



Special Issue

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## SNE Aims & Scope

**Simulation Notes Europe (SNE)** provides an international, high-quality forum for presentation of new ideas and approaches in simulation - from modelling to experiment analysis, from implementation to verification, from validation to identification, from numerics to visualisation - in context of the simulation process.

**SNE** seeks to serve scientists, researchers, developers and users of the simulation process across a variety of theoretical and applied fields in pursuit of novel ideas in simulation and to enable the exchange of experience and knowledge through descriptions of specific applications. **SNE** follows the recent developments and trends of modelling and simulation in new and/or joining application areas, as complex systems and big data. **SNE** puts special emphasis on the overall view in simulation, and on comparative investigations, as benchmarks and comparisons in methodology and application. For this purpose, **SNE** documents the **ARGESIM Benchmarks** on *Modelling Approaches and Simulation Implementations* with publication of definitions, solutions and discussions. **SNE** welcomes also contributions in education in/for/with simulation.

A News Section in **SNE** provides information on **EUROSIM** Simulation Societies and Simulation Groups.

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- **SN** Short Note, max. 6 p.
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## Editorial

Dear Readers – *The SNE Special Issue ‘EUROSIM Promotion’ was initiated by the EUROSIM Board on the occasion of the board meeting in Budapest, September 2018. Its aim is to promote the various activities of EUROSIM: the EUROSIM Congress, publications of activities of EUROSIM member societies in SNE, and the publication of the ARGESIM/EUROSIM Benchmarks. Representatives of the active EUROSIM societies have invited, reviewed, and prepared very interesting contributions. Most of these contributions have been published in SNE 28(4), December 2018 – ‘Special Issue EUROSIM Promotion’. Because of the big response on the call for the special issue, we had to continue with the contributions in SNE 29(1), March 2019 – ‘Special Issue EUROSIM Promotion cont.’. The electronic versions of both special issues will be announced via the EUROSIM mailing list and the printed versions will be part of the handouts at the EUROSIM Congress 2019 in Spain (see next page).*

*Two novelties for the ARGESIM Benchmarks are coming along with these special issues. First, the contributions to the ARGESIM Benchmarks are enriched by a broader variety of contribution types (Solution – Report – Study) and by an educational component (as it has turned out that the Benchmark Definitions are frequently used as basis for exercises in simulation education (details see the benchmark overview contribution in this issue). And second, the SNE Editorial Office has introduced a new classification for the benchmarks: a three-step classification consisting of i) general benchmark type (continuous, discrete, ...), ii) modelling aspects (state events, implicitness, higher modelling approaches as Modelica, System Dynamics, etc.), and iii) simulation experiments with the model (necessary and suggested). This content classification is extended by an educational classification, indicating the educational suitability for modelling, and for implementation and the addressed education level.*

*I would like to thank all authors for their contributions, and I would like to thank the Special Issue Editors for their very successful work. And last but not least thanks to the SNE Editorial Office for layout, typesetting, and publishing work with DOI indexing – allowing publication in time. Hope to see July in July in La Rioja at the EUROSIM Congress !*

*Felix Breiteneker, SNE Editor-in-Chief, eic@sne-journal.org; felix.breiteneker@tuwien.ac.at*

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Scope: Developments and trends in modelling and simulation in various areas and in application and theory; comparative studies and benchmarks (documentation of ARGESIM Benchmarks on modelling approaches and simulation implementations); modelling and simulation in and for education, simulation-based e-learning; society information and membership information for EUROSIM members (Federation of European Simulation Societies and Groups).

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## Editorial SNE Special Issue 'EUROSIM Promotion cont.'

Dear Readers,

This SNE issue SNE 29(1) *Special Issue EUROSIM Promotion cont.* continues the SNE special issue SNE 28(4) *Special Issue EUROSIM Promotion*. Because of the big response on the call for a special issue, publication of contributions had to be continued in this SNE issue. Both issues intend to promote the efforts of EUROSIM in distributing information on development on modelling and simulation – by means of the EUROSIM Congress, by means of EUROSIM's scientific journal *SNE Simulation Notes Europe*, by means of the work in EUROSIM's member societies, and by means of the EUROSIM/ARGESIM *Benchmarks on Modelling Approaches and Simulation Implementations*.

The triennial EUROSIM Congress is the main event of EUROSIM, the *Federation of European Simulation Societies and Simulation Groups*, with a long tradition since 1992, or 1986 resp., organized by one of EUROSIM's member societies. For July 2019 the *Spanish Simulation Society CEA-SMSG* invites experts in modelling and simulation to participate in the 10<sup>th</sup> EUROSIM Congress in Logroño, La Rioja, Spain. The organizers are preparing a thrilling programme: science, culture and social events (visit the congress website [www.eurosim2019.com](http://www.eurosim2019.com) or visit the *News Section* in this issue). EUROSIM and EUROSIM's member societies are promoting the congress by several activities. This SNE special issue will be part of the congress handouts, intending to attract authors to publish in EUROSIM's scientific journal, which is also open for post-conference publication of contributions to conferences of EUROSIM Societies.

Members of the EUROSIM Societies are working in very different thematic areas of *modelling* and simulation, and in different working environments – industry, research centers, universities, development companies, etc. For the SNE special issues, the publication coordinators of the most active societies have selected contributions which show this broad spectrum of modelling and simulation.

Contributions from CEA-SMSG, the *Spanish Modelling and Simulation Group* – organizer of EUROSIM Congress 2019, from SIMS, the *Scandinavian Simulation Society* (acting in Sweden, Norway, Denmark, Finland, and Iceland), from UKSIM (UKSIM is active in Great Britain and on international level), and partly from ASIM, the *German Simulation Society* (acting in Germany, Austria, and Switzerland) and from ARGESIM, the Austrian non-profit society for organization of simulation activities and publisher of SNE, have been already published in SNE 28(4).

The contributions for this issue have been provided by ASIM, DBSS, KA-SIM, and ARGESIM. DBSS, the *Dutch Benelux Simulation Society*, candidate organizer of the EUROSIM 2022 Congress, has decided for a contribution on a simulation-based framework for establishing capacity boundaries at airports – a very interesting *Overview Note*.

KA-SIM, the *Kosovo Simulation Society*, part of KA-CASE, the *Kosova Association of Control* (NMO of IFAC), has seized the offer for postconference publication in SNE. This issue presents a *Short Note* contribution from *UBT Conference 2018*, Pristina, on data mining for forecasting freight train delays (further postconference contributions in the next issues).

ASIM, the *German Simulation Society* (acting in Germany, Austria, and Switzerland), has also seized the postconference publication offer and has selected four contributions from the *ASIM Workshop GMMS/STS Braunschweig*, February 2019, which has been hosted by DLR Braunschweig (*German Aerospace Center*). Due to the host, the workshop presented a majority of contributions on aviation, two contributions published in this SNE issue: an *Overview Note* on the Virtual Test Aircraft Benchmark, and a *Technical Note* on an aircraft cabin simulation environment. Furthermore, a *Software Note* on comparison of variant managers for simulation models and an *Educational Note* on probabilistic state space models have been provided for this issue (further postconference publications in the next SNE issues).

And last but not least, the *SNE Benchmark Editorial Board* of ARGESIM has compiled an overview on development of the ARGESIM Benchmarks, presenting a new benchmark classification and an investigation on the educational suitability of the benchmarks.

The editors of this special issue would like to thank all colleagues from the EUROSIM Societies for selecting the contributions, and for providing the peer review. Furthermore, the editors express their hope that this issue indeed promotes the EUROSIM activities and animates simulationists to attend the EUROSIM Congress 2019 in Spain.

*Emilio Jiménez, EUROSIM President, Organizer EUROSIM Congress 2019 in La Rioja, Spain (CEA-SMSG)*

*Juan Ignacio Latorre, Organizer EUROSIM Congress 2019 in La Rioja, Spain (CEA-SMSG)*

*Felix Breitenacker, EUROSIM Treasurer, Past President, Editor-in-Chief SNE (ARGESIM, ASIM)*

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*Thorsten Pawletta, ASIM Vice President, SNE Benchmark Editorial Board (ASIM)*

*Umut Durak, ASIM Board Member, Organizer of ASIM Workshop GMMS/STS 2019*

We hope to see you all at the EUROSIM Congress 2019!

# Inside the Virtual Test Aircraft (VIRTTAC) Benchmark Model: Simulation Architecture

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**Abstract.** This paper presents the newly introduced Virtual Test Aircraft (VIRTTAC) model for use in benchmarks for aeronautics research. This model is shared in a black-box form and the core of an open-source benchmark suite. The model needs to remain undisclosed to fulfill its purpose but the principles underlying its internal structure are described in the paper. They permit to ensure that the model equations, parameters, and states are not accessible to the user, that the model can be easily ported to other simulation environments than MATLAB/Simulink, and that it is well maintainable on the long-term.

## Introduction

One of the major goals of research and innovation in aviation is to enhance the overall air traffic safety and to make traveling even more comfortable for both pilots and passengers. Novel aircraft safety and control features are normally developed for a distinct aircraft type due to e.g. a certain demand from the aircraft manufacturer or its availability for research facilities in terms of the existence of high-quality simulation models or flight testing capabilities. In the last years, numerous interesting and noticeable innovations to enhance aviation safety have been published for different aircraft types. For example, a very small study of developments in the field of aircraft flight envelope protection revealed that 12 different aircraft types or models were used in numerous publications [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17]. Hence, comparison of all the different developments is very difficult. Furthermore, the assessment of the

applicability of a published new methodology for a different type of aircraft is very difficult as normally the reader's knowledge about the underlying system is quite small. To overcome this problem and provide a common simulation model to the research community, NASA introduced in 2011 a generic aircraft simulation model called the "Transport Class Model" (TCM) derived from a sub-scale "Generic Transport Model" (GTM) simulation [18]. It is a fully functioning aircraft simulation including realistic engine and actuator behavior, sensor models and a flight control system. Although a significant number of failure scenarios were considered, computed and tested in CFD and wind tunnels [19], only a few of them were implemented in the distributed Simulink simulation model.

Moreover, the problem of comparability between various new developments is also present within the field of aircraft system identification. Various algorithms for parameter estimation and simulation model identification as well as related software tools have been developed during the last decades, but most of them were tested and verified for different aircraft. For example, Refs. [20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38] show results of various system identification techniques for more than 20 different aircraft types. Consequently, there is the problem to assess the quality of each methodology as there is no common base for an objective evaluation. The proposed high-quality model will be made available to all developers and will constitute a good complement to the already existing/available models.

This paper presents a new generic benchmark model that can be freely downloaded and used by the community for all kinds of investigations and in particular for defining benchmark applications to compare various approaches. This model is called VIRTTAC-Castor and is the first member of a model family called VIRTTAC, see Sections 1 and 2. The way this model works internally and the main choices made for the internal architecture of the current model implementation are



presented in Section 3. The conditions of use and licenses are mentioned in Section 4. The foreseen applications (see Section 5) include but are not restricted to supporting the investigations related to the estimation of the reduced flight envelope, fault-tolerant aircraft flight control, or the development of enhanced system identification techniques. It is built based on the knowledge gained at DLR over several decades of flight research, including all aspects of model building based on wind tunnel and CFD data as well as from flight testing (see [39] and references therein). By distributing this benchmark model and scenarios the authors intend to share some of this knowledge with the community and to help building comparisons across techniques used by different research groups.

## 1 VIRTAC: VIRTual Test AirCRAFT – Motivation and Objectives

### 1.1 Motivation

The whole idea of creating VIRTAC comes from the observation of the authors that in the area of flight dynamics and flight control there is a lack of commonly available, good and realistic benchmark models close to real aircraft behavior and characteristics. Most engineers and researchers are developing and/or using proprietary models for their work, but they often cannot share these models. Very often these restrictions result from the vehicles themselves and the fact that the manufacturer consider that these models might reveal some trade secrets or that they might lose some control over the investigations made based on the models of their vehicles. Within very large companies and organizations other types of issues can often be observed: dilution of responsibilities across several sub-organizations, internal dynamics, lack of incentive for long-term actions (constant changes in the intermediary management levels), often leading individuals to the conclusion that releasing some models and information is a potential risk for their career with little to no expected personal benefit.

Apart from slowing down research and innovation, this situation is also problematic in the sense that good science thrives through comparing hypotheses with observations and through independent validation of the results by different teams. Reproducibility of the results and cross-checking have been one of the corner stones in science and will remain so. Engineering-related dis-

ciplines differ from more fundamental science in the sense that its actual goal is less to produce new knowledge than to create something of economical or strategical value from the current body of knowledge. Whilst new knowledge might be produced along the way, the context strongly drives engineering work towards a future return on investment. In this context, openness is mainly seen as a potential future loss of revenue and as potentially endangering the currently foreseeable revenues (e.g. through additional risks). In order to support research and science in their domains, the authors decided to build and provide VIRTAC to the entire community.

### 1.2 Objectives

VIRTAC is developed with two main objectives in mind.

1. Provide high-quality representative models to engineers and researchers who need some but do not have access to the kind of research infrastructure that the authors have access to.
2. Provide a wide range of benchmarks to the community with various complexity levels, including some which include as many real-world effects as possible. The objective for the most complex benchmarks is that it should never be possible to pass them successfully but fail in the real-world due to effects that could not be tested with VIRTAC. Whilst the objective is to build complete benchmarks, the current work focuses on the development of the dynamic aircraft model at the heart of these benchmarks.

This last element “never pass the most complex benchmark if it fails in practice” directly leads to the need for representative system architectures and for modeling of all kinds of real-world effects. Information that would not be available in practice should also be hidden from the users by VIRTAC in order to ensure that it cannot be exploited. This includes information on the internal working of the models, their exact structure, parameter values, etc. This also includes all values that are required for performing the simulations but which would not be available in practice (e.g. information for which no sensor exists or is installed/available in a real aircraft).

*“VIRTAC users are basically aeronautical engineers who are confronted with a new aircraft. They can flight-test the aircraft and learn how it flies, but there is still a difficulty to predict how it behaves and they cannot access physical quantities unless there is a sensor measuring them.”*

Most users have prior knowledge about flight mechanics/dynamics and control and should use it. The behavior of VIRTAC will be very familiar to flight dynamics specialists, since the vehicle behaves like an aircraft. However, no equations and no aerodynamic coefficient derivatives will be made available. Precise knowledge of the aircraft can be gained by “virtually flight-testing” it (i.e. performing simulations). Knowledge can be exchanged with the rest of the community (e.g. through exchange of identified models) and is encouraged. The authors intend, aside from the website where VIRTAC and its updates can be downloaded, to organize with the interested parties an exchange platform for the community and gather information regarding all investigations that were performed by VIRTAC.

In the long term, the authors expect to build several models with slightly different characteristics and behaviors. For each of these models a rough description of the model will be provided. This description will include some basic description of the shape of the aircraft and its geometry and can be imagined as what a specialist would notice by looking at the aircraft. A few key technical specifications will be provided too. It is not intended for users to generate alternative data sets on the aircraft from other sources than the provided simulation model, therefore no detailed design data of any kind will be provided (no CAD geometry, structure design, etc.). The simulation is based on a nonlinear rigid-body model, which is meant to be valid for a pre-defined flight envelope and will include several high-lift configurations and additional effects like stall or ground effect in its final version. The aircraft briefly described in the present paper is the first of the VIRTAC family. As it will receive some siblings, a simple naming nomenclature is introduced.

### 1.3 The VIRTAC Family: Naming Conventions

VIRTAC is meant to become a family composed of several models. The idea of using a naming nomenclature for the whole VIRTAC family has been considered and rejected, at least for now, due to the diffi-

culty of ensuring that this nomenclature will be precise enough to differentiate the models that would be integrated in the future and also stable over time, such that the references made to one or the other model stay valid over extended periods of time.

