change its position in free space. It will take three steps towards increasing the X coordinate from 419.5 to 426.7 in 0.6 seconds. The distance traveled is calculated taking into account the number  $D$  according to the formula shown above:

$$l = (426.7 - 419.5)/4.8 * 2 = 3m,$$

which corresponds to the speed  $v = 3/0.6 = 5m/sec$ . The animation will show that in 0.6 seconds the GV1\_3 object will travel in the horizontal direction a distance equal to one and a half cells in the “transport\_network” worksheet.

#### 4.3.4. Description the movement of objects along the specified trajectories

In the “Dynamic routes” table, the user describes the trajectory of each object using the previously defined sections of the airport transport network (Figure 4.15). In the “Dynamic routes” table, two lines are used to describe each trajectory, so the object name, for example, GV1\_4, is repeated two times in a row in the “object name” column. The “positioning time” column indicates the start time of movement along the trajectory, and the “speed (m/s)” column indicates the basic movement speed, which can be changed during the simulation. The “number of sections” value indicates the number of sections that are part of this path. Further in the columns of the “section 1” type, the names of the individual sections are indicated, from which the trajectory is composed. The number of such columns is not limited. In the “comment” column, the meaning of the object's movement along this trajectory can be explained in any language.

<i>Dynamic routes</i>											
positioning time	object name	object color	comment	speed (m/s)	number of sections	section 1	section 2	section 3	section 4	section 5	section 6
0	GV1_4	orange		10	6	GV1	GV2	GV4	GV5	GV7	GV61
	GV1_4							8&20			
5	GV1_1			10	5	GV55	GV57	GV48	GV49	GV51	
	GV1_1									1000	
12	AC1_2	standard		12	6	AC150	AC162	AC164	AC165	AC166	AC178
	AC1_2										

Figure 4.15. Example of filling the “Dynamic routes” table

If a number other than 1000 is written under the section name, then this number is interpreted as the individual speed for this section, measured in (m/s). If no such speed is specified, the model will use the speed specified in the “speed (m/s)” column. Everywhere it refers to the maximum speed since the actual speed can be reduced due to the inability to overtake the object in front. If the cell contains the number 1000, then after passing this section the object will be removed from the model, otherwise it will remain at the last point of the last section. If the “&” symbol is used in the cell, then the number after it is interpreted as the time in seconds for which the object will be delayed at the end of this section before it starts moving in the next section. For example, the entry “8&20” under the name of the GV4 section means that

the GV1\_4 object in this section will have a speed of up to 8 m/s and at the end of the section it will stand motionless for 20 seconds.

#### 4.3.5. Model run modes

Figure 4.16 shows the tools for managing the model run located on the “transport\_network” worksheet. The model can be run in one of two modes, for which the buttons “start scenario” and “start protocol” are used.

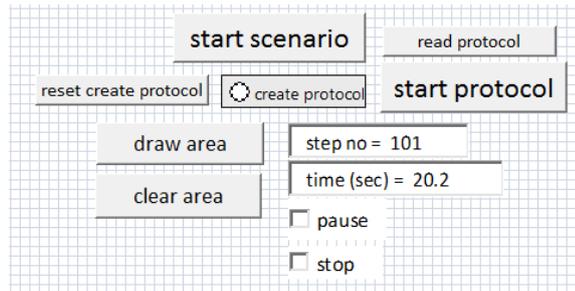


Figure 4.16. Model run controls

#### Running the model while simulating a scenario

The “start scenario” button is used to start the model in the direct simulation of the scenario defined in the “Static positions” and “Dynamic routes” tables.

When working in this mode, the user has the possibility to get a record of the process implemented based on a given scenario in the State Protocol format (see section 4.2.2). The State Protocol is the main result of debugging a specific scenario, as it is intended to be used during the “system training” phase when working with the real control program begins (see section 4.1).

Figure 4.17 shows a fragment of the State Protocol in the form of a table, in which the states of objects are fixed only for three points in time with a step of 0.2 seconds. All data in this protocol refers to only three mobile objects GV2\_2, GV2\_3 and AC2\_1. Time in the State Protocol is discrete, that is, it takes only those values that are used in the model in accordance with the “delta T” principle.

The “location” position indicates the name of the section if the object moves along a given trajectory. As an example, Figure 4.17 shows a situation when the GV2\_3 object moved from section GV28 to section GV29 and at the same time its movement speed and orientation to the cardinal points changed. If the object is not associated with a section, then the position “location” contains the coordinates [i, j] of the cell in which it is located. The “target” position is considered known for each object that moves along a given trajectory. The “priority” position is an example of additional parameters that a centralized motion control system can take into account. The

State Protocol generated during scenario processing is part of the DT and can be saved as an external .TXT file.

State protocol								
discrete time	object name	X coordinate (points)	Y coordinate (points)	location	speed (m/s)	direction ID	target	priority
11.8	GV2_2	573.60	314.74	GV108	5	S	GV51	1
11.8	GV2_3	680.09	377.69	GV28	4	NW	GV51	1
11.8	AC2_1	525.60	376.80	AC197	4	N	AC218	1
12.0	GV2_2	573.60	318.54	GV108	5	S	GV51	1
12.0	GV2_3	679.52	377.12	GV28	4	NW	GV51	1
12.0	AC2_1	525.60	376.00	AC197	4	N	AC218	1
12.2	GV2_2	573.60	319.54	GV108	5	S	GV51	1
12.2	GV2_3	679.20	373.00	GV29	5	N	GV51	1
12.2	AC2_1	525.60	372.40	AC197	4	N	AC218	1

Figure 4.17. Fragment of the State Protocol in the form of a table

Before running the model, a decision must be made as to whether the process to be modelled should be saved as an external .TXT file in State Protocol format. If the modeled process is to be saved, then the Option Button with the name “create protocol” must be switched to active state. If no process save is required and the Option Button named “create protocol” is active, the “reset create protocol” button should be pressed to reset this state.

If saving of the process is required, the user sets the time values in the “start of recording?” and “end of recording?” dialog boxes after starting the model. Next, the name of the .TXT file is specified in the “name of protocol?” window. Figure 4.18 shows a fragment of a real text file, in which the states of 14 objects are fixed at a time of 10 seconds.

State protocol								
discrete time	object name	X coordinate (points)	Y coordinate (points)	location	speed (m/s)	direction ID	target	priority
10.0	"GV1_1"	"626.400024414063"	"300.000030517578"	"GV106"	"5"	"W"	"GV51"	"1"
10.0	"GV1_2"	"645.599975585938"	"300.000030517578"	"GV106"	"4"	"W"	"GV51"	"1"
10.0	"GV2_1"	"736.799987792969"	"199.200012207031"	"GV67"	"3"	"E"	"GV51"	"1"
10.0	"GV2_2"	"584.200012207031"	"300.000030517578"	"GV108"	"5"	"W"	"GV51"	"1"
10.0	"GV2_3"	"694.400024414063"	"386.400024414063"	"GV28"	"4"	"W"	"GV51"	"1"
10.0	"GV3_1"	"728.200012207031"	"117.600006103516"	"GV55"	"3"	"W"	"GV51"	"1"
10.0	"GV3_3"	"751.200012207031"	"357.600006103516"	"point( 75, 157)"	"",	"W"	"",	"1"
10.0	"GV3_4"	"895.200012207031"	"386.400024414063"	"GV25"	"6"	"W"	"GV51"	"1"
10.0	"GV3_5"	"674.157348632813"	"93.8426742553711"	"GV4"	"5"	"SW"	"GV51"	"1"
10.0	"GV3_6"	"895.200012207031"	"84"	"GV1"	"6"	"W"	"GV51"	"1"
10.0	"AC1_1"	"698.400024414063"	"146.400009155273"	"point( 31, 146)"	"",	"W"	"",	"1"
10.0	"AC2_1"	"525.599975585938"	"395.200012207031"	"AC197"	"4"	"N"	"AC218"	"1"
10.0	"AC4_1"	"756"	"343.199981689453"	"point( 72, 158)"	"",	"E"	"",	"1"
10.0	"AC5_1"	"708"	"252"	"point( 53, 148)"	"",	"W"	"",	"1"

Figure 4.18. Fragment of a real State Protocol file

The mode with animation or without animation is set after launching the model by setting the time in the “animation begin?” dialog box. If the value is set to 0, then the animation will continue throughout the entire run of the model. If a value is set equal to or greater than the "max

time" run time, then the model will not show animation at all, and after the start it will immediately stop at a given moment in time, that is, at the end of this run, and show the final location of moving objects in the network. For other values of the "animation begin" time, less than "max time", the animation will start exactly at the moment of time "animation begin". When animating, the process in the model is approximately 2.5 times faster than the actual process.