As the number of models and variants expected to be developed and shared within the community will remain relatively low (most likely below 15), it was decided to give names to these models and to maintain a directory with the corresponding information for each of them. The individual names will be chosen such that:

1. They can be relatively easily pronounced by a wide range of speakers and easily distinguished even if pronounced by a non-native speaker.
2. They can be easily found with a search engine. For this a web search using both “VIRTAC” and the name of the configuration should lead only or mostly to documents related to that aircraft model, for instance past publications using this model.

Whilst the authors might chose other types of names in the future, these requirements should be satisfied with many star and galaxy names. The name VIRTAC-Castor is chosen for the first aircraft of the VIRTAC family introduced hereafter. This aircraft is a twin-turbofan configuration in the 100-passenger category. A twin-turboprop variant of this aircraft is foreseen and the name VIRTAC-Pollux is already reserved for it.

## 2 VIRTAC-Castor Model

### 2.1 Aircraft Geometry and Configuration

VIRTAC-Castor represents a generic short- to medium-haul transport aircraft for around 100 passengers with a high wing (small anhedral) and a T-tail configuration. This configuration has been completely created from scratch for VIRTAC. It has a configuration that remembers the Dornier 328 JET but is significantly larger. It is somewhat between a BAe 146-200 / AVRO RJ85 and a BAe 146-300 / AVRO RJ100 in terms of size, but only has two turbofan engines. Note that, even if DLR did identify models for the Dornier 328 [26] the herein proposed model was not derived from these data. As already mentioned, this configuration will receive a sibling (VIRTAC-Pollux) later that will be based on two turboprop engines, leading to different engine dynamic behavior as well as



greater coupling of the engines and the aerodynamics due to the propeller slipstream.

An artistic illustration of the VIRTAC-Castor is given in figure 1 and as well in figure 2 as three-side view. This illustration is provided for a common understanding of the modeled aircraft but no CAD model and precise geometry is given/distributed (at least for now). This aircraft was not produced through a complete pre-design process but its dimensions and characteristics should correspond to a short-to-medium range commercial air transportation role with a capacity of around 100 passengers. Table 1 provides an overview on its current dimensions and characteristics, which is not complete but can give the user the necessary information for subsequent model use.

## 2.2 Aircraft Aerodynamics

The aircraft model’s aerodynamics contain formulations to consider nonlinear and unsteady effects of wing and empennage. The model benefits from DLR’s large experience in modeling and identifying complex aerodynamic models for different airplanes, regions of the corresponding flight envelope and distinct applications in simulation [40, 41, 26]. The aerodynamic model is primarily formulated as a derivative model but includes several specific and complex extensions to enhance the model’s capabilities. It allows for example to cover unsteady trailing edge flow separation, which allows to model the normal stall behavior for an aircraft configuration as given in figure 1. The aerodynamic model formulation further allows to easily implement failure cases of an aerodynamic degradation of various sources as defined in section 2.7. A ground effect model (ground currently always at the elevation of 0 meters) is already included.



**Figure 1:** Artistic illustration of the VIRTAC-Castor configuration.

AC length	30.0 m
wing span	28.0 m
horizontal tail span	10.4 m
wing area	75.0 m <sup>2</sup>
horizontal tail area	20.0 m <sup>2</sup>
wing aspect ratio	10.4
mean aerodynamic chord	2.17 m
max. take-off weight	56 000 kg
empty weight	33 000 kg
max. fuel weight	16 000 kg
max. payload / PAX weight	12 000 kg
max. range	5 500 km
max. altitude	35 000 ft
max. operating Mach number	0.76
cruise Mach number	0.725

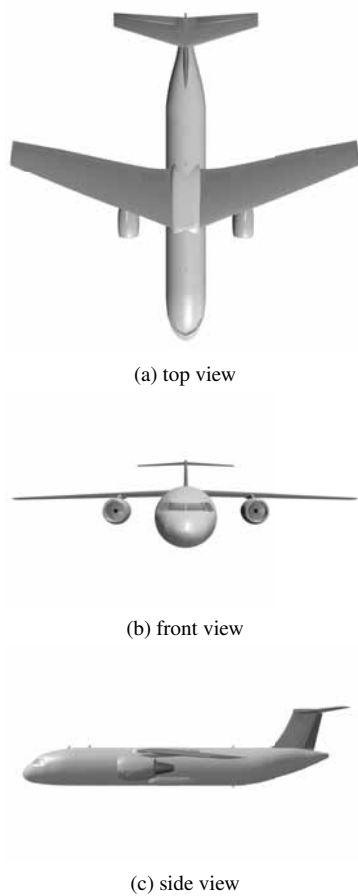
**Table 1:** Overall dimensions and characteristics of VIRTAC-Castor.

## 2.3 Propulsion

The VIRTAC-Castor model includes two turbofan engine models which can be controlled separately. The engine command inputs virtually correspond to a N1 (engine fan shaft rotation speed) expressed in %. The dynamic model will therefore correspond to the behavior of the engine plus the corresponding FADEC.

In the long-term quite good engine dynamic models will be integrated in VIRTAC-Castor and in all or most models in the VIRTAC family. However, a significant amount of work is still required from the authors in order to finish building up these models and to integrate them into the VIRTAC structure. As a consequence, the first versions of VIRTAC-Castor are expected to be delivered with much simpler preliminary models. These models will be representative for most scenarios, but as soon as the user-implemented flight control system will be very dependent on the engines’ transient response, the validity of results will have to be checked. For instance, no serious development and tuning of a control law or autopilot based only on the engines (i.e. a propulsion-controlled aircraft or PCA as in [42, 43, 44, 45]) will be possible with the preliminary model. Simple relatively low-gain autothrust/autothrottle functions would however not be too strongly affected.





**Figure 2:** Artistic illustration of the VIRTAC-Castor configuration, multiview projection.

## 2.4 Flight Controls

The simulation model of VIRTAC-Castor contains several control surfaces including various spoilers on the wing which may be more than usual for this size of airplane. In detail, the model provides:

- trimable horizontal stabilizer
- left and right elevators
- left and right ailerons
- rudder
- five spoilers on each side (four roll spoilers/airbrakes and one ground spoiler)

Actuator models are included for all control surfaces. Limits (deflection, deflection rate, and acceleration) are included. The actual control surface deflection is measured internally by the actuator and provided as output of the VIRTAC-Castor model. The com-

manded signal and the measured deflection can therefore be compared; for instance users might want to compare them within a flight control system fault detection logic. Numerous possible faults will be integrated in the actuator models and be added over time, see section 2.7 hereafter.

## 2.5 Sensor models

Sensor models are a crucial element for VIRTAC: they are the only way to know what is happening to the aircraft during the simulation. The physical quantities measured, the sensor characteristics (e.g. calibration, noise, dynamic behavior, quantization errors) as well as all the real-world issues related to where and how they are installed on the airframe will be defined as closely as possible to the state-of-the-art regular aircraft instrumentation. Currently, the authors are considering future inclusion of better sensors, which would resemble a complementary flight test instrumentation (FTI) and could be used for system identification studies. If FTI-like sensors were included in VIRTAC in the future, these sensors should not be used for flight control, flight control adaptation, or fault detection and isolation studies as they would not normally be available on the aircraft in regular operations.

The usual list of measurements provided by air data and inertial reference systems on Part/CS-25 airplanes is available for VIRTAC(-Castor). This includes attitude angles, rotational rates, accelerations, inertial velocity vector, static and total pressure and vertical speed, the various airspeeds, inflow angles ( $\alpha$ ,  $\beta$ ), air temperature, etc. and many derived quantities. For each available measurement sensor characteristics and real-world effects are considered. When it is common practice to have redundancies in the regular aircraft instrumentation, several sensors will also be modeled. The relationships used in practice to derive the physical quantities that are not directly measured will be modeled such that the propagation of faulty measurements can be correctly simulated during faulty scenarios.

For now, VIRTAC-Castor contains three inertial reference units providing the corresponding measurements of accelerations, rotational rates and attitude. Furthermore, there are four air data systems measuring angle of attack, angle of sideslip, and calibrated airspeed as well as static pressure, static temperature and barometric altitude<sup>1</sup>.

<sup>1</sup>with VIRTAC-Castor version 0.5-alpha



## 2.6 Landing gear

The influence of the landing gear on the aerodynamics is already included, but the gear itself, the wheel and tire dynamics as well as the braking system are not implemented yet. In the future, VIRTAC will also include models for the landing gears and their systems as well as more realistic ground elevation profiles and runway characteristics.

## 2.7 Test scenarios and failure cases

For the first version of the benchmark model several test scenarios and failure cases are already available and will be extended in the future. The currently foreseen set of scenarios mainly contains aerodynamic degradation and control surface actuator failures:

### Wing Ice Case

Ice can have hazardous effects on the aircraft's flight characteristics. Large accumulations on the wing – mainly mostly near the wing leading edge – increase the drag and reduce the maximum angle of attack and consequently increase the stall speed. This has a direct influence on the safe flight envelope and poses a threat to crew and passengers. VIRTAC-Castor (and probably most future VIRTAC family models) will be capable of considering the effects of a generic wing ice accumulation in terms of the resulting aerodynamic degradation. The timely increase of degradation resp. accumulation as well as a de-icing can be triggered by the user whereas the details about the degradation itself are part of the closed model to allow a fair and realistic test of new developments like detection algorithms or robust flight controllers. The corresponding knowledge about the expectable effects and a realistic amount of degradation is derived from previous icing research at DLR [46, 47] where high-quality simulation models were identified from flight data.

### Horizontal Tail Damage & Icing

The model will include changes of dynamic behavior caused by a partial loss (various levels) of one side of the HTP similar to [48] resulting in a changed controllability of the aircraft. Partial damage at the HTP or VTP leading edge as well as local icing of the empennage will probably be included in the future.

### Actuator Faults

Faults in the actuators will be included in the future. Each actuator will be controlled independently (ailerons, elevators, rudder, spoilers) and possibly be subject to faults. The faults cases that will be implemented include the typical actuator faults such as hardover, runaway, frozen at a given position, change in dynamic behavior, etc.

### Engine Bird Strike

Bird strike damage to engines is considered for later inclusion in VIRTAC-Castor. Simulation models were developed at DLR for the EU FP7 Man4Gen project [49, 50], which could be adapted for the VIRTAC-Castor turbofan engine, once its nominal version will be available. These models are relatively simple and the variability of the effects of bird strikes in engines makes it very difficult, if not impossible, to build a generically valid model for such events. Investigating the adverse consequences of such failures onto advanced fault detection algorithms and their robustness against them is certainly interesting. This would be possible when such engine fault models will be integrated into VIRTAC.

## 3 Implementation Challenges

### 3.1 Need for a Black-Box implementation

The internal implementation of the VIRTAC dynamic models is hidden from the user (black-box), which permits to prevent users from accessing any information which would not be available in practice. In the MATLAB/Simulink environment this is done by encapsulating the dynamic model in a Simulink s-function. This has also the advantage of significantly speeding-up the simulations while still letting the users be able to include their part (e.g. a flight control system) around the VIRTAC flight mechanics models. At the time of writing this paper, the current implementation of the VIRTAC-Castor model runs about 50 times faster than real-time on a Desktop PC with MATLAB/Simulink R2007b 32bit under Windows 7 Enterprise SP1 and with an Intel Core i7-2600 @3.4 GHz.

### 3.2 Availability beyond MATLAB/Simulink

The authors (and designers of VIRTAC) also aim at ensuring the wide availability of the VIRTAC models and their long-term maintainability. The wide availability includes the possibility to bring VIRTAC to other environments, including other scientific software suites than MATLAB/Simulink. The internal implementation therefore makes a clear separation between the MATLAB/Simulink-specific features/APIs and the code responsible for the trim and simulation of the aircraft. The former is confined to the s-function code which is only a wrapper for the actual dynamic model (the latter). The latter is implemented in a library to which the s-function is statically linked. This decomposition should permit to create VIRTAC implementations which could be used with a large variety of other tools, such as Scilab/Xcos or even using the Python programming language. The authors want to have the possibility of offering VIRTAC for other tools than MATLAB/Simulink with a reasonably low amount of work; however, it is crucial to ensure that the capabilities provided by VIRTAC and its specific benchmarks remain the same for all these implementations. A benchmark scenario will only be officially supported by the authors if it is available for all supported implementations, or if there is a valid technical reason for not doing it. A valid technical reason might be that the benchmark scenario includes VIRTAC and another component which cannot be ported to the other tools/platforms (e.g. due to intellectual property restrictions or if porting this component would require an unreasonable effort).

### 3.3 Modularity for Long-Term maintainability

The long-term maintainability includes the need for a modular internal structure of the simulation code. This is done by using a general structure, whereby the different model parts can be defined separately and “connected” to each other. This makes the modeling paradigm used inside the VIRTAC models similar to the one used in graphical modeling tools, like Simulink or Xcos. No graphical editor has been developed to create or edit these connections but the C++ syntax used for this is as simple as the MATLAB/Simulink “add\_line” command. The internal implementation concept chosen might evolve over time without the VIRTAC users noticing any change<sup>2</sup>. Currently, the

<sup>2</sup>Beyond possibly slightly modified rounding errors, which could also be caused by changing the compiler or the compiler flags.

internal implementation is a compromise between modularity and complexity of the implementation workflow. More automated or even code-generation-based solutions have not been chosen because it has been estimated that their additional level of complexity and their restrictions<sup>3</sup> outweigh the benefit expected for VIRTAC. Depending on the future evolution of VIRTAC and of the corresponding aircraft models and benchmark scenarios this choice might be reevaluated. One of the important features that the current implementation requires is a mechanism permitting to call the different model parts in the right order such that the simulation results remain correct, i.e. as if the model had not been split into different entities. Note that such a mechanism is also required in simulation tools like Simulink and Xcos.

The main modules that are currently defined are:

- Flight Control Actuators
- Propulsion
- Airframe Dynamics (which includes the aerodynamics and the equations of motion)
- Sensors
- Landing Gear (foreseen but not implemented yet).

A simple environment model is already included in the current version of VIRTAC but is not a separate module. It includes a standard atmosphere model and a Dryden turbulence generator. The possibility to bring some icing conditions is currently being developed to enable icing-related envelope reduction benchmark scenarios. The implementation of the environment model is likely to be largely redesigned in the near to mid-term future.

## 4 Conditions of Use

### 4.1 Who can use VIRTAC? What are the conditions of use?

#### Source files

As of now, anyone can download and use the VIRTAC models. Any part of VIRTAC provided in source form (e.g. MATLAB .m files or Simulink models) is subject to the very permissive MIT license:

<sup>3</sup>They always include some assumptions on the structure of the system and/or produce a barely human-readable code.



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## 5 Foreseen Applications and Community Involvement

VIRTAC is expected to become a very useful tool for a quite large community of researchers and engineers working in the areas of atmospheric flight mechanics (AFM) and guidance, navigation and control (GNC). A couple of foreseen uses are listed hereafter and the authors are welcoming further development suggestions linked to any other potential application of VIRTAC.

### System Identification / Machine Learning

Aircraft system identification is a rather obvious potential use of VIRTAC, as it allows its users to perform *virtual* flight tests. Very few organizations and companies worldwide possess the financial resources and the technical means to perform large flight test campaigns for system identification purposes. VIRTAC is expected to give many researchers and engineers access to a (virtual) test aircraft, who would not have this kind of possibility otherwise.

### Flight Control, Flight Guidance, and Fault-Tolerant Control

The flight control and flight guidance communities can also benefit from VIRTAC models as they constitute fully working and representative aircraft models on which control and guidance concept can be developed, tested, and compared among teams that would otherwise not have common benchmarks, for instance due to intellectual property restrictions. VIRTAC is designed from the beginning to support fault-tolerant control in all its possible forms by providing representative models with many possible fault scenarios. The objective of the VIRTAC models is to provide valid models 1) which help the users (e.g. control scientist) to understand the exact consequences of these faults on the overall system and 2) which can be used to validate and demonstrate the fault-tolerance capabilities of some controllers. Very often the fault-tolerant control techniques will require specific model formulations to be designed or to be used online: VIRTAC provides no simplified model for control design, each user should build his/her own simplified model or reuse some that might have been built and shared by others.

Within a few years period, it is planned that VIRTAC models will also be ported to the DLR AVES simulator in order to permit pilot-in-the-loop evaluations of the most interesting control concepts developed for

VIRTAC and for which a pilot-in-the-loop evaluation could be valuable. Please contact the authors for further information on VIRTAC@AVES or to send some suggestions.

### Teaching Flight Mechanics and Control

The authors expect that VIRTAC could become very useful for teaching purposes (in aerospace engineering but also for pilot training), even though teaching is not in the focus of the current developments. Nevertheless, the authors would be happy to support such efforts, within what can reasonably be performed without limiting the usability for the other potential user groups.

### Long Term Evolution of the Model and Community Involvement

The model provided with this paper is only the first step of a long-term initiative aiming at providing good and representative models to the community. Even if the task of building a flight dynamics model is a very instructive, the amount of work spend in our community to build models for the purpose of our research activities is very high. Additionally these models are often very restricted due to unavailability of the required data to the model builder or to other practical constraints. The multiplication of models and the relative lack of a common benchmark often makes it difficult to compare the proposed approaches.

The evolution of the herein proposed benchmark models and scenarios will be strongly oriented towards the needs of the community. In order to remain a good validation tool, the system will need to remain only partly observable to the end user and therefore some parts will remain undisclosed (at least for several years). For everything else (e.g. definition of new test scenarios, automatized evaluation scripts, etc.) VIRTAC will be as open as possible and contributions from the community are very much welcome.

## 6 Summary

This paper presents the recently started development of a series of generic aircraft models gathered within the VIRTAC family. These models will be available to the research community in the future, e.g. as high-quality validation benchmark models or for testing new methodologies in the fields of robust control or reduced envelope protection. The first model of this family, the 100-passenger jet airplane VIRTAC-Castor, already



provides within its preliminary 0.5-alpha version a basis including various necessary functions to simulate respectively virtually flight test the aircraft on the one hand. On the other hand, the aircraft might already been used for its foreseen purposes. After finishing the development of VIRTAC-Castor in the near future, it will be followed by a turboprop version of similar size called VIRTAC-Pollux.

## VIRTAC download and contact information

To provide the models of the VIRTAC family to the community, a GitHub repository was created. This repository is located at

<https://github.com/VIRTAC/VIRTAC>

and will be updated if necessary due to new model developments of aircraft within the VIRTAC family.

For any questions on VIRTAC-Castor, the VIRTAC family or for general support concerning the VIRTAC simulation, please use the following VIRTAC email address:

VIRTAC@dlr.de.

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# Model-based Methodology for Identifying Capacity Limitations in Airports: Mexico City Airport Case

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**Abstract.** The current study presents a methodology for analysing and identifying the limitations in capacity of an airport, the methodology has been implemented in the case of Mexico City Airport which is a congested airport in Mexico. The methodology allows identifying what room is left for absorbing more traffic and what options are available while a new infrastructure is in place. The methodology revealed, that there is still room for absorbing more traffic under certain conditions and starting from that, actions can be taken in order to increase the capacity or reducing congestion in the airport.

## Introduction

Simulation is the imitation of the operation of a real system or process over time. It is used to generate artificial history and data of a system, and the observation and analysis of that artificial history to draw inferences concerning the operating characteristics of the real system (Banks et al. 1996).

The behaviour of a system as it evolves over time is studied by developing a simulation model. This model usually takes the form of a set of assumptions concerning the operation of the system. These assumptions are expressed in mathematical, logical, and symbolic relationships between the entities, or objects of interest of the system. Once developed, verified and validated, a model can be used to investigate a wide variety of “what-if” questions about the real-world system (Banks et al. 1996). Potential changes to the system can then be simulated to predict their impact on the system’s performance.

Furthermore, simulation can also be used to study systems in the design stage, before such systems are built based on relationships taken from a similar system.

Thus, simulation techniques can be used both as an analysis tool for analysing and predicting the effect of changes to existing systems, and as a design tool to predict the performance of new systems under varying sets of circumstances. Simulation itself has proven to give good solutions in different fields such as transport industry (Longo, 2011), manufacturing (Latorre et al., 2013) and in some airport problems (Mujica Mota 2015), (Yan et al. 2002) among others.

Simulation’s power lies in its capacity of using different abstraction levels and being able to stress many aspects of the problems than cannot be addressed with other techniques such as stochastic behaviour, emergent dynamics or cause-effect relationships. When analysing specific problems such as scheduling or optimization of resources, it cannot ensure the optimal outcome since the experiments performed with the model explore a subset of the whole different configurations of the system under study. However, with the inclusion of uncertainty in the form of probability distributions, we ensure that we consider extreme situations, (that were not part of the data used for the construction of the model) that put in risk the behaviour of the system, also known as tail behaviour (Biller and Nelson 2002).

Furthermore, the outcomes from simulation are more feasible or realistic for being implemented in the real system, which sometimes is not the case of exact solutions coming from traditional analytical techniques. Some authors can argue that with the use of simulation for the decision-making process there is an implicit level of uncertainty, this is correct, however this drawback can be overcome by increasing the number of experiments with the model (Law 2015).

Simulation has been traditionally considered an evaluative tool in which the analysis of systems is performed executing several experiments with the simulation model to obtain insight about the behaviour of the system under study in combination with statistics.

The simulation models can be developed using different tools that range from general-purpose to specific-purpose ones. The advantage of using a general-purpose tool over a specific one is that it provides the developer or analyst more freedom for including different angles, elements and/or resolution levels of the problem under study. On the contrary, specific-purpose tools are limited to the perspective of the owner/developer of the tool which in most of the cases involves the payment of a commercial license for its use.

For general-purpose tools that can be used for studying aviation-related problems we can mention modelling formalisms such as coloured Petri nets (Jensen & Kristensen, 2009) or commercial software such as SIMIO (SIMIO 2017) or ARENA (Rockwell 2017). In the case of specific-purpose tools for aviation we can mention ARC's CAST (2015), SIMMOD (ATAC 2017), or TAAM (Jeppesen 2017) among others in which the modeller uses mostly a drag & drop approach from a library of pre-defined objects for developing the model(s). Regarding the aviation systems, simulation has been relatively recently applied in a diverse number of cases and problems; in the following section a review is presented.

## 1 Literature Review on Airport Modelling

The studies in airport modelling are diverse. In the following paragraph we present the diverse angles in which some aviation-related problems have been tackled in order to establish why the authors consider the use of simulation as a valid and more powerful tool than the traditional analytical techniques that in most of the cases generate exact solutions.

In literature, one can find many studies that analyse runways systems or allocation problems (check-in or gate allocation), few that include taxiway systems or aprons areas, some others tackle air traffic management policies and operations. In general, most of them are considered isolated problems in which the precedence of processes does not affect the solution, therefore only few analyse all these subsystems in an integral fashion.

Several studies focus on improving the runway throughput due to its importance on the overall airport capacity, for example the studies of Pujet et al. (1999) and Simaiakis and Balakrishnan (2015) uses queue models for increasing capacity, Rathinam et al. (2009) applies dynamic programming for a scheduling problem, Sandberg et al (2014) makes field tests for improving the capacity controlling the pushback rate. Pavlin et al. (2006), put the focus on increasing capacity by ana-

lysing the runway occupancy time by making a descriptive analysis of the situation while Burnham et al. (2001) focus on increasing airport capacity of a close parallel runway system by modifying the arrival procedures. On the other hand, Wei and Siyuan (2010), Bazargan et al. (2002), Bertino et al. (2011) present studies using specific-purpose simulators (SIMMOD and TAAM) while Mujica et al. (2017) uses a general-purpose simulator for including handling operators and aircraft in the same model.

Regarding airport surface management there are relevant work such as the one from Montoya et al. (2010), Simaiakis et al. (2014), and Khadilkar and Balakrishnan (2014), these approaches represent the airside system as a network and then they apply techniques coming from the mathematical programming field to organize the schedule of aircraft.

Other work focuses on how to alleviate congestion problems in airspace and on the ground, especially, they focus on operative problems as the following review illustrates. Concerning problems related to the airspace management, the sequencing and merging or scheduling of arrivals in the terminal manoeuvring area (TMA) has been studied mainly by Beasley et al. (2000), Beasley et al. (2001), Hu and Chen (2005), Michelin et al. (2009), Balakrishnan and Chandran (2010), and Zuniga et al. (2011). Most of the methodologies make an abstract representation of the airspace in order to apply the mathematical optimization techniques for finding efficient solutions to the arrival and departure management.

Studies related to ground operative problems can also be found such as the gate assignment problem presented by Bolat (2000) using a mixed binary math model; Chung and Adeleye (2006) used simulation for the evaluation of turnaround operations, Dorndorf et al. (2007) presents a review of mathematical models in which most of them are exact solutions, Kim and Feron (2012) approach the gate assignment problems using queue models, Mujica Mota (2015) presents a combination of simulation and heuristics for assignment problems in the terminal that can be also implemented in gate assignments or Narciso and Piera (2015) which go further and use a modelling formalism such as coloured Petri nets for gate assignment.

Other researchers have studied the taxi systems such as Mori (2012) whose approach is based on a car traffic congestion model. The research focuses on decreasing the "taxi-out time" and managing the time needed for pushback and engine start. On the other hand, Cetek et al. (2013) uses simulation models for analysing the congestion problem in the manoeuvring areas for identi-

fying problems of congestion, it uses different runway configurations for identifying potential solutions. Mirkovic (2014) focuses on the study of apron capacity using generic simulation apron models, he calculates apron capacity based on the number of stands and he evaluates different strategies for managing the apron.

Herrera et al. (2014) uses a simulation model for evaluating a new strategy for attending take-off and landings in Mexico City International Airport through the analysis of the air traffic control (ATC) activity. Jacquilat and Odoni, (2015) reported the interdependencies between flight scheduling and airport operations. They proposed a capacity utilization and scheduling model which combines three different models; first, a model of airport congestion that quantifies flight delays as a function of flight schedules and arrival and departure service rates, using a stochastic queuing model; the second model optimizes the sequential control of capacity utilization procedures to minimize congestion costs, for any flight schedule; they use a dynamic programming model. The third one is an integer programming model for scheduling interventions which uses a schedule of flights determined by airline scheduling as its starting point and modifies that schedule in a way that it reduces the imbalances between airport demand and capacity.

As it can be perceived from the review performed, some problems of aviation are tackled with exact methods in which the solution(s) are considered mathematically optimal, however, in most of the cases the solutions might be difficult to be implemented due to the abstraction level in which a minor modification of the situation make the proposed solution unfeasible. In comparison with traditional analytical techniques such as integer and dynamic programming, simulation is a more flexible approach that can be used in a bottom-up fashion, so it is not necessary to oversimplify the description of the system in order to approach it. Furthermore, it can integrate not only all the elements considered in the other techniques such as the causal relationships, but also the uncertainty or variability present in the different processes in the form of probability distributions that capture diverse situations which are used in the model as stochastic variables. For this reason, the authors decided to develop a simulation model that can incorporate the uncertainties of the processes at different levels (strategic and operational) and then evaluate what would be the impact of the proposed implementations with the aggregated effects of the variability present in the system.

In the current paper, we present the methodology for studying a real case study: Mexico City International

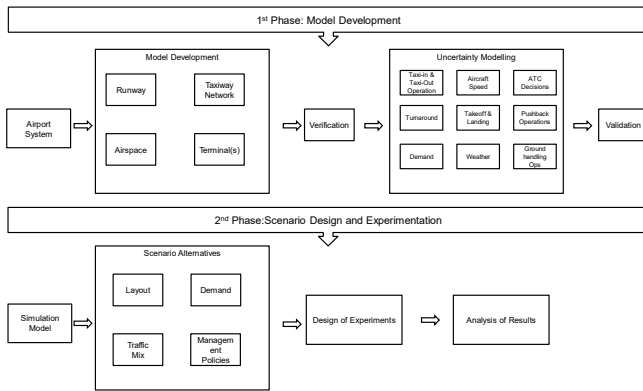
Airport. The methodology presented is based on discrete-event systems following a particular one in which we include the strategic uncertainty and stochasticity of the most relevant operational processes in the system to make the simulation as accurate as possible. By using the general-purpose approach, we take advantage of two things; first, we are not limited to the boundaries set by the simulation paradigm of the developers of the available commercial simulators and second we can use the model to scale it up for tackling more complex problems such as the study of the airport network in Mexico (see Wellens and Mujica 2017); this approach could not be possible using a commercial tool as it has been previously discussed. Furthermore, the modelling details are presented in such a way that the reader can replicate the study in a similar airport with a general-purpose tool. We use the methodology for evaluating feasible implementations that can alleviate congestions problems under close-to-reality conditions.

Our work uses a novel methodological approach in the aviation field that can be followed by the reader for evaluating the impact of strategic uncertainty considering also the actual variability of the stochastic processes inherent to the airport. The approach can provide support for airport planners that aim at reducing the risk of over-dimensioning an infrastructure or are interested in finding the practical limitations of growth in a particular airport facility.

## 2 Methodological Approach

A simulation-based approach was used to analyse the performance of the airside of the airport, with the objective of identifying the limitations and bottlenecks during the operation of a high-demand day and for proposing alternatives to alleviate the congestion problems. The model simulates the movements over a 24-hour period; based on a public flight schedule of the airport (OAG 2015). The model was validated using information from Flight Stats and Flight Radar (Flight Radar24 2017); these applications are live representations of the positions and speeds of aircraft worldwide and are based on Automatic Dependant Surveillance Broadcast (ADS-B) which are transponders installed in the aircraft.

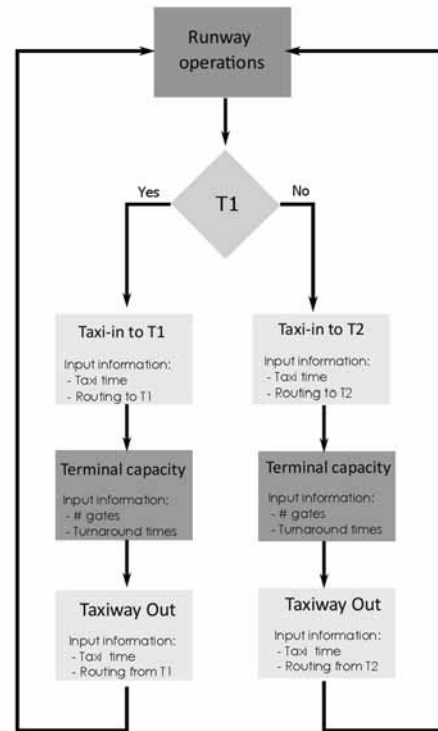
The model was composed by putting together the main elements of the airport system, namely: runways, taxiway systems, terminal I and terminal II in the case of Mexico City Airport. The handling operations as well as the modelling of passenger movements were left out of the model. The general approach for the modelling of the system is the one presented in Figure 1.