After clicking the "start scenario" button and defining the animation mode in the "animation begin?" the user enters the run time of the model in seconds in the "max time?" window. If there are no events left in the model that should be simulated, then the model will automatically stop earlier, that is, at the moment when the last event is processed.

The "pause" button can be used to interrupt and then continue the model run again. An important feature of a model running in MS Excel is the ability to change data in any of the tables in the model while the model is being interrupted. This data will immediately become up-to-date when the model continues to run. The "stop" button can be used to end a model run early. During a pause or after completion of the model run, the "draw area" and "clear area" buttons can be used to see the control areas of all existing moving objects in the model (Figure 4.9).

### **Running the model in the protocol interpretation mode**

The protocol interpretation mode is used to demonstrate the process previously recorded as an external .TXT file in the State Protocol format. In this mode, the model is verified, since the correctness of its main result is checked, that is, the contents of the file in which the State Protocol of a specific scenario is recorded. The main way to do this is to compare the animation pictures that are observed during direct simulation of the scenario and the interpretation of the recorded protocol. These animation pictures must be completely identical.

If the .TXT file with the process protocol has not yet been uploaded to the "moving\_protocol" worksheet, then start by clicking the "read protocol" button. The program will ask for the name of the .TXT file with the process log and start downloading it. After the file has finished loading, the program will open the "moving\_protocol" worksheet, where the first lines of the loaded protocol will be visible (Figure 4.19). The log lines shown in Figure 4.19 are the result of reading lines from the file shown in Figure 4.18.

State protocol								
discrete time	object name	X coordinate (points)	Y coordinate (points)	location	speed (m/s)	direction ID	target	priority
10.0	GV1_1	626.40	300.00	GV106	5	W	GV51	1
10.0	GV1_2	645.60	300.00	GV106	4	W	GV51	1
10.0	GV2_1	736.80	199.20	GV67	3	E	GV51	1
10.0	GV2_2	584.20	300.00	GV108	5	W	GV51	1
10.0	GV2_3	694.40	386.40	GV28	4	W	GV51	1
10.0	GV3_1	728.20	117.60	GV55	3	W	GV51	1
10.0	GV3_3	751.20	357.60	point( 75, 157)		W		1
10.0	GV3_4	895.20	386.40	GV25	6	W	GV51	1
10.0	GV3_5	674.16	93.84	GV4	5	SW	GV51	1
10.0	GV3_6	895.20	84.00	GV1	6	W	GV51	1
10.0	AC1_1	698.40	146.40	point( 31, 146)		W		1
10.0	AC2_1	525.60	395.20	AC197	4	N	AC218	1
10.0	AC4_1	756.00	343.20	point( 72, 158)		E		1
10.0	AC5_1	708.00	252.00	point( 53, 148)		W		1

Figure 4.19. Representing State Protocol data in a model as a result of loading an external file

To run the model, it is necessary to go to the worksheet “transport\_network” and to click on the “start protocol” button. The next steps for model run control are the same as those described for the scenario simulation mode.

#### 4.3.6. Demo model verification

The following steps will be described to check the error-free operation of the GTSS program when processing the demonstration model described above.

#### Interpreting the “Static positions” table

The essence of the check is to visually analyze the positions and directions of orientation of moving objects listed in the “Static positions” table. Figure 4.20 shows a table with six objects marked AC1\_1, AC4\_1, GV3\_1, GV2\_1, AC5\_1, and GV3\_3. For each object, the color used for animation, the coordinates of the cell [i, j], in which the object's reference point is located, and the orientation direction code is specified. It also shows an animation of the model at time  $t = 0$ .

Analysis of the animation picture shows that it accurately takes into account all the data in the “Static positions” table.

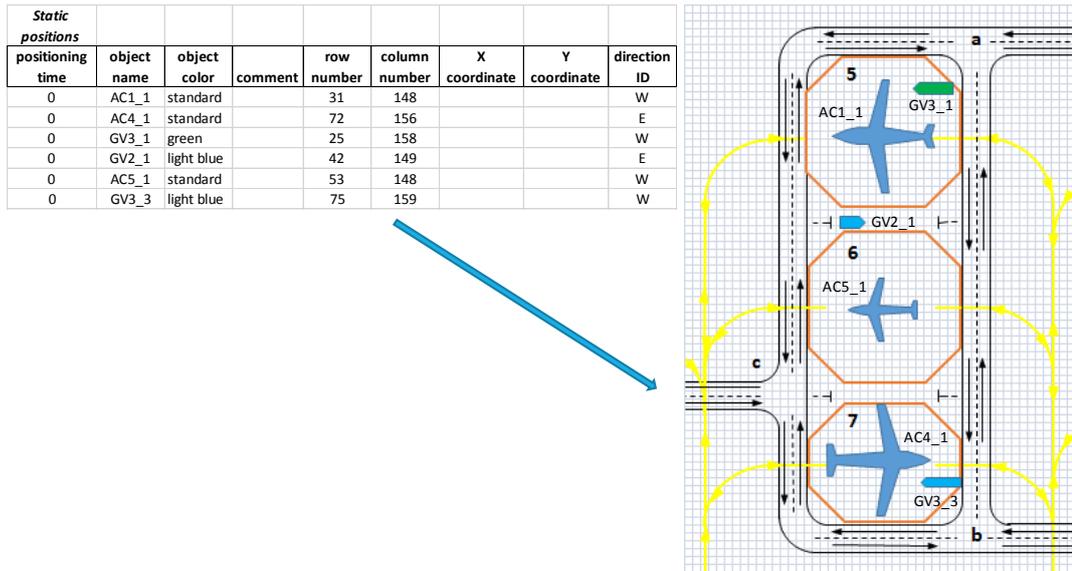


Figure 4.20. Checking the interpretation of the data in the “Static positions” table

### Interpreting the “Dynamic routes” table

The essence of the check consists in visual and numerical analysis of the state of objects that have made movements in accordance with the data specified by the user in the “Dynamic routes” table. Figure 4.21 shows a fragment of the “Dynamic routes” table, in which the movement of the last GV3\_2 object starts at time  $t = 17$ . The model is stopped at time  $t = 20$ . Figure 4.22 shows the location of objects in the model at this point in time. The “step no” window shows that with a step  $\Delta t=0.2$  sec, exactly 100 timesteps are implemented in the model.