**Figure 1:** Methodological approach for simulating airport systems.

As one can note, the first phase of the methodology consists of the identification of the elements that should be included in the model, together with the logic and layout. The answer to this question will come from the objective of the study. The next step is to verify the correct logic of the model (verification step). Then, one can decide which elements to include where variability is expected to have more impact in the performance of the system. For the different elements, a different approach can be suggested:

- **Taxi Operation:** in most of the cases the taxiing speed variability plays an important role in the capacity of the taxi network. It can be modelled as a Uniform probability distribution of speeds or as a Normal or Triangular distribution depending on the data availability.
- **Aircraft Speed:** the speed has more impact in the modelling of airspace. It can be modelled as a Uniform distribution with the same probabilities for the range of speeds that the different aircraft use based on the radar information.
- **ATC:** the decision of ATC can be modelled as management policies within the airside, such as the departure priorities. It can be modelled as a scenario using a specific policy for the scheduling of departures or arrivals.
- **Turnaround:** the turnaround time depend mostly in the type of aircraft and business model of the company (LCCs vs FSCs). It can be modelled as probability distributions that consider the turnaround times of the different combinations Carrier-Aircraft.
- **Take-off and landing:** It can be modelled as a probability distribution for the runway occupancy times.
- **Pushback:** It can be modelled as a probability distribution of the delays in pushback start.
- **Demand:** It can be modelled as different scenarios with different demand levels. This is useful for planning purposes.



**Figure 2:** Conceptual approach of the simulation model.

- **Weather:** this can be modelled as discrete distributions in which the wind direction and strength have a discrete probability of occurrence.
- **Ground handling:** the operations in ground handling can be modelled as a sequential or parallel probability distributions that are constructed based on the real values of the operations.

For the case under study, the turnaround operation was modelled by a sum of processes represented by delays. The conceptual approach of the model of Mexico is depicted in Figure 2.

Once the model is validated (Sargent 2011), a flight schedule of a representative day has been used as the main input for it. The simulation model allows incorporating the strategic uncertainty or variability of the operations in the airport such as traffic mix, growth, variation in turnaround times, taxi times among others. Furthermore, the level of detail enables the integration of technical and operative restrictions imposed by the airport authority following the International Civil Aviation Organization (ICAO) rules. The most relevant characteristics are the wake-vortex and taxiway separation, taxiway routing for landing and take-off, and the routes followed by the aircraft in the taxiway network and the correspondent speeds during the different considered phases: landing, taxi-in, taxi-out and take off.

In addition, the aircraft speed, equipment type, and the routing followed by the different aircraft have been also included in the model. In the following paragraphs the characteristics used for the modelling of the different elements of the airport are described in detail.

### 3 Case Study: Mexico City International Airport

In 2015, the Mexican airports network transported more than 73 million passengers and about 655,500 tons of cargo. Regarding the passengers, 63% were domestic and 37% international. Mexico City International Airport (IATA code MEX) moved 38.43 million passengers, more than a third of the total traffic of the country (SCT,2015), besides Mexico City being one of the gateways to the country, it is a centralized country which means that the main governmental offices and federal institutions are in Mexico City; for this reason, it is important not to limit the growth and development of the airport in Mexico City. It is forecasted that the demand will continue to grow in the coming years (around +5% in aircraft movement and +12.2% in number of passengers) and 41 million passengers are expected by 2020.

#### 3.1 Airport infrastructure at MEX

MEX runway system consists of two runways with dimensions of 3963x45m and 3985x45m, respectively. Runways operate in a dependent and segregated mode which means that one is used for arrivals and the other for departures. According to Herrera et al. (2014), the arrivals are performed on the runway 05R/23L and departure on runway 05L/23R. It includes 96 parking positions, 36 direct boarding gates in Terminal 1 (T1), 34 in Terminal 2 (T2), and a total of 74 operative gates. MEX accounts for two passenger terminals, T1 and T2 which are interconnected by a 3km monorail and road access. T1 is used for both domestic and international flights and the main partners of SkyTeam for which Aeromexico is part of, whereas T2 is operated mainly by Aeromexico and other airlines. Figure 3 depicts a schematic view of the airside of the airport.

#### 3.2 Traffic growth in MEX

According to data from SCT (2015), the biggest domestic airlines in terms of transported passengers are Aeromexico, Volaris, Interjet and Aeromexico-connect. In Mexico, the Low-Cost Carriers (LCCs) business model arrived in 2005 with 5.5% of the market share and a fast and steady growth allowed them to get to the 60% of the domestic market by 2013.

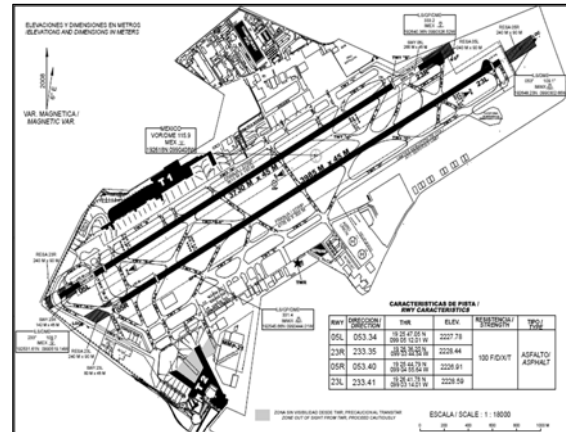


Figure 3: Schematic view of the airport.

This sector is operated by 3 main companies (Interjet, Volaris and VivaAerobus). Unlike these companies, there has been limited development of LCCs, while the potential in the market is clearly there (see Figure 4).

In recent years, LCCs from the US have started operations in MEX, in particular Southwest and JetBlue which is translated into more pressure for the Mexican ATC. Furthermore, it reveals the capacity of LCCs to use their flexible business model for using available slots in congested airports such as MEX in contrast with the Legacy carriers which operate mostly in a Hub-Spoke basis and require attractive slots so that the feeder traffic can connect with the log-haul flights.

To release the pressure of the current facilities and for allowing the continuous growth of demand, the government has announced the upgrading of a new airport in the vicinity of the current one. This airport will be operational by 2022 in which two runways are expected to be operational. As the previous figures suggest, airlines are interested in increasing their operations in MEX but until the new airport is constructed there is the need of tools that help managers to understand what the true capacity of the current airport is for absorbing more traffic; and they also require tools that provide support in the transition from the operation with the current airport to the operation with the new one.

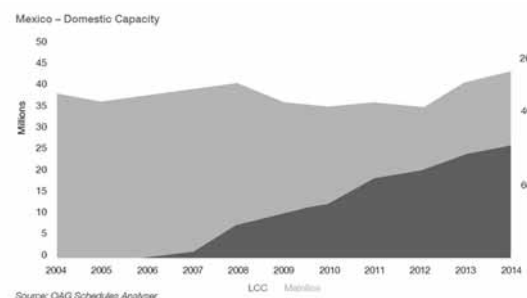


Figure 4: Evolution of traffic on Mex.

The authors have developed a robust simulation-based methodology that replicates the current operations of the airport combining different models and it is used to get insight about the bottlenecks of the system. It is possible also to understand what the consequences would be in case of the increase in demand and most importantly, it has been used to answer the question if the airport is able to handle more traffic while the new airport is being built.

### 3.3 Runway system modelling

The runway system is composed by two runways separated 330 m. The operation implemented is a segregated one but dependent which means that one runway is used for take off and the other is used for landing, however the separation does not allow using them independently but dependent on each other like in a single runway operation. For the runway operations (landing and take off) there are other characteristics implemented such as runway occupancy time (ROT), landing speeds and restrictions that need to be complied. Due to the lack of information in the schedule, at the beginning of the simulation there are no aircraft parked in the airport, so the simulation starts with empty gates at 5 am which corresponds to the first record of the database. Regarding this assumption, we do not expect that it affects much the analysis, since the airport operates in theory 24 hrs therefore the commercial traffic starts arriving and departing around 5 am when there is enough capacity at the system and it is progressively reduced during the day with the increment in demand.

### 3.4 Terminal buildings and turnaround times

The airport has two terminal buildings (T1 and T2), the first one T1 is mainly used for international traffic, LCCs and the partners of the SkyTeam alliance for which the flag carrier (AEROMEXICO) is part of. The modelling approach for both terminals consists of a set of available stands where the entities (aircraft) are parked and suffer a delay which simulates the turnaround time (TAT) for each of them. The capacity evaluated of each terminal is the amount of connecting gates which for T1 is 36 and for T2 is 34. The utilization of the terminal building is based on the TATs and the airlines are allocated in accordance with their equipment and company as it is in reality. The turnaround times used are one of the key elements necessary for a correct representation of the operation in the Airport. To construct the probability distributions, we performed data collection and analysis for the different airlines in combination with type of equipment.

The previous data collection was performed extracting information from Flight Radar24 (Flight Radar 2017) and then after pre-processing the data we performed a probability distribution fitting (Banks et al. 1996). In this case, we use an innovative approach by grouping the TATs in pairs of Company-Equipment. This approach captures the effect of the business model of the airline company in the turnaround time of the equipment which is supposed to be high. It differs from other authors such as Herrera et al. (2014) or Wei and Siyuan (2010) that only consider the equipment in their fitting. Table 1 presents the results of the probability distributions used for modelling the TAT.

Since it is unfeasible timewise to extract data for all the airlines and equipment that operate in the airport, we collected information for the companies whose footprint is the biggest in the airport such as Aeromexico-Delta, Volaris, and United. The benefit of using the aforementioned approach is evident in the case of the LCC segment which has very short turnaround times and differ from company to company and differ greatly from the legacy carriers. One can distinguish, and then introduce in the model, the difference of the business models; for example, comparing Interjet A320 and Volaris A320 in which the distributions are different. For those airlines that have less movements in the airport (with the correspondent impact) we assigned a turnaround time similar to the one of an airline for which we collected the data, that is the case of Copa B737-800 and Aeromexico 737-800 which use the same distribution.

### 3.5 Taxiway system

The taxiway system was approached as a network of segments interconnected via nodes that enable the aircraft to land and depart using those segments as the taxiways towards and from T1 or T2. Figure 5 illustrates the network developed. The segments are scaled to the real distance they represent; therefore, all the timing calculations are based on Newton's laws taking into consideration length, speed and acceleration of aircraft.

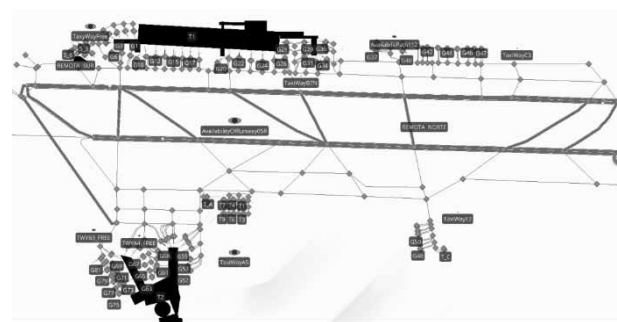


Figure 5: Taxiway system of the MEX model.

Airline - Aircraft	Probability Distribution (Minutes)
Aeromexico B787-8	$(8220+Weibull(4.52, 6760))/60$
Aeromexico 737-700	$(1980+7920*Beta(3.18, 4.18))/60$
Interjet A320	$(2040+Lognormal(7.68, 0.508))/60$
Aeromexico 737-800	$(3420+LogLogistic(3.97, 3030))/60$
VOLARIS A320	$(4140+LogLogistic(1.95, 1480))/60$
Aeromexico 777-200	$(8040+Weibull(1.78, 8640))/60$
Aeromexico 787-900	Uniform (4380,24700)/60
AA-B737-800	$(3420+LogLogistic(3.97, 3030))/60$
ALL Boeing 747s	$(8040+Weibull(1.78, 8640))/60$
AEROMAR-ATR	Weibull ( 1.100, 23.89 )
Aeromexico (EMJ,E70,E75,ER4)	PearsonVI( 1.065, 4.835, 209.4 )
Aeromexico-B767-200	$(8040+Weibull(1.78, 8640))/60$
Aircanada-A319	Weibull ( 0.8675, 46.16)
Alaska-73H B737-800	$(3420+LogLogistic(3.97, 3030))/60$
Avianca Embraer	PearsonVI( 1.065, 4.835, 209.4 )
Avianca-A319	Weibull ( 0.8675, 46.16)
Avianca-A320	$(1980+7920*Beta(3.18, 4.18))/60$
Copa B737-800	$(3420+LogLogistic(3.97, 3030))/60$
Cubana A320	$(1980+7920*Beta(3.18, 4.18))/60$
Delta B73w(737 winglets)	$(1980+7920*Beta(3.18, 4.18))/60$
Delta B757	$(3420+LogLogistic(3.97, 3030))/60$
Iberia A345	Uniform (4380,24700)/60
Interjet SU9	PearsonVI( 1.129, 2.721, 129.2 )
LAN B763--767-3	$(8040+Weibull(1.78, 8640))/60$
Aeromexico B787-8	$(8220+Weibull(4.52, 6760))/60$
Aeromexico B737-700	$(1980+7920*Beta(3.18, 4.18))/60$
Cargo Flights	Triangular(180,420,660)
UNITED A320	$(1980+7920*Beta(3.18, 4.18))/60$
UNITED B737	$(3420+LogLogistic(3.97, 3030))/60$
UNITED B378	$(3420+LogLogistic(3.97, 3030))/60$
UNITED Airlines A319	Weibull ( 0.8675, 46.16)
International- B737s	$(3420+LogLogistic(3.97, 3030))/60$
InternationalMD83,MD82	$(3420+LogLogistic(3.97, 3030))/60$
International – E45X	PearsonVI( 1.065, 4.835, 209.4 )
International- A319	Weibull ( 0.8675, 46.16)
International- A346	$(8040+Weibull(1.78, 8640))/60$
Domestic- B737s	$(1980+7920*Beta(3.18, 4.18))/60$
International - A320s	$(1980+7920*Beta(3.18, 4.18))/60$
International A330	Uniform (4380,24700)/60
Domestic LCC-A320-A319	$(2040+Lognormal(7.68, 0.508))/60$
Domestic LCC-B733	$(4140+LogLogistic(1.95, 1480))/60$

**Table 1:** Turnaround times for the airlines in the airport.

As it has been mentioned, all the different elements are interconnected with each other following the logic of the airport system. It is important to note that the runway (RWY) system is shared by the two terminals and taxiway systems hence the capacity will be stressed by the utilization of the runway system by the entities going and coming from T1 and T2.

## 4 Experimental Design: Analysis of Demand

The experimental design aims at determining what the limitations and bottlenecks of the current system are and what options this system might have for absorbing more traffic. The approach followed first runs replications of the base case scenario with a validated model of MEX (Mendoza et al. 2015). This allows to determine not only the performance indicators but also the impact of the variability present in the system, which in most of cases is due to the turnaround operations and congestion present. Then, three scenarios are evaluated increasing the traffic progressively so that it is possible to determine when the system is not able to absorb the traffic and where the system might collapse.

With the previous approach, we identify if the dynamic of the system behaves linearly with demand or the congestion levels generate such problems in the system that it will be complicated to manage.

Regarding the runway occupancy times and the runway utilization during peak hour, in most of the cases the values were very similar if not identical and since these values do not affect much the congestion levels will not be addressed further in the paper. The main values obtained for the different experiments are presented in Table 2.

Parameter	Value
Runway Occupancy time_ Arrival	40.10 sec, STD 1.4 E-14
Runway Occupancy Time Departure	55.9 sec STD 0.07
RWY Usage (Peak Hour)	100%

**Table 2:** Performance parameters of RWY.

### 4.1 Base case: current operation

We will use as input for this base case one of the two busiest days of 2014 (OAG data): 27<sup>th</sup> of July. For the traffic, we included the cargo movements and the governmental operations which were very active in that day (normally they stand for 10% of the day movements).

Regarding the actuality of the data, the day selected is considered valid for the analysis of 2017 operations despite it is from 4 years ago. This is due to the fact that it was one of the busiest days of 2014 and assuming the growth since 2013 reported by the Mexican government is correct



(AICM, 2017), the traffic demand of this day would fall in the first quartile of busy days of the current year.

In this study, we characterize the system using the standard performance indicators of any stochastic system which are normally queuing time, throughput, queue lengths and utilization of resources (Shortle et al. 2017). In aviation systems, the practitioners use their particular names and other similar indicators are used such as On Time Performance, average delay arrival, average delay departure among others, but as for any dynamic system with variability they are correlated with the ones used in the current study. For instance, operational delays are consequence of the queuing times which in turn are a consequence of congestion levels and utilization levels of the resources at the airport. The same applies with the delays in the scheduled flights, due to the congestion levels, the slots are not available when they were originally requested by airlines; thus, by putting attention to the general performance indicators we elaborate our point when comparing one scenario against another. The output indicators provide us with insight about if there is still some spare capacity in the system to accommodate more traffic; and the focus will be put on peak hour-times and throughout the complete day.

For the base case scenario and all the ones performed, we ran 30 replications and obtained the statistics of the performance indicators under study. This is necessary to address the impact of the variability present in the system since it is a stochastic one as it will be illustrated in the correspondent subsections. The base scenario will be detailed so that the reader gets the right understanding of the procedure followed in the study however for the remaining ones we will present only the graphical representation of results which we consider provide more value to the reader about the consequences of the actions taken.

Figure 6 illustrates the evolution of the air traffic movements per hour (ATMs) during the day for one replication while Table 3 presents the performance indicators analysed in the study.



Figure 6: Evolution of ATMs during the day.

In the graph, five indicators are plotted. The first two correspond to the punctual arrivals in a time slot (Arrivals and Departures), the graph called ATM TOTAL corresponds to the rolling ATM/hr calculated from the correspondent plotted time back to one hour; while the ATM Arrivals and ATM Departures are calculated in the same way and they refer to ATM/hr of arrivals and departure respectively. One can appreciate that the ATM indicator (ATM TOTAL) builds up from the morning until it gets to the declared saturation level which occurs around 11:00 hrs in which the limit of 61 ATM/hr is almost reached. It can also be appreciated that the saturation continues until approximately 23:00hrs where the arrivals decrease; the movements from 1 am until 5 am correspond to the aircraft that finalize their turnaround in the simulation. From the figure, one can note that during the morning and partially in the evening there is room for allocating more traffic.

The performance indicators of Table 3 characterize the congestion levels of the model under the assumptions and restrictions mentioned. As it was expected, the RWY is the most limited element of the system as the usage percentage reveals. This is a claim given by the airport operator since years ago.

Parameter	Value
ATM/hr (24-hr based)	Mean 38.9, STD 0.17
ATM/hr Arrival (24-hr based)	Mean 19.6, STD 3.6 E-15
T1 Gates usage (24hr-based)	Mean 21.6 (60%),STD 1.9
T1 Gates usage (Peak Hour)	Mean 27.05 (75%), STD 2.6
T2 Gates Usage(24hr-based)	Mean 15.1 (44%), STD 1.3
T2 Gates Usage (Peak hour)	Mean 22.3 (65.6%), STD 3.1
Time in queue (hr)	MEAN 0.4, STD 0.08
TWY B A/C in queue (24hr-based)	Mean 3.8, STD 0.71
TWY B A/C in Queue (Peak hour)	Mean 1.96, STD 1.04
TW-A A/C in Queue(24hr-based)	Mean 4.6, STD 1.23
TWYA A/C in Queue (Peak hour)	Mean 8.2, STD 3.0
RWY Usage (24hr – based)	65%

Table 3: Performance Indicators of the Base Case.

In addition, also the ATM/hr during the saturated times is around 61 ATM/hr which is the declared limit for this airport. Another value to note, is the Gate utilization which is 60% for T1 and 44% for T2 during the day, these values suggest that there is still room during the day for accommodating more aircraft just paying attention to the terminal facilities.

During the simulation runs we identified hotspots in the taxiway system, those are TWY B and TWY A (See Figure 3) coming from T1 and T2 respectively.



Those taxiways are the ones used to get to the head of the runway, therefore when there is high traffic the aircraft queue towards the RWY. As Table 3 shows, sometimes the number of A/C queuing is as high as 8.2 in line with a standard deviation of 3. In other words, during peak hour times the expected amount of aircraft queuing in TWYA in the 95% of the cases would be between 2.2 and 14.2 aircraft while for TWY B would be between 0 and 4 aircraft. Furthermore, as the reader can note, the range is quite high therefore it makes difficult to predict the length of the queue during peak hour.

It is also relevant to mention that besides the main restricted element (the RWY) the other elements in the system have still some space for absorbing traffic. This will be investigated with the following scenarios.

#### 4.2 Scenario I: traffic increase from 10% to 30% more traffic

The main assumptions for this scenario are the following:

- The government operations are moved out of the airport. This is an old discussion in Mexico related to the governmental operations, so it leaves room for more commercial traffic which is the objective pursued by developing the new airport.
- When the demand increases, slots will be granted only in the morning and in the evening. We consider that this allocation makes sense since MEX is a Level 3 coordinated airport with high levels of saturation, therefore it is very difficult that slots are released or granted during the busiest period of operation.
- We do not consider the monopolistic behaviour that the legacy carriers might have over the slots since at this point is still difficult to model.
- The type of new traffic allocated was selected randomly. Thus, the TAT of these dummy aircraft will have diverse timings; therefore, we did not make a distinction between legacy or LCC carriers.

This scenario uses as input the original flight data base with a) 10% more traffic than the current case, b) 20% more traffic and c) 30% more traffic. This increase is to evaluate the practical limitations of the system and it does not follow any particular forecast for the following years.



Figure 7: Evolution of ATMs during the day 10% more traffic.

Regarding the allocation of aircraft, in the case of 10% increase of traffic, it corresponded to 57 aircraft in the day of operation since we had 589 arrival flights in the data. We allocated 46 flights evenly in the morning from 00:00 to 9:00 which corresponded to 6 more flights every hour (+6 ATM/hr) in this period; or one new flight every 11 minutes. For the evening, in the time from 23:00 to 1:00 of the next day we allocated evenly separated the remaining 11 flights. This means approximately an increase of 5 ATM/hr. The traffic was randomly assigned to T1 and T2 and the gate used, and TAT was also allocated on a random basis. For the remaining scenarios (+20%, and +30%), the allocation followed the same reasoning, but it changed the number of aircraft to 117 and 176 more flights correspondingly. Figure 7 illustrates how the traffic evolves with 10% more flights and Figures 8, 9, 10, 11, and 12 present the dependencies of the performance indicators with the increase of traffic.

Figure 7 is similar to Figure 8 but with the increase in 10% more traffic. The indicators are calculated the same way as explained in the previous sections. As it can be seen, with 10% increase, the saturation from the morning until the evening is still present as expected, but the morning seems to grow a bit compared with a similar graph from the base case.

In Figure 8, two graphs are presented, the one that plots the average values of the different experiments, and the other that plots the maximum values that were reached during the experiments in particular moments of time (the practical maximum capacity). One appreciates that the average values of the ATM/hr grow linearly with the increase of traffic, however the maximum values reached are limited. The limitation is because the levels of congestion limit the maximum values that can be reached as it can be appreciated in the following figures. It is worth noting, that the Max Reached line show that in moments of time, the declared limit of 61 ATM/hr is surpassed which might cause congestion (and extra ATC workload) in different elements of the system as the following figures confirm.

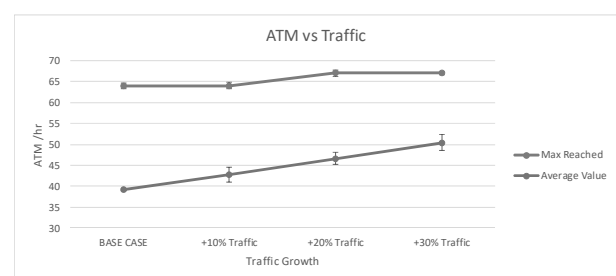


Figure 8: Evolution of ATM/hr vs traffic increase.

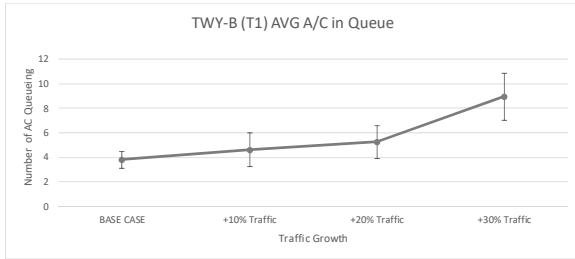


Figure 9: Evolution of A/C queuing in T1.

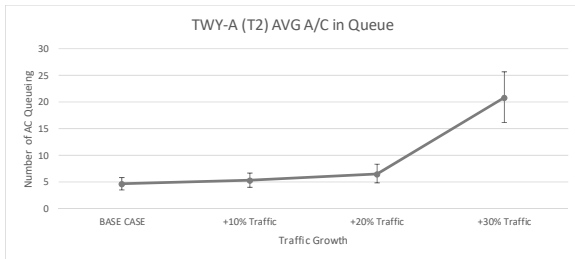


Figure 10: Evolution of A/C queuing in T2.

In Figure 9, it is possible to appreciate that the queue lines grow linearly until the 20% increase, while in the 30% scenario it grows to 9 aircraft in average as it can be appreciated. Furthermore, the standard deviation increases also representing that in the 95% of the cases during a 30% traffic scenario the expected queue will be between 7 and 11 A/C coming from T1 to the RWY.

Figure 10 illustrates the effect that demand has in the queue levels of aircraft coming from T2. In this case, until the 20% scenario, the number of A/C queuing is about 5 with as small variability as can be perceived from the standard deviation line. On the other hand, with the 30% scenario, the amount of aircraft queuing increases dramatically to a level of 21 with a variability of 5 approximately. This means that for the +30% scenario, we might expect to have in the 95% of the cases queues of 16 to 26 aircraft. These queues will directly impact the expected amount of time waiting for take off as the following figure illustrates.

Figure 11 illustrates the effect in the overall indicator of the time in queues that are expected for the scenarios. Again, until the 20% growth, the average waiting times might be, in the worst case, around 40 minutes.

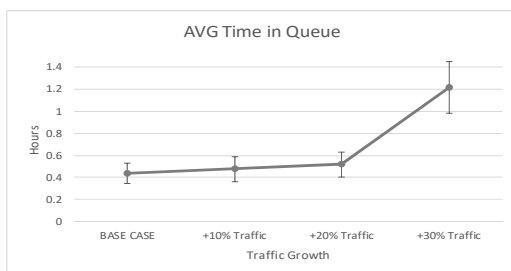


Figure 11: Evolution of average time in queue in the airport.

But in the 30% scenario the waiting times would increase dramatically that might have to wait between 50 minutes to 1.5 hrs in the 95% of the cases as the standard deviation lines show.

Regarding the utilization of the gates of the two terminals, the impact is not as with the other performance indicators. Figure 12 illustrates that in general terms, with the increase of demand, the utilization of the gates grows linearly. This behaviour is considered normal, since as with any stochastic system with sequential operations the limiting element is the one that suffers the most and in our case the runway is the one that is hindering the smooth operation of the system.

From Figure 12 it can be appreciated that until the +20% scenario T1 has a utilization of 72% approximately with some events of 85% of its capacity. In the case of T2, the case of the scenario of +30%, the utilization grows and the variability of the utilization. T1 falls in the interval of [58%, 98%] in 95% of the cases while T2 between 65% and 79% of its potential. This clearly shows that the limiting factor is the runway and the terminals still have room for absorbing growth in certain moments.

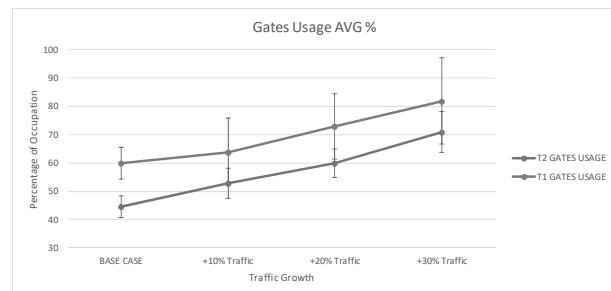


Figure 12: Evolution of gates utilization.

### 4.3 Scenario II: increase of traffic as LCCs being the main entrants

For investigating another situation that might become an alternative to the current situation, we make another extra scenario, one in which we assume that following the trend of the recent years, only Low-Cost Carriers enter to operate at MEX.

For this scenario, the following assumption was taken:

- The increment in traffic continues as it has been since 2006 in which mainly the LCC traffic is the one that grows in the airport (see Figure 12).

The reasoning behind this scenario, is that the LCCs have a more flexible business model and they can operate at slots that would not be attractive to legacy carriers. So, for this scenario, only LCC-type aircraft were added in the model.

To investigate the impact of this allocation, we simulated the progressive increment of +10%, +20% and 30% of traffic. These flights were allocated randomly between both terminals as with the previous scenario; the main difference with the previous one is that the probability distribution that models the TAT is the one used for the LCCs that currently operate in MEX. This probability distribution is the following measured in minutes:

$$2040 + \text{Lognormal}(7.68, 0.508))/60 \quad (1)$$

Once we run the model with these inputs, we obtained the following graphs which illustrate the impact in the performance indicators for this scenario.

Figure 13 presents the line of Average ATM/hr values and the one of Max ATM/hr reached. In this scenario, it can be appreciated that the average ATM/hr grows linearly with very low variability in the average values; however, in the +30% case, the variability makes its presence as it can be seen in the plot of the standard deviation. The other line represents the maximum values reached in the scenarios with the standard deviations representing the variation among experiments of the same scenario. In this case, the maximum values reached are around 64 ATM/hr however in the last one it increases until approximately 67 ATM/hr revealing that the system is stressed beyond the declared saturation levels with the correspondent operational problems in the different elements of the system. The following figures illustrate the impact that this increase has in the performance values.

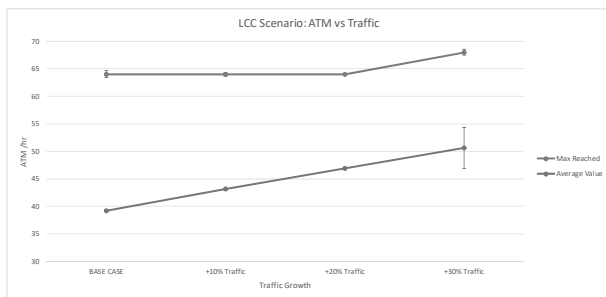


Figure 13: Evolution of ATM/hr.

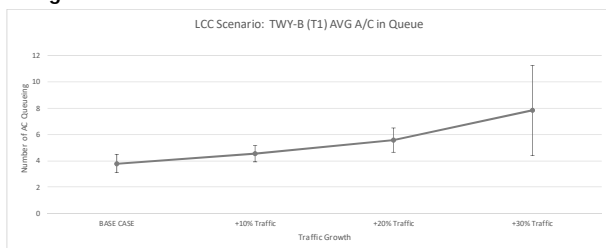


Figure 14: Evolution of aircraft queuing.

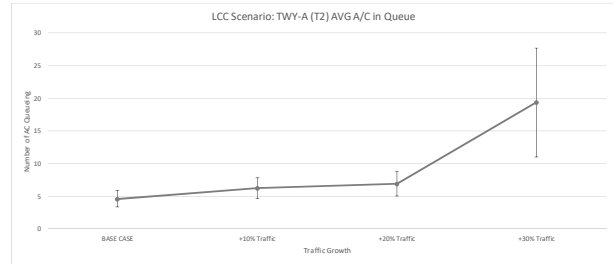


Figure 15: Evolution of aircraft queuing.

As Figure 14 shows, the number of aircraft queuing from T1 to RWY grows linearly with approximately the same variability of 1 A/C, however in the +30% case, the average value goes up but most importantly the variability has increased drastically to 3.5 AC approximately. In other words, in the +30% case, 95% of the time we expect to have between 4.5 to 11.5 A/C queuing. In comparison with Scenario I, the numbers are similar, but in this case the variability in the +30% case is higher than in the same case of Scenario I.