Dynamic routes																			
positioning time	object name	object color	comment	speed (m/s)	number of sections	section 1	section 2	section 3	section 4	section 5	section 6	section 7	section 8	section 9	section 10	section 11	section 12	section 13	section 14
0	AC2_1	standard		13	14	AC153	AC191	AC195	AC197	AC198	AC189	AC188	AC170	AC171	AC191	AC193	AC205	AC207	AC218
0	AC2_1					10	8	6	48&240										1000
0	GV2_2	blue		6	22	GV12	GV15	GV106	GV108	GV117	GV119	GV120	GV121	GV133	GV134	GV135	GV137	GV36	GV39
0	GV2_2					5	4	5	5	5	5	4&26	3	5	5	4	5		
0	GV2_3	blue		6	24	GV26	GV28	GV29	GV32	GV106	GV108	GV117	GV119	GV120	GV121	GV133	GV134	GV135	GV137
0	GV2_3					4	5	4	5	5	5	5	4&27						
0	GV1_1	red		6	22	GV147	GV11	GV12	GV15	GV106	GV107	GV110	GV138	GV116	GV134	GV135	GV137	GV36	GV39
0	GV1_1							5	4	5	5	4&72							
0	GV1_2	red		6	23	GV9	GV147	GV11	GV12	GV15	GV106	GV108	GV113	GV115	GV116	GV134	GV135	GV137	GV36
0	GV1_2							5	4	4	5	4&67							
0	GV3_4	light blue		6	14	GV25	GV26	GV28	GV31	GV91	GV93	GV95	GV99	GV100	GV101	GV102	GV103	GV104	GV51
0	GV3_4							4	3	38&115									1000
0	GV3_5	light blue		6	19	GV2	GV4	GV145	GV5	GV6	GV9	GV147	GV11	GV12	GV17	GV84	GV85	GV86	GV100
0	GV3_5							5						4	4	4&125			
0	GV3_6	light blue		6	20	GV1	GV2	GV4	GV145	GV5	GV6	GV9	GV147	GV11	GV12	GV17	GV84	GV85	GV86
0	GV3_6							5						5	4	4&137			
7	GV3_1	green		5	39	GV55	GV58	GV5	GV6	GV9	GV147	GV11	GV12	GV15	GV106	GV108	GV112	GV114	GV116
7	GV3_1					3	4							5					
8	GV2_1	light blue		6	6	GV67	GV68	GV102	GV103	GV104	GV51								
8	GV2_1					3	4	5	5	4	1000								
10	GV2_4	light blue		5	14	GV1	GV2	GV4	GV145	GV5	GV6	GV10	GV66	GV67	GV68	GV102	GV103	GV104	GV51
10	GV2_4													&22					1000
12	GV2_5	light blue		5	14	GV1	GV2	GV4	GV145	GV5	GV6	GV10	GV66	GV67	GV68	GV102	GV103	GV104	GV51
12	GV2_5													&22					1000
14	GV1_3	orange		5	11	GV1	GV2	GV4	GV146	GV140	GV57	GV48	GV222	GV223	GV49	GV51	1000		
14	GV1_3								&48										
16	GV1_4	orange		5	10	GV1	GV3	GV54	GV56	GV57	GV48	GV222	GV223	GV49	GV51	1000			
16	GV1_4							&48											
17	GV3_2	green		5	14	GV25	GV26	GV28	GV30	GV92	GV94	GV95	GV99	GV100	GV101	GV102	GV103	GV104	GV51
17	GV3_2									&148									1000

Figure 4.21. Fragment of the “Dynamic routes” table

If during the simulation the objects were not removed from the model, the number of objects in the model should be equal to the sum of those that were marked in the “Static

positions” table (6 objects), and the new objects that appeared in the model in accordance with the “Dynamic routes” table before time  $t = 20$ . The paths of 15 objects are visible in the “Dynamic routes” table, but the objects GV3\_1 and GV2\_1 are not new, as they were marked in the “Static positions” table. Thus, the number of new objects is 13 and the total number of objects is 19. All these 19 objects can be seen in Figure 4.22.

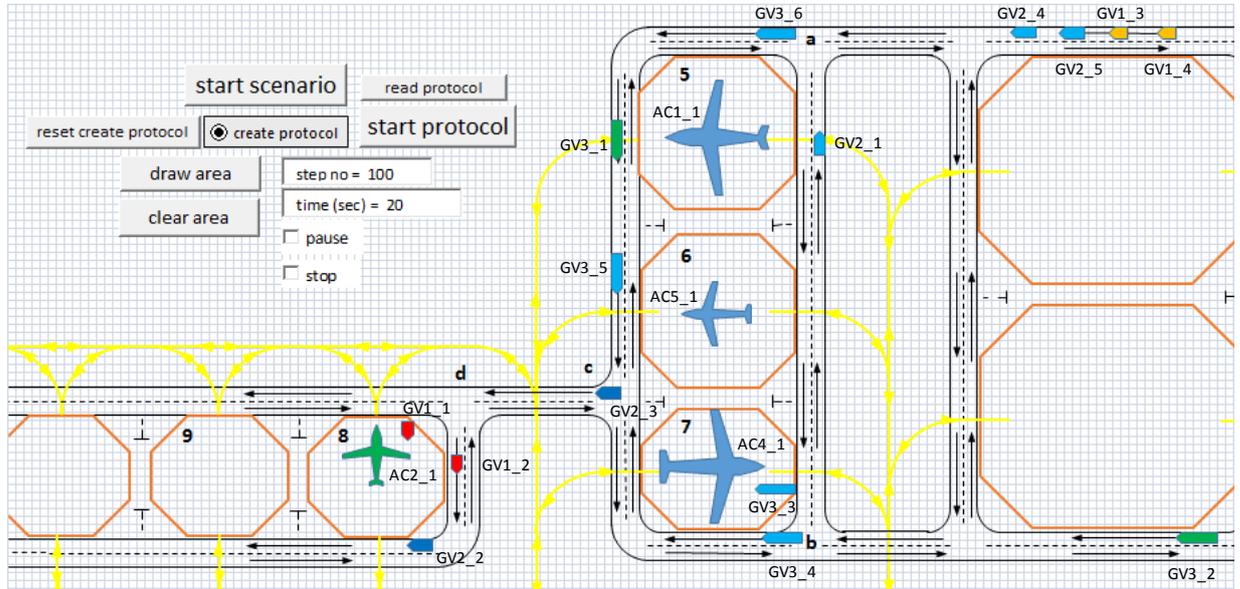


Figure 4.22. Location of objects in the model at time  $t=20$

### State Protocol Check

Figure 4.23 shows the situation in the model at time  $t = 20$  as a fragment of the State Protocol. This snippet is shown in two formats: as data in a saved text file and as data in a table based on this file. The data in the State Protocol contains exactly 19 lines, i.e. the protocol shows all 19 objects that can be seen in Figure 4.22.

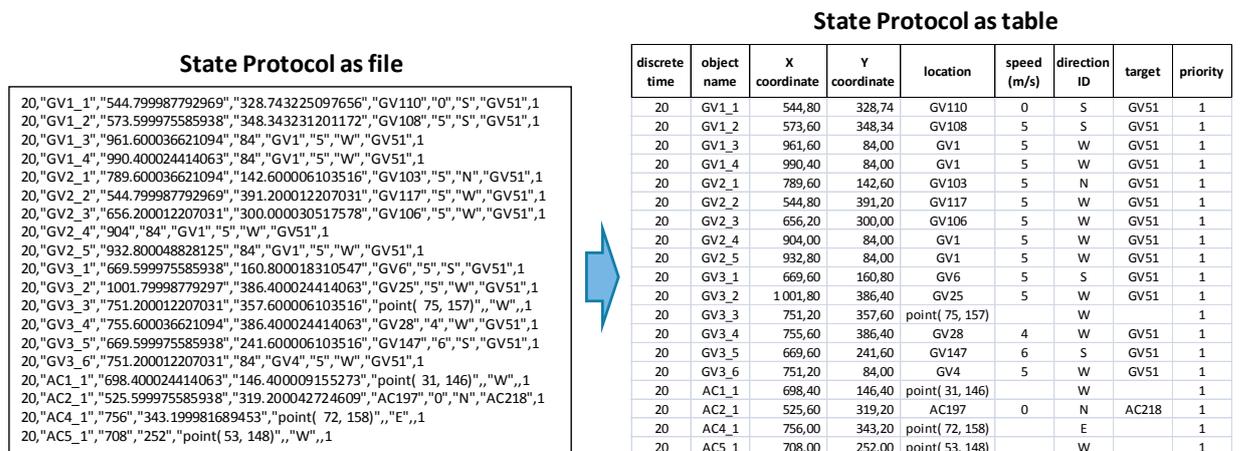


Figure 4.23. State Protocol data at time  $t=20$

A direct way to assess the correctness of the State Protocol is to compare animated pictures that are generated by two simulations at certain points in time. Simulation 1 is the execution of the model based on the scenario specified in the tables “Static positions” and “Dynamic routes” (Figure 4.24). Simulation 2 is the execution of the model based on the read external State Protocol file. The user must run two Excel programs in parallel and, by switching windows on the display, compare the animation pictures of both simulations at the same time  $t_{stop}$ . When performing such a comparison, both simulations must end at time  $t_{stop}$ .