In this configuration we see a similar behaviour as the one for the queuing at T1. In both cases the variability increases with the last demand number and the queuing size increases but not proportionally. In comparison with Scenario I, the queuing numbers are higher, which is logical, since the type of added traffic makes shorter turnaround times with the consequence of being at the taxi network earlier than in Scenario I.

Figure 16 shows that the time in queue is very similar to the Scenario I, and the graph confirms that with the +30% traffic the time waiting is not acceptable for the type of traffic expected to operate at MEX.

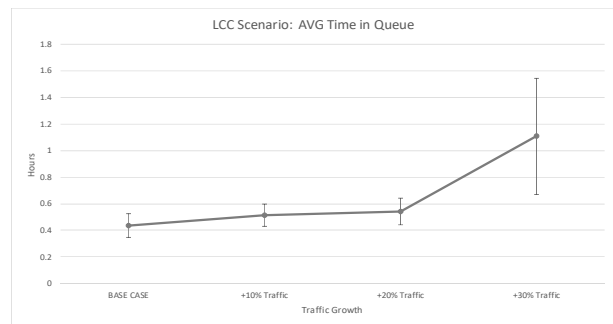


Figure 16: Evolution of time queuing.

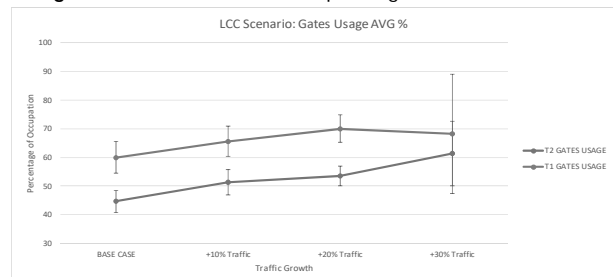


Figure 17: Evolution of gates utilization vs traffic increase.

Figure 17 illustrates that with the LCCs the gates utilization is less than in the case of Scenario I. For example, in Scenario I, the utilization of the gates sometimes got up to 98% for T1 while in this scenario T1 does not get to 90% of utilization and the average utilization is around 70%; this makes a contrast with Scenario I which was approximately 80% in average. In other words, the utilization of this type of traffic might put more pressure on the runway and taxi system but will release capacity for the gates; therefore, the decision makers need to put attention to the taxi system and runway if the trend continues as it has been in the past years.

## 5 Conclusions and Future Work

The current study presents a methodological approach for analysing capacity limitations in a congested airport. We took the case of International Airport of Mexico City as case study. Since in Mexico City, a new airport will be developed in the vicinity for solving congestion problems it is important to have tools that allow decision-makers get insight about the possibilities for the future operation of the current one. The current study analyses the practical limitations of the system using an operative simulation model of the airport system. It aims at evaluating the levels of saturation, since it has been claimed that the airport has reached unbearable levels of saturation. The study demonstrates, that the runway is the main bottleneck of the system but not all the different elements of the system are at the same level of saturation. For this reason, there are still windows of time that can absorb different types of traffic. Taking that into consideration, the simulation model suggests that the current system can absorb more traffic under the current conditions of operation moving out the governmental operations and allocating the traffic early in the morning and in the evening, especially low cost carriers. It is also important to note that due the sequential dependency of the different elements, solving one problem in one element might cause problems to other elements in the system as the second scenario illustrates.

The methodology presented can be used as a blueprint for analysing the current and future limitations of an airport system. As future research we will study the different allocation layouts so that we are able to determine the best progressive implementation of a new facility in combination with the analysis of the TMA which also needs to be considered in order to provide an integral and efficient solution for congested airports.

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# An Adaptable Full-Scale Aircraft Cabin in an Interconnected Simulation Environment

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**Abstract.** An aircraft cabin is – apart from interactions with the cabin crew – the most important interface between an airline and its passengers. The Institute of Flight Guidance (IFF) of the Technische Universität Braunschweig developed and built a full-scale aircraft cabin section comprising the structure and electronic systems of a short- to medium-haul single-aisle commercial aircraft. In this paper, we describe the ongoing work of setting up the cabin simulation and the developed solutions to a variety of technical challenges. We present our structural hard- and software architecture focusing on high realism or plausibility while maintaining a high flexibility in the design for future developments. By means of two more detailed examples – an outside view simulation system and an interconnection network for the simulation environment – we show our approach.

## Introduction

The most lasting impressions (positive or negative) of a past flight come from aspects related to the aircraft cabin interior. Apart from pre-flight experiences and crew service quality, studies (e.g., [1] [2]) show that cabin systems have a high impact on the revenue of an airline through passenger comfort and the resulting desire to re-book with the same airline and/or the same aircraft. Although the cabin is partly subject to high safety requirements, its influence on the safe execution of the flight is mainly secondary. Thus, it offers more chances for the successful introduction of new developments than other parts of the aircraft structure. These aspects are contributing to the fact that aircraft cabin

systems increasingly receive attention both in research and economic contexts.

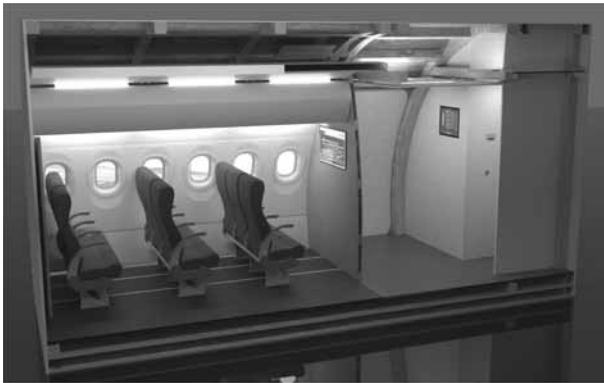
New procedures and systems aim at the sometimes contradicting aspects of increased safety, greater operational efficiency and an improvement in passenger comfort. For their validation, models and simulations are required since a test during real-life operation is often too time- and cost-intensive. However, the multitude of cabin systems and the necessity of simulating a large number of influences on the operation in the cabin, pose a variety of challenges for the technical simulation.

In order to meet the resulting requirements of educational and research purposes, the Institute of Flight Guidance (IFF) of the Technische Universität Braunschweig developed and built a full-scale aircraft cabin section of a short- to medium-haul single-aisle commercial aircraft. The fixed-base cabin section is attached to an aircraft cockpit simulator and embedded into a superordinate simulation environment.

In this paper we describe the ongoing work of setting up the cabin simulation and the developed solutions to the mentioned technical challenges. We present our structural hard- and software architecture focusing on high realism or plausibility while maintaining a high flexibility in the design for future developments.

As a detailed example, we show the currently implemented outside view simulation and discuss the technical and perception-based challenges faced during development. Furthermore, the results of an examination with multiple test persons are featured.

Our subsequent outlook on future work contains ideas on an approach for data exchange. We envisage a publish-subscribe-based architecture to not only connect the individual components within the cabin simulator, but to also enable the interaction with other participants within the surrounding simulation environment as well as in external networks.



**Figure 1:** Computer-rendered representation of the cabin simulator cross-section.

## 1 Simulator Architecture

The fixed-base aircraft cabin simulator comprises the structure and electronic systems of the entrance area including the forward galley and lavatory as well as the full lining of the the first three to four seat rows in the passenger cabin deck (cf. Figure 1). It is equipped with relevant cabin systems and can be flexibly adapted to test systems from current research. The focus is on networking, sensor technology and human-in-the-loop simulations for the optimization of cabin-related processes. The cabin simulator is spatially adjacent and electronically connected to the aircraft cockpit simulator of the IFF and therefore constitutes part of a full-scale airliner simulation platform, which is orientated on an Airbus A320. This platform in turn is interconnected to other simulation systems and embedded into an air traffic management simulation environment consisting of a Diamond DA42 simulator and two working positions, each of which can be operated either by a (pseudo) pilot or an air traffic controller. This enables us to not only investigate the processes and interactions between cockpit and cabin, but also to consider the cabin as a further entity within the overall air traffic transport system.

### 1.1 Structure

The integration and evaluation of new and further developments requires a continuous adaptation of the cabin structure. For this reason, a modular approach was chosen, which makes it possible to flexibly modify or replace cabin modules, parts and systems. Furthermore, in order to give test persons a realistic impression, great

importance was attached to reproducing the look and feel of the interior as true to original as possible and in particular the inner dimensions. The outer dimensions of the cabin are slightly larger in order to provide more space behind the lining components.

The basic structure of the cabin simulator is fully composed of wooden ribs and beams in combination with wooden panels and walls. Due to a reinforced floor structure, the cabin simulator can be easily lifted and moved. The outer shell is made of large PVC sheets. The cut-outs of the cabin doors on both sides are already in place, while the actual doors have already been designed, but not yet manufactured. In total, the cabin is approximately 5.6 m long, 4.2 m wide and 3.0 m in height and features twelve cabin windows (six on either side), which however do not have an opening to the outside.

For the lining of the passenger area, mostly used but refurbished original parts – such as window panels, ceiling panels and overhead bins – were incorporated. The total of 18 passenger seats (three groups of three seats on either side) are used originals as well and have a fold-out cocktail table to establish a business configuration. All other interior parts (e.g. the floor carpet) have been selected or replicated to resemble their counterpart in reality. Two self-developed bulkheads separate the passenger area from the entrance area. Except for the forward galley on the right-hand side, the entrance area was reconstructed for the most part. The lavatory on the left-hand side in the passage to the flight deck is only a dummy. It contains the computers and most of the other hardware components for controlling the cabin simulator as described in the following section.

### 1.2 Hardware

The cabin hardware offers input and output devices as human-machine interface for cabin operation on the one hand and on the other hand provides computing power for the simulated systems on board as well as for the environment simulation. In addition, it provides the basis for stimulating human senses through the visual and auditive channel; the haptic stimulus results from the structure and interior. The cabin simulator has its own power grid, which is divided into sub-grids by a main distributor. For cabin operation, five computers are used that are connected via Ethernet: two high-performance computers, each with two graphics cards for the outside view simulation and ambient noise as well as one computer each for internal audio and video streaming,



for the Cabin Management System (CMS) and Flight Attendant Panel (FAP) and for the provision of various interfaces and aircraft buses (e.g. ARINC 429, RS232, RS485, CAN, etc.).

For the illumination of the cabin simulator, pairs of bright white and RGB LED strips were installed that are controlled independently via Digital Multiplex (DMX) dimmers. Within the passenger area, the LED strips are located on both sides of the ceiling panels, below the overhead bins and on floor level; within the entrance area, multiple pairs of LED strips are mounted in the ceiling only.

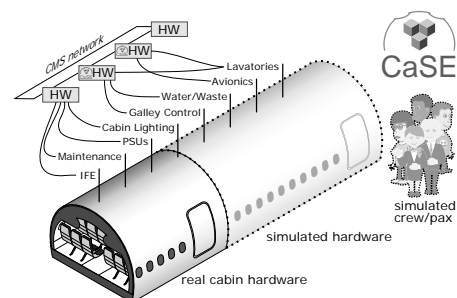
The output of cabin internal audio signals takes place via structure-borne sound speakers mounted on the ceiling panels. A separated surround system hidden behind the lining is used for the aircraft and ambient sounds. To enable the outside-view simulation (see Section 2), one screen is mounted behind each of the twelve cabin windows, three of which are connected via daisy chain to one graphics card of the high-performance computers. A large-scale screen is also installed in each of the two bulkheads for information and In-Flight Entertainment (IFE). Additionally, a touch-screen is available attached to the lavatory wall within the entrance area. The installation of a ventilation system for the air conditioning of the cabin is currently in progress. While the air conditioning unit and the ventilation outlets are already installed, the individual components are not yet connected.

### 1.3 Software

Building on the hardware and structural features, the systems and functions of the simulator are represented in a set of programs and software parts. These are classified into mock-ups, device simulation modules and auxiliary modules. Mock-ups mimic real software which is available in a real operational context. An example of a mock-up software is the FAP software implemented for the simulator. Device simulation modules imitate the behavior as well as the usage of cabin hardware – e.g. lavatory equipment. Auxiliary modules, on the contrary, do not match any real world software or device. They are necessary to provide interfaces between virtual and real hardware, provide functions for the simulation control and serve as abstraction layer between cabin systems and simulator systems.

While the mock-up software and the auxiliary modules are implemented as stand-alone binaries, interconnected via TCP/IP-based interprocess-communication, device simulation modules heavily depend on a simulation framework we named Cabin Simulation Environment (CaSE). CaSE provides such features as event-based data exchange, scenario generation and replay as well as lock-free concurrent interfaces to a variety of data buses. This ensures that new simulation devices can be implemented as light-weight components enabling developers to focus on remodeling the real device's behavior and providing seamless integration.

Device simulation modules may both simulate the behavior of a device and the usage of cabin systems by passengers and crew. Respective scenarios, triggering actions of virtual humans in the cabin and in turn leading to reactions by device simulation modules, can be generated and replayed using the graphical user interface of CaSE. For example, modules are available for the usage of lavatories (door locks, call buttons, water tank levels) or temperature control. Thus, as shown in Figure 2, CaSE expands the simulation from the first three seating rows to a full aircraft cabin layout by providing virtual additions to the real hardware.



**Figure 2:** Schematic representation of the cabin simulator comprising the real and simulated hardware of the cabin interior, cabin systems and their usage.

Central component of the whole software architecture is the mock-up software for the CMS. It provides information for and communication between systems and takes control of all connected systems in the cabin. The interface between this management system and the flight crew is the FAP. Its main purpose is to provide a graphical user interface for interacting with all systems on board and to be the link to the CMS. The FAP software is visible at the touch-screen monitor in the front section of the cabin (cf. Figure 1), which is also the corresponding input device.

The auxiliary modules, generally also connected via the CMS, serve as interfaces and converters to their respective connected hardware. For example, the lighting module provides pre-defined mood lighting scenarios which can be selected at the FAP. The resulting request is sent via the CMS to the lighting module, where it is converted into an ARTNet-compliant message which triggers the DMX dimmer hardware. Another auxiliary module serves as media streaming device for the IFE and passenger announcement system. Thus, it grants access to the bulkhead monitors and the structure-borne sound speakers (cf. Section 1.2) for video and audio transmission into the cabin.

## 2 Outside-View Simulation

The visual perception is one of the key senses to be stimulated for a high immersion of the participants of studies. This does not only apply to the interior, where materials, forms and colors have to match the past experience of the passengers. Instead, it applies especially to the view of the outside world which is provided through the cabin windows. Because of the fixed-base character of the simulator, this is the main way to create the impression of motion of the simulated aircraft. On the other hand, errors and misconceptions of this simulation component may easily lead to discomfort or even Simulation Sickness Syndrome (SSS).

Our 12-monitor-setup and twelve independently generated views provide a realistic outside view for test persons. Apart from bandwidth concerns and image generation performance, the selection of the depicted content and the implementation of optically correct perspectives were addressed while developing the system. The main challenge the hardware setup poses is the contradiction between multiple persons looking from different positions and directions to the same fixed, 2D representation of a 3D outside view. However, we expect that deviations from reality are easily accepted if a plausible view is obtained that matches the test person's past experience. We targeted at exploiting this feature by averaging the views to minimize the perceptible deviations between the simulation and reality. We used human-in-the-loop simulations with multiple test persons to evaluate the level of immersion as well as the impact on the involved humans with respect to visual perception of movement while lacking a kinesthetic stimulus.

### 2.1 Architecture and setup

The system uses the hardware architecture described in Section 1.2 with twelve screens in the outer walls and can therefore access a total of two CPUs and four GPUs for image generation. The used software strongly influences the available visual content, performance and synchronizing features. Thus, the experiments were conducted using varying software platforms, more specifically, Laminar Research's X-Plane 11, Prepar3D by Lockheed Martin and – deviant from using a flight simulator software – Google Earth Pro.

The two flight simulation programs were set up to have one master instance, calculating the flight status vector using the flight model and three to five slave instances which only generated synchronized views with different viewing angles of the environment. Both flight simulations provide configuration files for setting up the correct parameters of the outside view. In case of Prepar3D, multiple views can be specified together. For X-Plane, different instances of the software have to be launched. However, this also allows for the separate instances to use different associated GPUs, balancing the load of image generation across the available hardware. Another challenge is synchronicity and temporal resolution, which is not only crucial for holding up the illusion of steady movement. When using different software instances, information like the shape and position of clouds, ground vehicles and other traffic must be interchanged or propagated. Both simulations use TCP/IP-based proprietary protocols for that purpose.

Google Earth Pro instead was connected to the flight simulation of the adjacent cockpit simulator used as data provider and is only capable of one sole view which was stretched across the screens. Though we tested this setup, we did not consider it for the evaluation as the huge drawbacks of this approach stood out at an early stage.

### 2.2 Viewing layouts

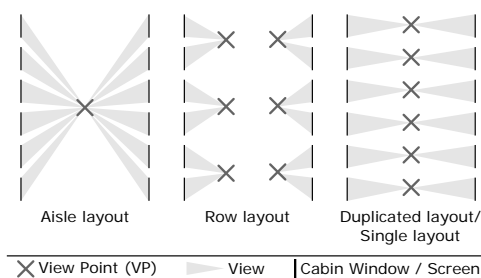
In order to consolidate and average the multitude of possible viewing directions and positions to a set of views that can be shown on the different screens, we considered different combinations of number of viewing points, number of independent views of these points and positions of the viewing points. These layouts, of which three were later used for the evaluation, are defined in Table 1.

	Viewing Points (VP), in total	Views per VP	VP Height
Row layout	6	2	1175 mm
Aisle layout (high)	1	12	1570 mm
Aisle layout (low)	1	12	1033 mm
Duplicated layout	1	2	1175 mm
Single layout	6	2	1175 mm

**Table 1:** Configurations of view layouts.

Each layout entails advantages and disadvantages concerning feature visibility, degree of realism, generation performance, etc., depending on the passengers position in the cabin and the simulated flight phase. Although the according considerations were made, the detailed discussion exceeds the scope of this paper.

In Figure 3, the different viewing layouts resulting from varying the input parameters are schematically depicted. The chosen layouts determine the optical parameters of the system, which in turn can be calculated and implemented in the used software.



**Figure 3:** Schematic depiction of view layouts in the cabin simulator (top view).

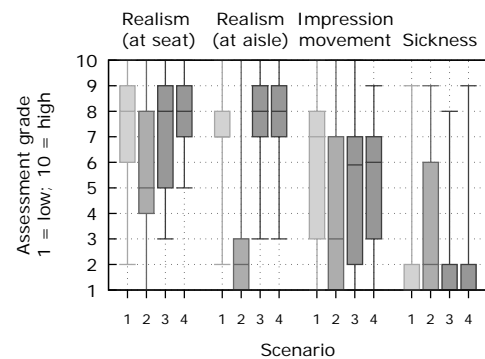
## 2.3 Evaluation

For the evaluation of our solution, we conducted human-in-the-loop tests including four different scenarios, each with a duration of approximately 15 minutes. Each scenario contained a short taxi phase, take-off phase and a climb phase up to a virtual altitude of 12000 ft. While climbing, the aircraft performed both a left and a right turn. In the different scenarios, the viewing layout and the software platform were varied, see Table 2 for reference. The 34 test persons were asked to choose a seat and fill in a questionnaire asking for grades from 1 to 10 concerning the assessment of realism, image quality, temporal resolution, synchronic-

	Viewing layout	Software
Scenario 1	Row layout	X-Plane
Scenario 2	Aisle layout (high)	X-Plane
Scenario 3	Aisle layout (low)	X-Plane
Scenario 4	Aisle layout (low)	Prepar3D

**Table 2:** Input parameters for the evaluation scenarios.

ity, impression of movement and personal well-being taking the flight phase into account. Also, test persons were asked to look at the outside view from different positions in the cabin, at least once from their seat and once from the aisle. Combined with (optional) test person specific information concerning age, gender, body height as well as frequency of flight, this produces comprehensive data for the evaluation of the implemented system. As the excerpt from the results in



**Figure 4:** Grades concerning assessment of realism (while viewing from seat or aisle), of impression of movement and of individual sickness.

Figure 4 indicates, the system generally provides a good depiction of reality. The assessment concerning the impression of movement shows potential for improvement as the grades are on an average level. This feedback was to be expected since the simulator does not provide kinesthetic stimuli in the form of perceptible accelerations. Despite this missing sensation, which contradicts the test persons' observations, the experienced sickness level is low except for scenario 2. In general, scenario 2 shows the worst performance, especially when the simulation is viewed from the aisle. Test persons criticized the high visual tilt downwards in that scenario.

The overall results from the extensive study substantiated our tendency towards scenario 3. Thus, we selected this scenario for operation.

### 3 Interconnection Network

The interconnection of the simulators described in Section 1 should enable a composite simulation. Each simulator will be considered as a single entity within the simulation structure. Nevertheless, the cabin and cockpit simulators constitute a single entity in most of the use cases. Currently, each entity operates within its own network and – if required – the intercommunication is fulfilled via dedicated interfaces.

#### 3.1 Requirements

The aim of the next stage of development is to provide a more flexible connection between the entities and other modules. Therefore, it shall be possible to operate each entity individually and as a part of a composite simulation. For a quick integration of external modules, the interfaces have to be easily accessible. However, the interfaces must keep step with the development of systems.

#### 3.2 Envisaged implementation

In order to meet the requirements and to avoid the occurrence of single point of failure events, it is foreseen to use a distributed system design such as the Robot Operating System 2 (ROS 2) to connect the simulators. ROS 2 uses Fast Real Time Publish-Subscribe (RTPS) [3] which builds on the Data Distribution Service (DDS) middleware.

Using ROS 2, systems are able to publish data within self-defined topics to provide them to other entities. Participants can subscribe to the topics they require. On the application layer there is no further communication necessary between the entities and there is no central instance required for controlling the communication flow. Discovery of the participants is also handled transparently by the middleware.

Each topic holds one data type. Custom data structures have to be defined in Interface Definition Language (IDL) files provided for every system at compile time. It is envisaged to only use primitive data types as well as their corresponding arrays at first. Therefore, most of the data fields provided by our simulators are to be transferred within individual topics. Complex data types will be defined subsequently, if needed.

Since Fast RTPS internally uses UDP/TCP as transport protocol, it is mandatory that the subnets of each simulation entity will be connected within the Local

Area Network (cf. Figure 5). ROS 2 uses one DDS domain where all topics are available. Each module has to be part of this domain in order to subscribe to a topic and to automatically discover other systems. A router at the top level of the topology interconnects the subnets and acts as an internet gateway.

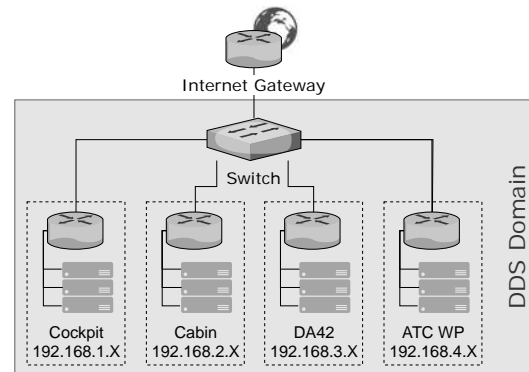


Figure 5: Envisaged network topology.

### 4 Conclusion

We presented our full-scale aircraft cabin section comprising the structure and electronic systems of a short-to medium-haul single-aisle commercial aircraft. The development process as well as the challenges and their solutions were illustrated on the basis of examples, particularly the implementation of an outside view simulation. The subsequent evaluation showed promising results concerning the level of immersion generated by the simulator. The next step will be the development of an interconnection infrastructure between the simulator entities.

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# Probabilistic State Space Models – A Theoretical Framework with Practical Relevance

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**Abstract.** Corresponding to the modeling purpose discrete models can be defined using very different approaches: For a precise description and thorough analysis one of the many different mathematical descriptions can be applied, while a working practitioner often will describe a model within a concrete simulation environment. To demonstrate that mathematical models are useful for practical purposes as well, we will present a simple state-space model for a stochastic discrete system. By means of a concrete example we will show, how the use of this model makes the practical modeling process much easier and leads to a more concise concrete implementation.

## Introduction

For the description of discrete systems a large number of different mathematical models can be applied, ranging from the simple finite state machine [1] to the complex PDEVS formulation [2]. If one includes stochastic processes, the models get more complicated, well-known examples being the non-deterministic finite automaton [1] and the generalized semi-Markov process [3].

Using mathematical models brings considerable benefits: First of all it allows a complete and precise specification of a model. Secondly the whole machinery of mathematics can be used for the analysis of important properties of the models like the reachability of states, reducibility of the state space or the existence of

equilibrium configurations [3].

These points are of a more theoretical nature, but there is a third advantage, often overlooked, which is important for the practitioner: A mathematical model can simplify the actual modeling and implementation in a concrete simulation environment considerably.

To illustrate this point we will present a pedagogical example and implement it in Simulink in a straightforward manner. This turns out to be more difficult than expected and leads to a structurally complicated solution. Next we will introduce a simple mathematical model using a probabilistic state space representation and show, how the reformulation of the example problem using this model leads to a much simpler and clearer implementation. Finally we will turn to the soundness of the basis by having a quick look at the mathematical status of some important simulation programs.

## 1 A Pedagogical Example

The model used in the following describes class sizes of a three-year third level school and the number of prospected school graduates. It is formulated in three steps of increasing detail, based on an example from [4] and extended here. The basic outputs are the class sizes  $x_i(k)$ ,  $i = 1 \dots 3$ , at the beginning of year  $k$  and the number of graduates  $x_g(k)$ .

As a first step we assume given constant rates  $R_i$  of students, who have to repeat year  $i$ , and  $D_i$  of dropouts during year  $i$ . The model is then defined by

$$x_1(k+1) = x_{in}(k) + R_1 x_1(k) \quad (1a)$$

$$x_2(k+1) = (1 - R_1 - D_1)x_1(k) + R_2 x_2(k) \quad (1b)$$

$$x_3(k+1) = (1 - R_2 - D_2)x_2(k) + R_3 x_3(k) \quad (1c)$$

$$x_g(k+1) = (1 - R_3 - D_3)x_3(k) \quad (1d)$$

The resulting class sizes are non-integer, representing “mean values” over several years.

In the next step the mean values are replaced by integer random numbers following a binomial distribution  $B(n,p)$ . In the defining equations the number of repeaters and dropouts are replaced according to

$$R_i x_i(k) \rightarrow \xi_{R,i} \sim B(x_i(k), R_i)$$

$$D_i x_i(k) \rightarrow \xi_{D,i} \sim B(x_i(k), D_i)$$

leading to integer-valued class sizes.

Finally we add a rate  $M_i$  ( $i = 2,3$ ) of pupils who return to the previous class at midterm – a realistic possibility at German schools. The concrete numbers are again drawn from a Binomial distribution:  $\xi_{M,i} \sim B(x_i(k), M_i)$ . This seemingly simple extension has drastic consequences for the modeling, because it leads to changes of the class sizes at half-integer years.

## 2 Straightforward Implementation

The implementation of the simplest model in Simulink can be done easily. One starts by introducing a generic component for a class with one input  $i$  for new pupils and three outputs: the class size  $c$  at the end of the term, the number  $t$  of pupils transferred to the next class and (for completeness) the number  $d$  of pupils that have dropped out during the current year. It is built with one `UnitDelay` block storing the class size  $x(k)$  and the usual arithmetic blocks to implement the following relations derived from the model equations (1)

$$x(k+1) = i(k) + Rx(k) \tag{2a}$$

$$c(k) = i(k) + Rx(k) \tag{2b}$$

$$t(k) = (1 - R - D)x(k) \tag{2c}$$

$$d(k) = Dx(k) \tag{2d}$$

The complete model is then just a chain of three class components (cf. Figure 1).

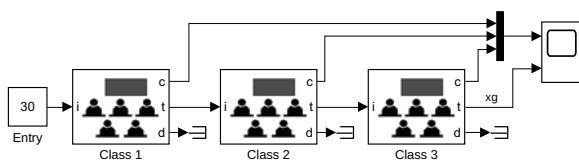


Figure 1: Simple school model.

To replace the fixed rates with binomial random variables, one creates a component that outputs a random value  $\xi \sim B(n,p)$ , where  $p$  is given as parameter, while  $n$  comes from an input. This can be done with a simple Matlab function. The corresponding class is shown in Figure 2.

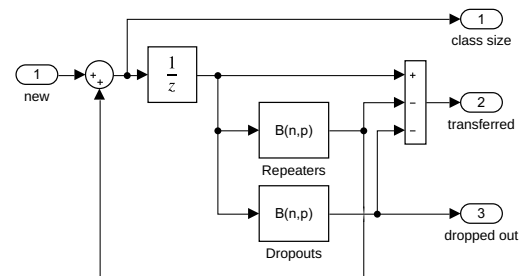


Figure 2: Class component with random values.

The real challenge is of course the inclusion of the midterm downgrading. On the upper level this is simple enough: Just add another output  $m$  to the class component that gives the number of downgraders and route it back to the input of the lower class (cf. Figure 3). Due to the different timing of the values,  $m$  cannot simply be added to the normal input. But a `TimeSwitch` that uses a standard `Switch` component to route its two inputs according to the time (integer or half-integer) solves this problem.

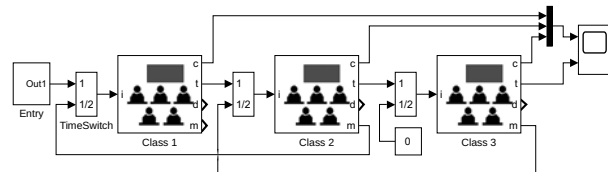


Figure 3: Complete school model.

The implementation of the new class component starts by adding a binomial block for the downgraders, whose output is routed back internally to another `Time-Switch`. But the interesting question is of course, how one realises the different sample times: The class size changes every half year, the numbers of repeaters and dropouts at the beginning of a year and the number of downgraders at midterm.

Apparently Simulink offers an easy solution: Setting the `SampleTime` parameter of the `UnitDelay` to 0.5 and adding two `Rate Transition` blocks,

which convert the signal to sample times  $[1, 0]$  and  $[1, 0.5]$ , should do the trick. The corresponding class component is shown in Figure 4, where the colors denote the different sample times.

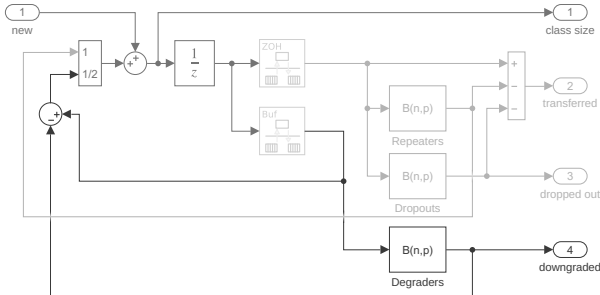


Figure 4: Complete class model.

But running the model we get the error message

Determinism of data transfer between 'school3a/Class 1/Unit Delay' and 'school3a/Class 1/Sum3' cannot be ensured because either or both blocks have non-zero sample time offset. You can resolve this by using a rate transition block whose parameter 'Ensure deterministic data transfer' is unchecked

The suggested resolution actually leads to a working model: After unchecking the option `Ensure deterministic data transfer` of the second `Rate Transition`, the model runs without problems, and the results are as expected. But do we really know what is going on here?