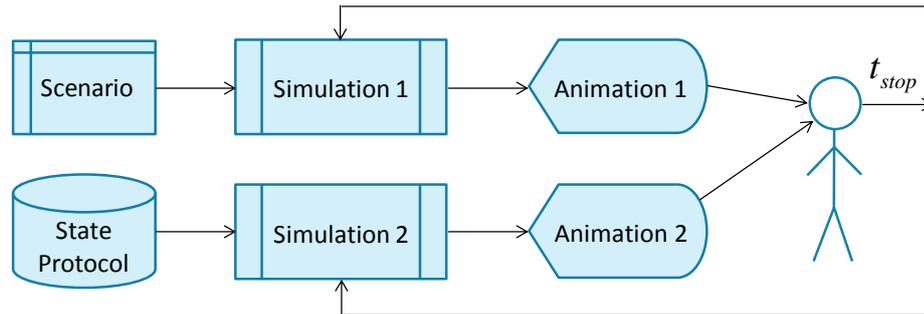


Figure 4.24. Comparison of animation pictures of two simulations

#### 4.4. Preparing and conducting a simulation experiment

Since in the course of the experiment, scenarios of the emergence of a critical situation and exit from it should be developed close to reality, an expert controller with practical experience in control of ground traffic movement at an airport should act as a user of the model.

##### 4.4.1. The methodology of conducting an experiment

The main steps performed by an expert controller in modeling a specific decision-making situation are as follows (Figure 4.25):

1. The controller selects one of the typical critical situations that may arise in the airport ground transportation system. Each such situation can be attributed to the class of explicit or recognizable situations. An obvious situation is that the controller receives a message from one of the airport services. An example of such a situation is the appearance of an obstacle on one of the sections of the transport network or the appearance of a priority vehicle, which must reach the destination of the route as quickly as possible. Recognizable situations include situations that the controller determines for himself by observing the processes in the ground transport system. An example of a recognizable situation can be a congestion of vehicles as a result of a traffic jam, a dangerous approach of objects with each other or with obstacles, or a dangerous excess of the permissible speed.

2. The controller constructs a scenario for the occurrence of the selected critical situation (Scenario 1). First, the scenario is written verbally, and then the behavior of all participants is described using the tables “Static positions” and “Dynamic routes”. Typically, this step is implemented through several iterations until the controller is satisfied with the animation being observed. The controller fixes the moment in time, which he will consider the moment of making a decision.
3. The controller constructs a scenario of the behavior of all participants in a critical situation after the moment of making a decision (Scenario 2). To do this, in the tables “Static positions” and “Dynamic routes”, he changes or adds rows, observing the condition that the time in the “positioning time” column necessarily follows the moment of making a decision or coincides with it. This scenario is brought to the desired state also with the help of several iterations.
4. The controller activates the “create protocol” option on the Excel sheet with the model image (Figure 4.26) and by pressing the “start scenario” key starts the simulation process, in which both scenarios described above are reproduced. The program will save a stream of data about the location of objects in the form of a State Protocol in a text file, the name of which must be specified by the controller.

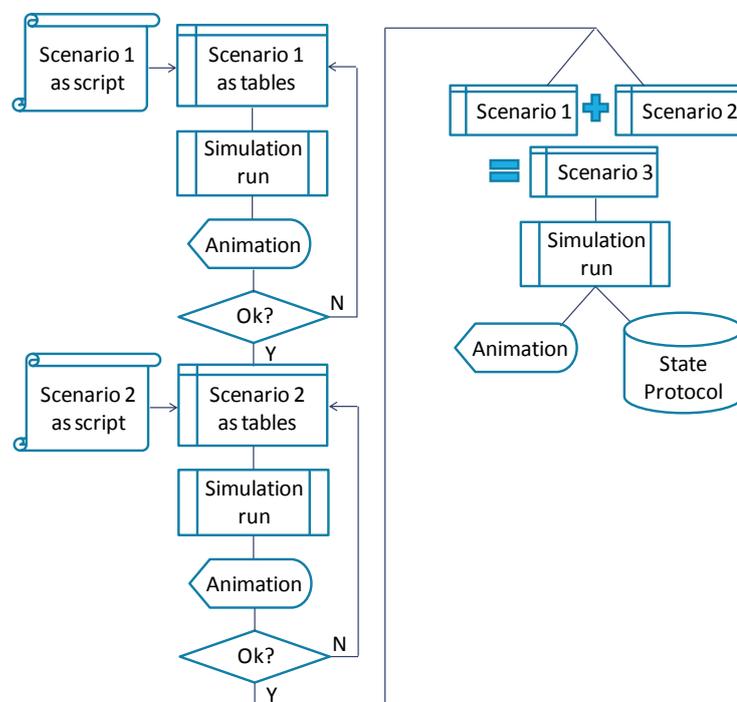


Figure 4.25. Sequence of actions when simulating a critical situation

#### 4.4.2. An example of modeling a critical situation

In the event of a critical situation, typical actions of the airport's centralized ground movement control system are, in particular, the following:

- stop a vehicle that is moving along a dangerous trajectory, or give a command to continue driving if the vehicle was stopped;
- inform new routes of movement to individual vehicles in case of interference or congestion at specific points of the transport network;
- stop the movement of all vehicles in a certain area of the network, except for one or several precisely defined ones, in order to ensure their early arrival at their destination.

Let's consider a simple example of a decision-making situation when, as a result of a specific event, traffic was interrupted in the section between AC stands 5 and 6 (see the cross in Figure 4.26). Suppose that objects GV2\_6 and GV1\_5 were to move towards intersection *c* and further to stand 9. Object GV2\_2 was supposed to pass intersection *a* and leave the network, moving further eastward. Objects GV2\_3 and GV1\_6, after passing the intersection *c*, had to follow the same path as object GV2\_2. All of this information about object routes is contained in the “Dynamic routes” table compiled for the primary process. At the time  $t = 80$ , the above event occurred, knowing about which, the user interrupts the simulation of the primary process. GTSS automatically saves data about the current state of the model, making it possible to continue modeling using new data, if any is entered into the model.

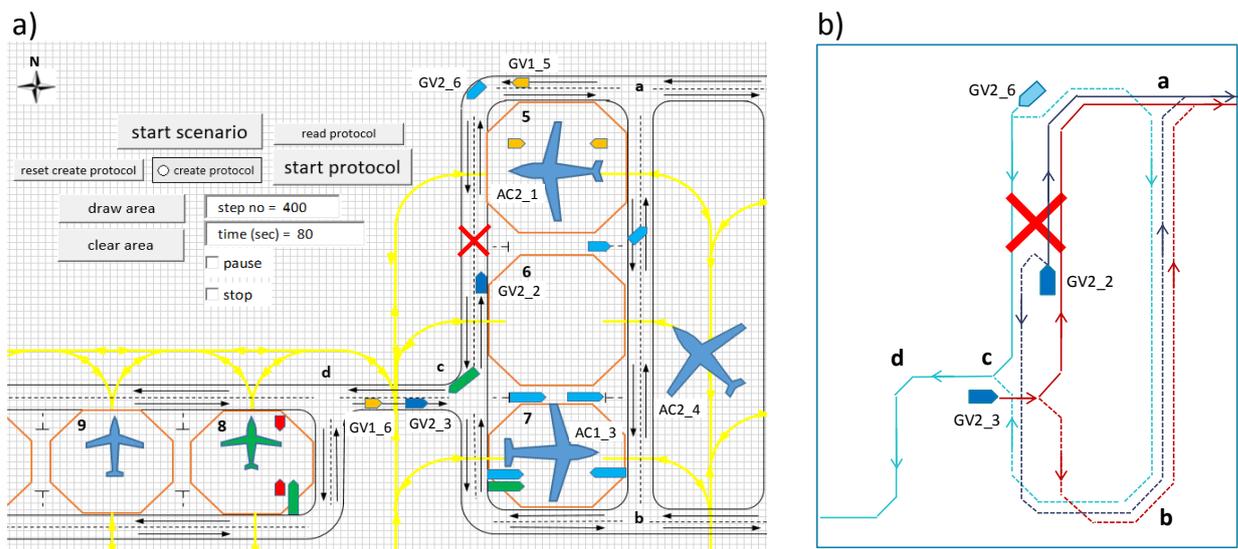


Figure 4.26. Making decisions about changing the routes of objects in the event of a critical situation

The meaning of the control commands that the user generates in this situation is to change the routes of all five objects listed above. New routes are defined by extending the “Dynamic

routes” table that already exists in the model. The new rows of the “Dynamic routes” table are shown in Figure 4.27. All new movements of objects should start no earlier than moment of time 80. The number of sections that the object must pass is not limited, but Figure 4.27 shows only the first 12 sections. In order to reduce the size of the table, solutions related to objects GV2\_6, GV2\_2, and GV2\_3 will be described below. After restarting the model at time 80, the movement of all three objects will first be stopped, since the “speed” column has a value of 0. Events at times 85, 87 and 89 will start the movement of objects along new trajectories. The number in the “speed” column indicates the nominal speed of the object. If there is a number under the section designation, for example 5 m/s, then this speed value will be applied only for this section.

positioning time	object name	speed (m/s)	number of sections	section 1	section 2	section 3	section 4	section 5	section 6	section 7	section 8	section 9	section 10	section 11	section 12
80	GV2_6	0													
80	GV2_2	0													
80	GV2_3	0													
85	GV2_6	10	19	GV48 5	GV222 5	GV223 5	GV50 5	GV52	GV59	GV70	GV82	GV88	GV89	GV96	GV28
87	GV2_2	8	15	GV147 5	GV11 5	GV12 5	GV16 5	GV18	GV21	GV23	GV98	GV99	GV100	GV101	GV102
89	GV2_3	8	12	GV136 5	GV18	GV21	GV23	GV98	GV99	GV100	GV101	GV102	GV103	GV104	GV51

Figure 4.27. Changing the routes of objects by continuing the “Dynamic routes” table

Figure 4.26a shows the location of the objects at time  $t = 80$ , when information about the problem appears, which requires the controller to make a decision, and Figure 4.26b shows the routes of the objects GV2\_6, GV2\_2 and GV2\_3. The solid lines show the previously planned routes, and the dashed lines show the new routes entered by the controller into the “Dynamic routes” table.

Object GV2\_6 is suggested to make a turn by 180 degrees and start moving along section GV48. At intersection *a*, the object will turn right and reach intersection *b*. After turning to the right, the GV2\_6 object will reach the intersection *c* and will head towards the stand 9. The GV2\_2 object will also first make a turn by 180 degrees, and then will start moving along the GV147 section in the south direction. After passing the intersection *c*, the object will continue to move southward, make a left turn at the intersection *b* and, moving northward, will reach the intersection *a*, after which it will leave the transport network. The GV2\_3 object will not make the previously planned left turn at the intersection *c*, but will turn right and, starting from the GV18 section, will repeat the trajectory of the GV2\_2 object.

By combining the primary “Dynamic routes” table with its continuation shown in Figure 4.27, a complete scenario of the processes that took place in the model both before the decision was made and during the implementation of this decision is formed. When processing this scenario, the GTSS program creates a State Protocol that simulates the flow of measurement data about the location of real objects in the airport transport network.

#### **4.5. Conclusions**

Based on the analysis of the material discussed in this chapter, the following conclusions can be drawn:

- The main function of the Digital Twin in the airport transport system control should be to collect and store data on the location and condition of traffic participants. Digital Twin must perform preliminary processing of data arriving in asynchronous mode, and in the form of a synchronized protocol provide this data to the automatic control system.
- The simulation model and the associated Digital Twin can be effectively applied at different stages of creation, training, testing and operation of software for automatic control of processes in the airport transport network.
- The GTSS modeling program created using the VBA programming language in the MS Excel environment is universal, since it can be used to create a model of the transport network of any airport by using only MS Excel graphical objects and tables. Additional programming is optional.
- The GTSS program is a laboratory prototype that provides the user with the ability to implement all the main stages of modeling scenarios for the occurrence and elimination of critical situations in the airport transport network. Methods for obtaining simulation results in the form of data streams with coordinates of moving objects in the form of protocols that are DT components have been developed and verified.
- The protocols obtained as a result of the work of the GTSS program coincide in form with those that can be created in the process of collecting measurement information from real technical means of determining the location of objects at the airport. Such data can be used at the training stages of the automatic process control system in the airport transport network.
- The developed methods for describing and modeling scenarios for the emergence and elimination of critical situations in the airport transport network make it possible to fully take into account the experience of expert controllers and save the scenarios

modeling protocols in a form focused on their application at the training stages of the automatic control system.

## 5. CONCLUSIONS

The content and results of this work are still far from the ambitious goal set by IATA to create automatic ground movement control systems at airports, but they are the first steps without which it is impossible to start moving towards this goal. The work performed is purely research in nature, and it gives an idea of the methods and tools that will need to be created and applied in the course of design work in the future.

From the content of the work, it follows that simulation modeling was used as the main method for studying processes in the airport transport network, but the chosen methodology of this type of mathematical modeling is very different from the one that has been used for many years in packages belonging to the classes airport simulation software or general-purpose simulation software. The movement of objects in conventional models is carried out on the basis of general rules that are described by the user at the stage of model development. The user can freely define the flow of objects at the input of the model, and then their behavior will be completely determined by the specified rules. **The modeling methodology developed in this work** assumes that the behavior of each object is determined by precise instructions relating only to it, which the user sets in the form of scenarios. The second feature of the methodology is the use of not only discrete time based on the “delta T” principle, but also discrete space, which is obtained by dividing the airfield area into 2x2 meter squares. In this case, to simulate the movement of objects in the same space, continuous coordinates (x, y) are used.

The following **work results** should be considered the main ones:

- Trends in the development of technical and organizational methods of control and management of transport processes at airports, which are prerequisites for solving the problem of complete automation of management of these processes, have been identified.
- About 60 examples of the use of various classes of software products for simulation modeling of transport processes at airports have been considered and a decision has been made on a way to build airport own tool for modeling scenarios of critical situations in the airport transport network.
- A critical analysis of the interpretation options for the concept of a Digital Twin (DT) has been carried out and the connection of this concept with the techniques “real-time simulation” and “online simulation” that appeared more than 20 years ago has been shown. A general concept for the use of DT has been developed both at the development stage and in the normal operation of the process control system in the airport transport network.

- The main paradigm was defined and a special methodology for modeling processes in the airport transport network, based on a discrete representation of both time and space has been developed. The second feature of the methodology is that the behavior of each object in the model is determined not only by general rules, but also by precise instructions that refer only to it.
- A universal modeling program GTSS has been developed focused on modeling scenarios of emergence of critical situations in the airport transport network. The model created using the GTSS program generates protocols with data that can be created in the process of collecting measurement information from real technical means of determining the location of objects at the airport.
- Simulation experiments have been carried out, within the framework of which the development of various critical situations in the airport transport network and ways of implementing decisions related to individual traffic participants and aimed at eliminating the negative consequences of emerging critical situations are shown.

Summarising the most significant results and taking into account the research questions formulated at the beginning of the paper, the following **conclusions** can be drawn:

- The prerequisites for solving the problem of automatic control of ground traffic are progress in the field of Artificial Intelligence and Unmanned Vehicles. A precondition for the use of such technologies is to improve the accuracy of determining the coordinates of moving objects in Positioning and Navigation Systems. The work provides examples of ideas and developments that should provide a solution to this problem in the near future.
- To date, the most advanced automated control of ground traffic functions are part of the Advanced-Surface Movement Guidance and Control System (A-SMGCS), but the controller's role is still the leading one in such a system. A-SMGCS can be seen as a starting point towards solving the problem of fully automated ground traffic control at airports.
- After considering about 60 examples of the development of simulation models of transport processes at airports, it follows that the most effective tools for the study of control algorithms for such processes are created by using general-purpose programming languages. It is these tools that provide enough degrees of freedom for the modeller and allow him to plan and conduct any experiments aimed at developing and testing control algorithms of ground traffic at airports.

- The main function of the Digital Twin in the management of the transport system in an airport should be to collect and store data on the location and condition of traffic participants. Digital Twin must perform preliminary processing of data arriving in asynchronous mode, and in the form of a synchronized protocol provide this data to the automatic control system. The presentation of data in the form of State Protocol creates conditions for the development of a large number of applications that can use this data both for controlling processes in real time and for retrospective analysis or forecasting their development in the near future.
- The developed methodology of simulation modeling of processes in the airport transport network, based on a discrete representation of both time and space, was experimentally tested during the development and application of the GTSS program. The methodology is effective since it makes it possible to simplify the solution of the problems of analyzing the relative position of moving objects while maintaining sufficient accuracy in displaying their location in the airfield space.
- The developed methods for describing and modeling scenarios for the emergence and elimination of critical situations in the airport transport network make it possible to fully take into account the experience of expert controllers and save the scenarios modeling protocols in a form focused on their application at the training stages of the automatic control system.

It can be stated that these conclusions contain full answers to the research questions and facts that support the consistency of the statements put forward for defense.

As the best option for the **application and development of the results** of this study, the emergence of a project is seen, within the framework of which the idea of training and testing the ground movement control system at a specific airport would be brought to the practical implementation. The first stage of such a project should be the solution of the problem of automatic identification of prerequisites or ready-made facts of the emergence of various kinds of critical situations. At the second stage, it is necessary to make the control system to determine traffic movement participants who can be affected by a critical situation and to whom personal control commands should be sent. Finally, at the third stage, the control system must learn to automatically generate such control commands. It is quite clear that in solving these problems, the main role will belong to the methods of artificial intelligence and machine learning.

Although the GTSS program demonstrates how to solve many fundamental problems of data generation intended for training a control system, it is only a laboratory prototype, as it works in the MS Excel environment. The main weak point of the program is the speed of its

processing on a computer, which may turn out to be insufficient when simulating a large number of critical scenarios typical for a particular airport. It is recommended to create a new version of the GTSS program using the “fastest” programming language, C++. At the same time, of course, the methodology for modeling processes in the transport network implemented in the first version of the program and the tabular method of entering a large amount of data required to describe user-defined scenarios will remain.

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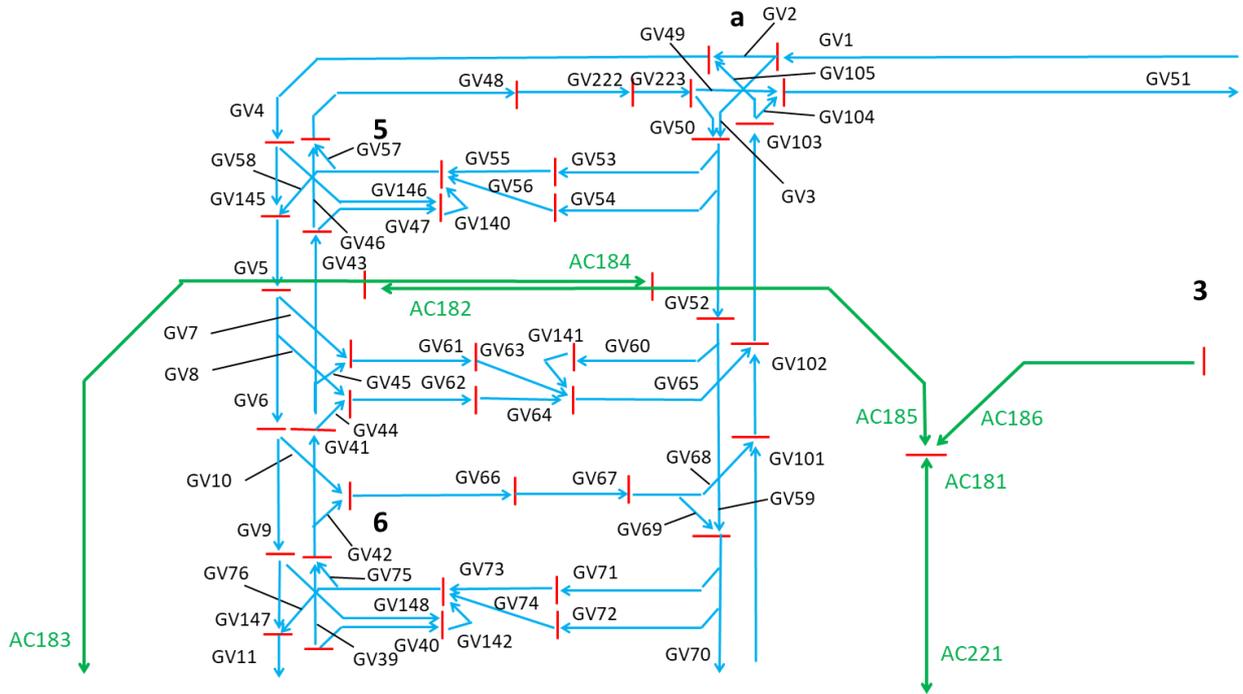
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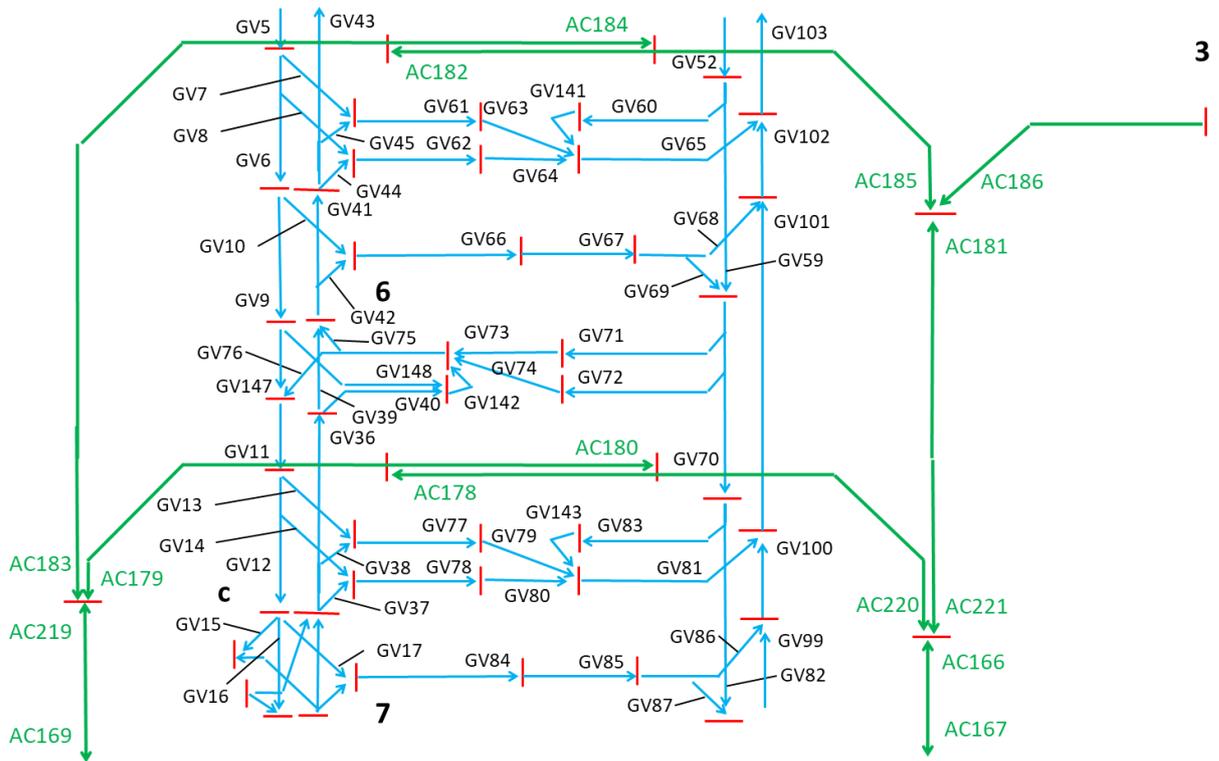
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APPENDICES

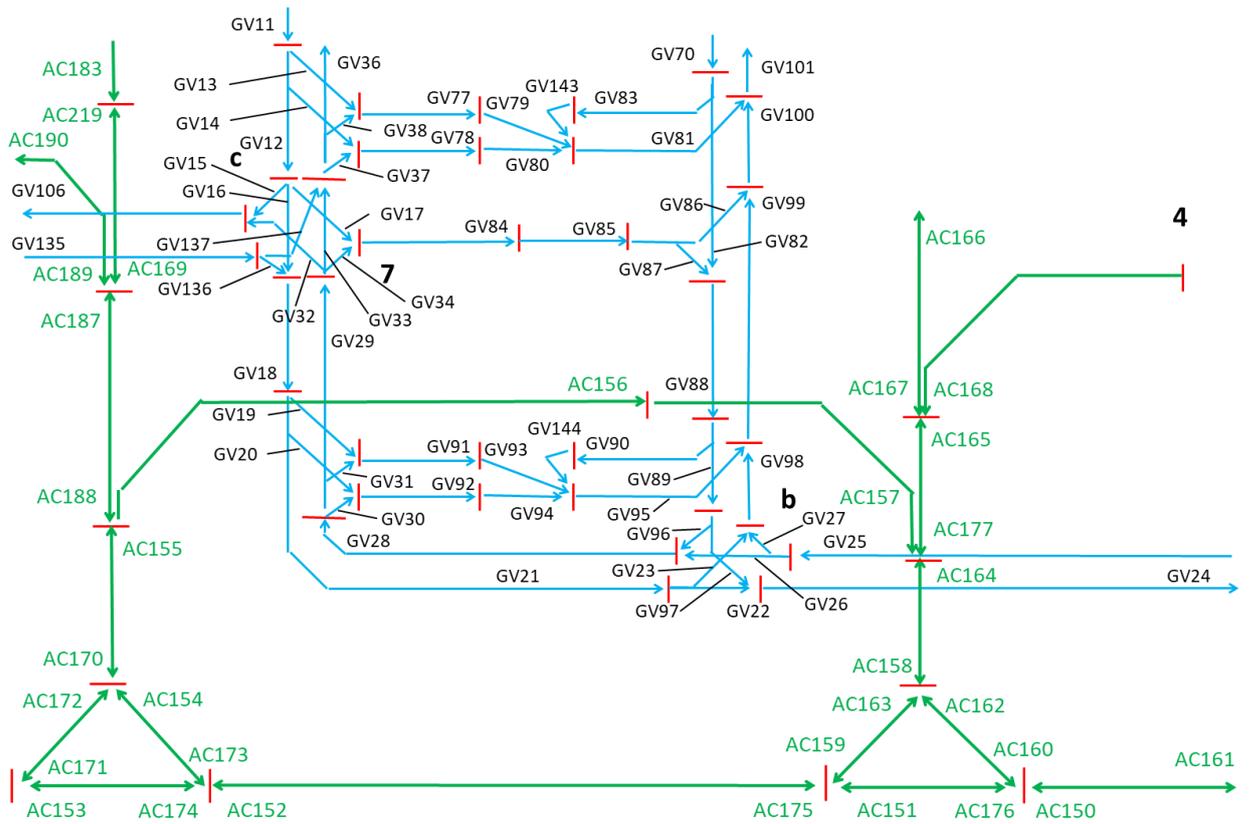
Appendix 1. Sections of the airport transport network



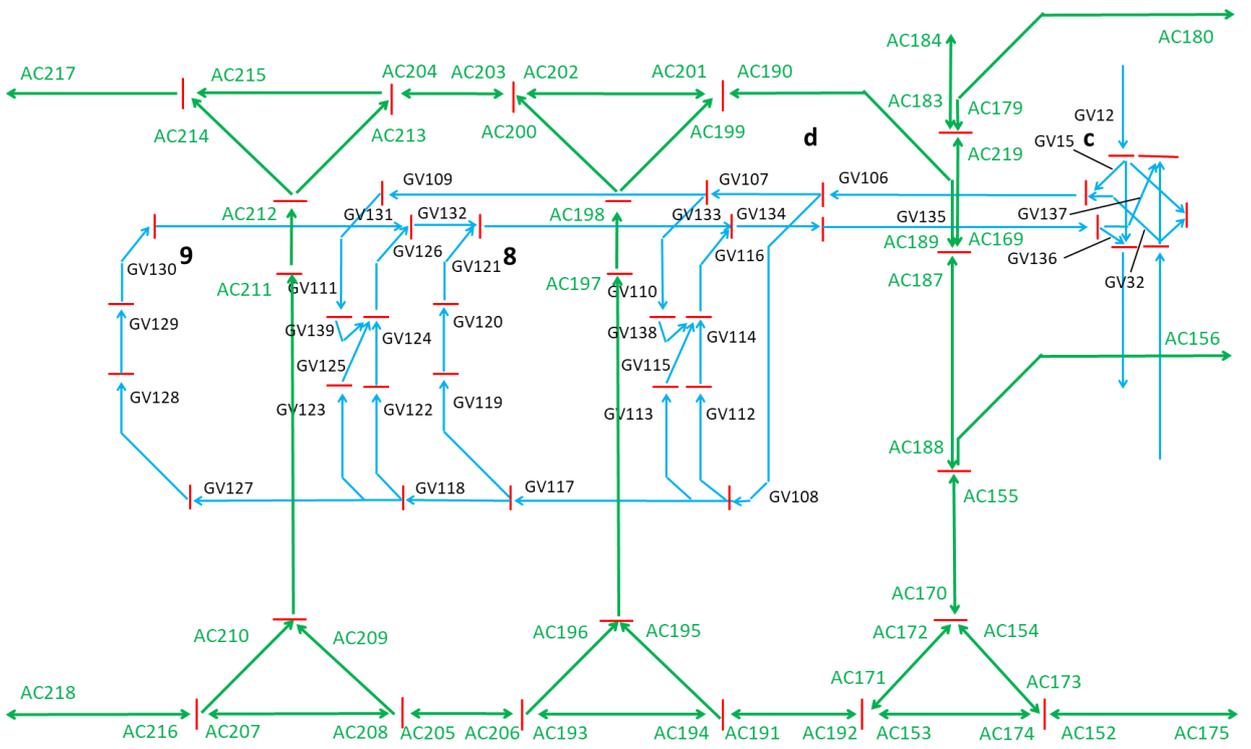
Fragment 1



Fragment 2



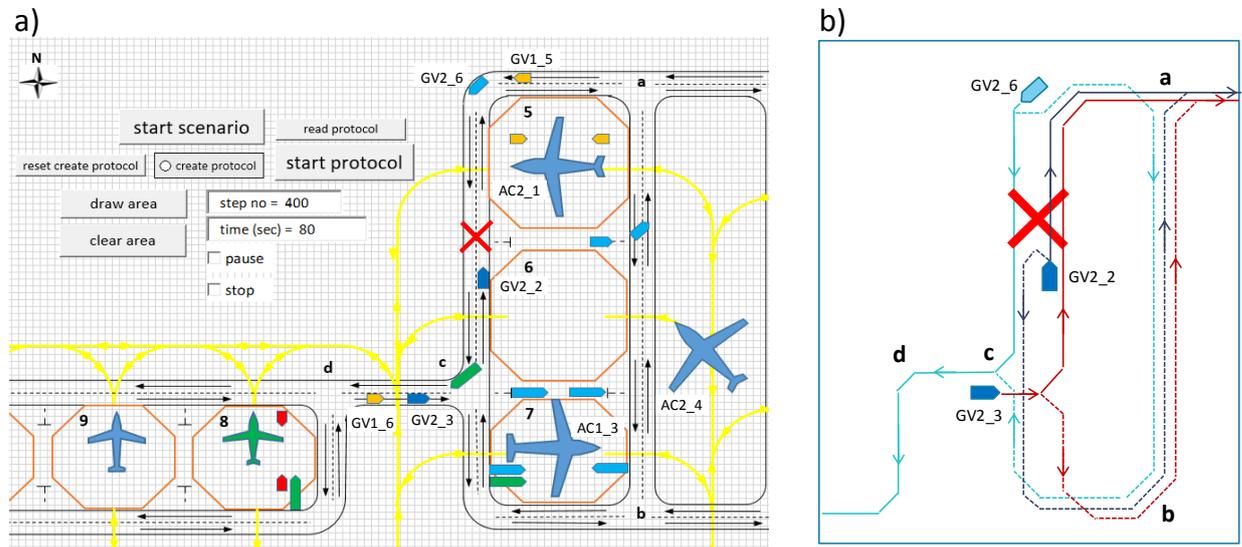
Fragment 3



Fragment 4

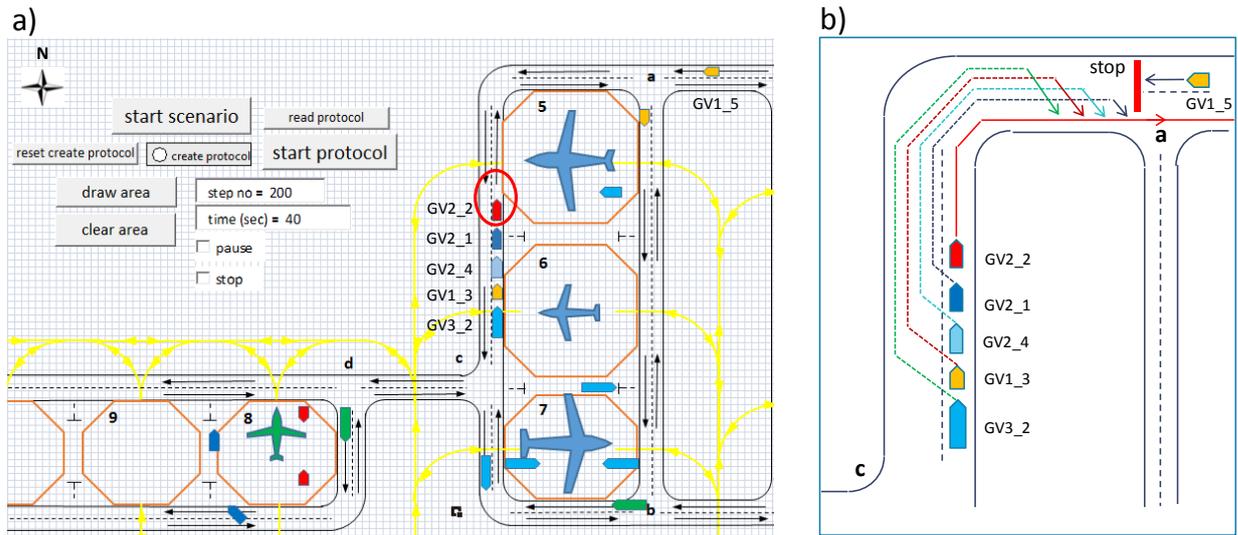
## Appendix 2. Animated pictures of critical situations in the airport transport network

### Critical situation 1



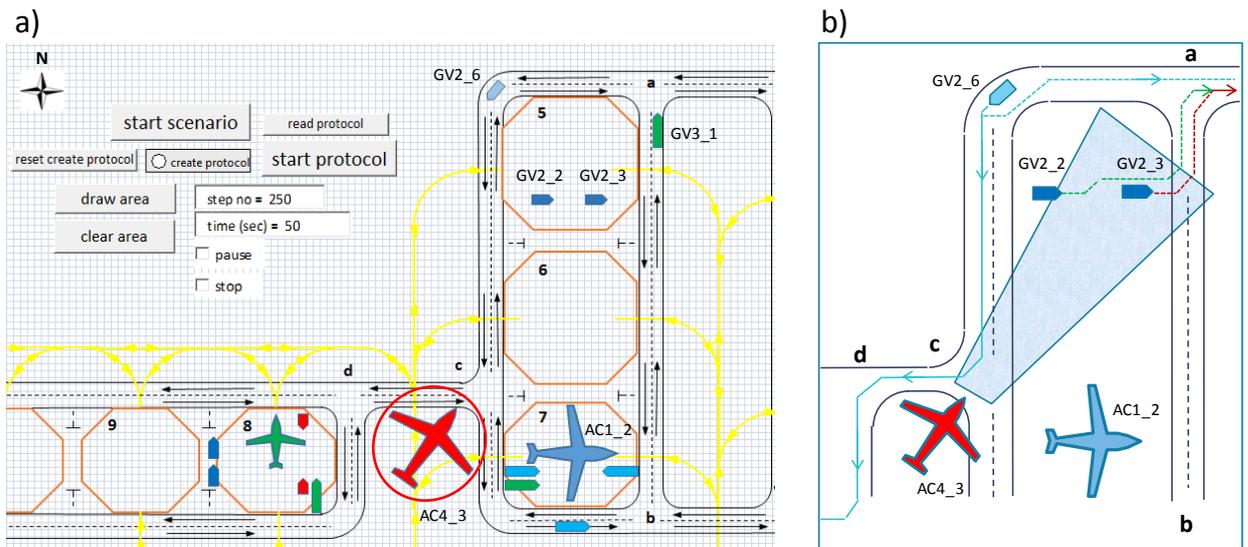
- a) As a result of a specific event, traffic was interrupted between stands 5 and 6 (see the cross in Figure a). Suppose that objects GV2\_6 and GV1\_5 were to move towards intersection *c* and further to stand 9. The object GV2\_2 was supposed to pass intersection *a* and leave the network, moving further eastward. The objects GV2\_3 and GV1\_6, after passing the intersection *c*, had to follow the same path as object GV2\_2.
- b) The object GV2\_6 is suggested to make a turn by 180 degrees and start moving along section GV48. At intersection *a*, the object will turn right and reach intersection *b*. After turning to the right, the object GV2\_6 will reach the intersection *c* and will head towards the stand 9. The object GV2\_2 will also first make a turn by 180 degrees, and then will start moving along the GV147 section in the south direction. After passing the intersection *c*, the object will continue to move southward, make a left turn at the intersection *b* and, moving northward, will reach the intersection *a*, after which it will leave the transport network. The object GV2\_3 will not make the previously planned left turn at the intersection *c*, but will turn right and, starting from the GV18 section, will repeat the trajectory of the GV2\_2 object.

## Critical situation 2



- a) The object GV2\_2 is moving at a very low speed due to engine failure. As a result of this, an accumulation of GVs was formed, which follow it. The objects GV2\_1, GV2\_4, GV1\_3 and GV3\_2 cannot overtake object GV2\_2, because it is forbidden to drive in the oncoming lane.
- b) The controller prohibits entering the network section between intersections a and c from the east direction (see the red line “stop” in Fig. 11b). The objects GV2\_1, GV2\_4, GV1\_3 and GV3\_2 are allowed to enter the oncoming lane, overtake object GV2\_2 and return to the right lane before the intersection a.

### Critical situation 3



- a) The aircraft with the designation AC4\_3 has a steering failure and there is a danger that, even in braking mode, it may drive into the zone of stand 5, where the GVs with designations GV2\_2 and GV2\_3 are located. Problems can also arise for the object GV2\_6, which is moving towards the aircraft AC4\_3. For the object GV3\_1 this situation is not dangerous, because in a few seconds it will pass the intersection a in the eastern direction.
- b) At the dispatcher's command, the objects GV2\_2 and GV2\_3 must urgently start moving towards the intersection a and pass it in the eastern direction. The object GV2\_6 must turn 180 degrees and start moving in the eastern direction with the maximum allowed speed.