Changing the sample rate is generally a non-trivial business, but a look at the relevant Simulink documentation [5] shows that there are more troubles looming around than one probably thought of, e. g. problems with timing when using multicore cpus. Without a precise understanding of the `Rate Transition` block, one cannot be sure that the `Class` component still works, when it becomes part of a very complex model – as real world components usually do.

The incremental modeling approach has lead into murky ground, since the simple structure of the model got lost on the way. Instead of relying on only half-understood remedies, we will therefore start afresh, this time with a solid foundation in the form of an underlying mathematical model.

### 3 A Probabilistic State Space Model

We start with the well-known state space description

$$z(k+1) = G(z(k), v(k)) \quad (3a)$$

$$w(k) = H(z(k), v(k)) \quad (3b)$$

The integer  $k$  is the number of the time step, while  $z$  denotes the internal state,  $v$  the external input and  $w$  the output of the model, all possibly being vectors. This model can be easily implemented in Simulink by using the generic model shown in Figure 5 and providing components for the functions  $G(z, v)$  and  $H(z, v)$ .

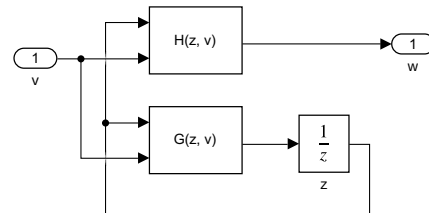


Figure 5: Generic state space model.

For the stochastic examples we have to enlarge the state-space description. A common approach is the inclusion of an additional disturbance term  $d(k)$  [6]:

$$z(k+1) = G(z(k), v(k), d(k))$$

$$w(k) = H(z(k), v(k), d(k))$$

In our case the disturbance is stochastic and its distribution depends on the state  $z$ . Therefore we define a random vector  $\xi(z)$  and the *probabilistic state-space description*

$$z(k+1) = G(z(k), v(k), \xi(z(k))) \quad (4a)$$

$$w(k) = H(z(k), v(k), \xi(z(k))) \quad (4b)$$

Again a generic Simulink implementation can be easily given, cf. Figure 6. The additional component `Random` computes the value of the random vector  $\xi(z)$  using the current state vector  $z(k)$ .

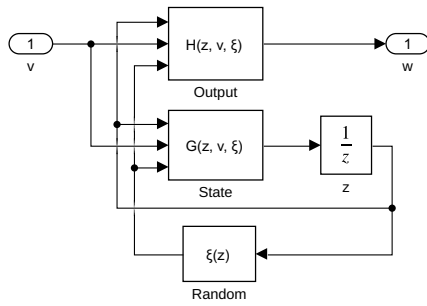


Figure 6: Generic probabilistic state space model.

## 4 Theory-based Implementation

We will now reimplement the example models using the mathematical descriptions and corresponding generic models defined above.

To reformulate the first model using eq. (3) we identify the state variable  $z$  with the class size  $x$ . Then we rewrite the defining equations (2) by setting  $v \equiv i$ ,  $w \equiv (c, t, d)'$  and get

$$G(z, v) = v + Rz$$

$$H(z, v) = \begin{pmatrix} v + Rz \\ (1 - R - D)z \\ Dz \end{pmatrix}$$

The Simulink implementation of  $G$  and  $H$  is completely trivial, but so was the version we started with. Therefore we didn't gain much here expect for making contact to standard mathematical formulations.

For the implementation of the second model we now use the probabilistic state-space description eq. (4) and write

$$\xi(z) \equiv \begin{pmatrix} \xi_R(z) \\ \xi_D(z) \end{pmatrix} \sim \begin{pmatrix} B(z, R) \\ B(z, D) \end{pmatrix}$$

$$G(z, v, \xi) = v + \xi_R$$

$$H(z, v, \xi) = \begin{pmatrix} v + \xi_R \\ z - \xi_R - \xi_D \\ \xi_D \end{pmatrix}$$

The component `Random` simply combines the outputs of two `Binomial` blocks into a vector.

The final example model is time-dependent, since its behaviour changes between full and half years. The standard trick here is to include the time as a compo-

nent of the state vector. In our case we only need to know whether we are at full or half term. Therefore we enlarge the state vector writing

$$z = \begin{pmatrix} x \\ s \end{pmatrix}, \quad z(0) = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

where  $x$  is again the class size and the variable  $s$  is 0 or 1 at full resp. half term. Its state equation then simply is

$$s(k+1) = 1 - s(k).$$

Now we have to define the functions  $\xi(z)$ ,  $G(z, v, \xi)$  and  $H(z, v, \xi)$ , especially their behaviour at  $s = 0$  and  $s = 1$ . First we define the random vector  $\xi = (\xi_R, \xi_D, \xi_M)'$ . The first two components describe the numbers of repeaters and dropouts, so they should be 0 at midterm. Correspondingly the number  $\xi_M$  of midterm downgraders should be 0 at the beginning of a term. Thus we have

$$\xi_R(z) \sim \begin{cases} B(x, R) & | \quad s = 0 \\ 0 & | \quad s = 1 \end{cases}$$

$$\xi_D(z) \sim \begin{cases} B(x, D) & | \quad s = 0 \\ 0 & | \quad s = 1 \end{cases}$$

$$\xi_M(z) \sim \begin{cases} 0 & | \quad s = 0 \\ B(x, M) & | \quad s = 1 \end{cases}$$

Similarly we arrive at the state equation

$$G_1(z, v, \xi) = \begin{cases} v + \xi_R & | \quad s = 0 \\ v + x - \xi_M & | \quad s = 1 \end{cases}$$

$$G_2(z, v, \xi) = 1 - s$$

Finally we enlarge the output vector to include the downgraders writing  $w \equiv (c, t, d, m)'$  and get the output function

$$H_1(z, v, \xi) = \begin{cases} v + \xi_R & | \quad s = 0 \\ v + x - \xi_M & | \quad s = 1 \end{cases}$$

$$H_2(z, v, \xi) = \begin{cases} x - \xi_R - \xi_D & | \quad s = 0 \\ 0 & | \quad s = 1 \end{cases}$$

$$H_3(z, v, \xi) = \xi_D$$

$$H_4(z, v, \xi) = \xi_M$$

This formal approach guarantees a completely precise problem specification, though it may seem a bit te-



dious. On the upside the Simulink implementation is now merely a matter of routine: We use the generic model from Figure 6 adding a Demux block to get the single output ports. Next we implement the equations for Random (cf. Figure 7), State (cf. Figure 8) and Output (along the same lines).

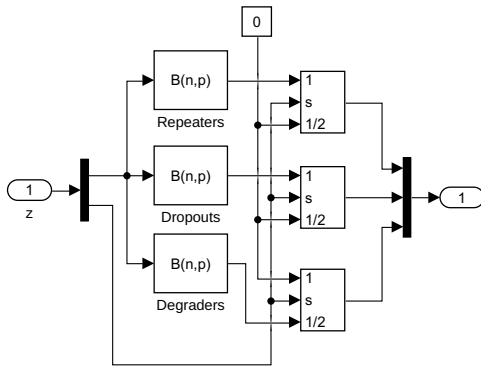


Figure 7: Implementation of the `Random` function.

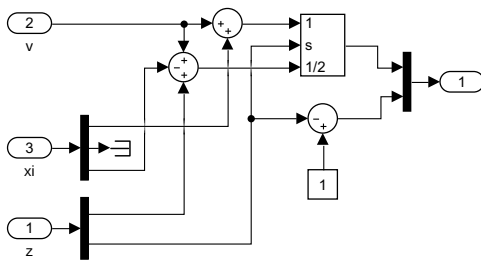


Figure 8: Implementation of the `State` function.

The auxiliary component `PhaseSwitch` (cf. Figure 9) helps to implement the case switches. Instead of a clock (as in the first implementation) it now simply uses the value of the state variable  $s$ .

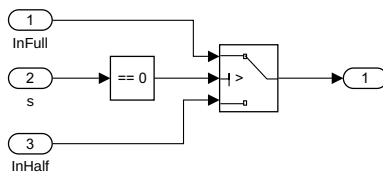


Figure 9: Implementation of `PhaseSwitch`.

The complete `school` model looks almost like before (cf. Figure 3), but the `TimeSwitch` components at the class inputs are replaced by simple summation

blocks. This is possible now, since all signals have the same sample time 0.5 and have meaningful values at all times.

## 5 Mathematical Foundation of Simulation Tools

Even if a model is based on a sound mathematical foundation, its simulation results may be not, namely when it is implemented using a simulation environment that is itself not precisely defined. The Simulink blocks that have been used in the above model, are very simple and can be easily described mathematically. But already the example of the `Rate Transition` block has shown that this may not always be the case. Therefore let's finally have a quick look at the mathematical status of some important tools.

While the model descriptions of continuous systems often boil down to differential or differential-algebraic equations, there is no generally accepted mathematical formulation of hybrid systems containing a few discrete events or even complex state charts [7]. So even the framework, in which to formulate a mathematical model of a simulation tool, is still under construction.

For Stateflow [8], a Simulink add-on to model hierarchical state machines and flowchart diagrams, the situation has been described as follows:

However, Stateflow lacks any formal definition. The semantics of a program is given by the result of its simulation within the Mathworks tools. This absence of formal definition is a big obstacle to static analysis, verification, or automatic test-cases generation of Stateflow designs.[9]

Therefore the authors proceed to define operational [10] and denotational [9] semantics for Stateflow in a formal way. One immediate result is the insight that Stateflow is structurally different from other, seemingly very similar formulations of statechart diagrams. A different way to formalize a hybrid Simulink/Stateflow model has been proposed in [11] with applications to the formal verification of such complex systems as the guidance control of a lunar lander or the control system of a high-speed train.

Another simulation program in the Matlab/Simulink tool chain is SimEvents [12] that implements the transaction-based modeling paradigm for discrete event systems. Earlier releases had some serious deficiencies

[13], therefore Mathworks came up with a complete redesign with version 5. A very interesting feature is that the design is based on a unifying theoretical description [14]. Unfortunately, Mathworks has chosen a new design instead of relying on the well-known PDEVS formalism [2] and doesn't provide these internal specifications in general.

The discrete-events simulation program Arena [15] from Rockwell Automation implements the process-based modeling approach. It is based internally on the simulation language SIMAN [16] and outputs a SIMAN program corresponding to the graphically constructed model. This can be useful for verification purposes, since the specification of the lower-level SIMAN constructs is much easier to understand than the complex blocks used on the upper level in Arena. And one can go down further: In [17] an essential part of the SIMAN language has been implemented using the PDEVS formalism, thereby providing a sound mathematical formulation of important parts of Arena.

## 6 Conclusions

Using a clear mathematical description of our example problem we arrived at a precise specification that could be implemented in Simulink in a completely routine way and is structurally simpler than the previous "straightforward implementation". But this idea only works, if the underlying simulation tools are grounded on sound mathematical models themselves. Though some efforts have been made in this direction, a lot needs to be done to reach a satisfying, well defined environment for our models.

The practitioner often works in the context of a given very large model that changes in the course of further development. He can't be an expert of every intricacy of the complex simulation tool he works with, and very often has not enough time to go to the bottom of every problem. This can lead to ad-hoc implementations that are potentially dangerous in the highly dynamic larger context. The only way out is to use a precise mathematical model – for the own problem as well as for the relevant features of the simulation tool.

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# MATLAB/Simulink's Variant Manager vs SESToPy

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**Abstract.** This paper describes how a complex case study for variability modeling and simulation from the documentation of MATLAB/Simulink can be remodeled with the extended System Entity Structure and Model Base (eSES/MB) approach using the Python-based tool *SESToPy* and the accompanying modelbuilder *SESMoPy*.

## Introduction

Generally, variability modeling can be seen as an approach to describe more than one system configuration. According to Capilla and Bosch [1], a software variability model has to describe the commonality and variability of a system at all stages of the software lifecycle. In simulation engineering, the problem of variability modeling is well known from the eighties. One of the first high level approaches for variability modeling in the design phase was introduced with the System Entity Structure (SES) by Zeigler in 1984 [2] and is constantly enhanced until today [3] [4]. The SES is a high level approach for variability modeling, particularly in simulation engineering. An SES describes a set of system configurations, i.e. different system structures and parameter settings of system components. In combination with a Model Base (MB), executable models can be generated from an SES.

A common tool for today's engineering applications is MATLAB/Simulink. It offers pragmatic solutions for variability modeling and can be seen as a quasi-standard in engineering. In the following section, the example of a power window control system modeled with different degrees of detail is introduced. This application is

taken from MATLAB/Simulink's examples section and can be found in the online documentation [5]. Therefore, the Simulink model did not have to be created but needed to be analyzed. Remodeling the example using the extended System Entity Structure and Model Base (eSES/MB) approach as described by Pawletta et al. [6] was successfully done.

After the problem description in Section 1, Sections 2 and 3 describe the two modeling approaches using the case study. Finally, a comparative evaluation is tried regarding: (i) the modeling effort, (ii) the clarity, (iii) the reusability, and (iv) the maintainability.

## 1 Problem Description

The passenger-side power window system of an automobile is modeled and simulated. The power window can be controlled from both the driver's and the passenger's side. Furthermore, closing should be stopped for security reasons, in case an obstacle is detected during upward movement of the window. The window shall be lowered by some centimeters in this case.

The system is modeled with different degrees of detail and with using different modeling concepts. From this problem specification, multiple model structures and configurations result, which are called variants. For all variants, main model parts are two switches for controlling the window, the control model, a process model of the window, and a model for 3D-animation. The occurrence of an obstacle can be controlled interactively. Furthermore, some outputs are needed to observe the window's behavior. A complete description of the *Power Window Control Project* example can be found in MATLAB's online documentation [5].

## 2 Implementation with Simulink's Variant Manager

Simulink as one of the most popular tools for model-based development provides special blocks for switching between model structures, the *Variant Subsystems Blocks*. Project management is facilitated by the *Simulink Project* capabilities. Anyhow, that means that all variants need to be coded in only one model. Models of this kind are called 150%-models. The main Simulink model is depicted in Figure 1. The model comprises five variant subsystems: (i) the *driver\_switch*, (ii) the *passenger\_switch*, (iii) the model for obstacle detection, which is a submodel of the *power\_window\_control\_system* model, (iv) the *window\_system* model, and (v) the model *window\_world*, that offers optional 3D-animation.

Both switches can operate either in a mode called normal mode or use a communication protocol (CP) implementation. For obstacle detection (DOE) four variants are available. The first variant is a simplistic continuous system model (Cont), the second uses power effects (PE), the third works with a visualization (Vis), and the last provides support for realistic armature and the communication protocol (RA CP). The *window\_system* model subsystem (WS) comprises three variants, one simple continuous model (Cont), one reproducing power effects and additional 3D-visualization options (PE Vis), and a third variant where the realistic armature and the communication protocol is included (RA CP). The two variants for the *window\_world* are a Simulink 3D animation or no animation at all.

Some of the variants use Stateflow, which is The MathWorks' implementation of state machines, and/or physical modeling, i.e. Simscape, submodels. One important aspect when modeling the variants is, that the number and names of input and output ports of variant subsystems need to be the same, no matter which variant is chosen.

The active variant of the main model can be programmatically changed prior to simulation via the control variable *CV*. Table 1 lists the possible configurations and corresponding values of the control variable *CV*. Not all combinations of selected variants in the subsystems are valid. If e.g. for the switches the communication protocol variant is chosen, the active variants of *window\_system* and of the obstacle detection modeled in *power\_window\_control\_system* need to

	Switches	DOE	WS
<b>CV=1</b>	Normal	Cont	Cont
<b>CV=2</b>	Normal	PE	PE Vis
<b>CV=3</b>	Normal	Vis	PE Vis
<b>CV=4</b>	Normal	RA CP	RA CP
<b>CV=5</b>	CP	RA CP	RA CP

**Table 1:** Valid variants, control variable values and selected submodels.

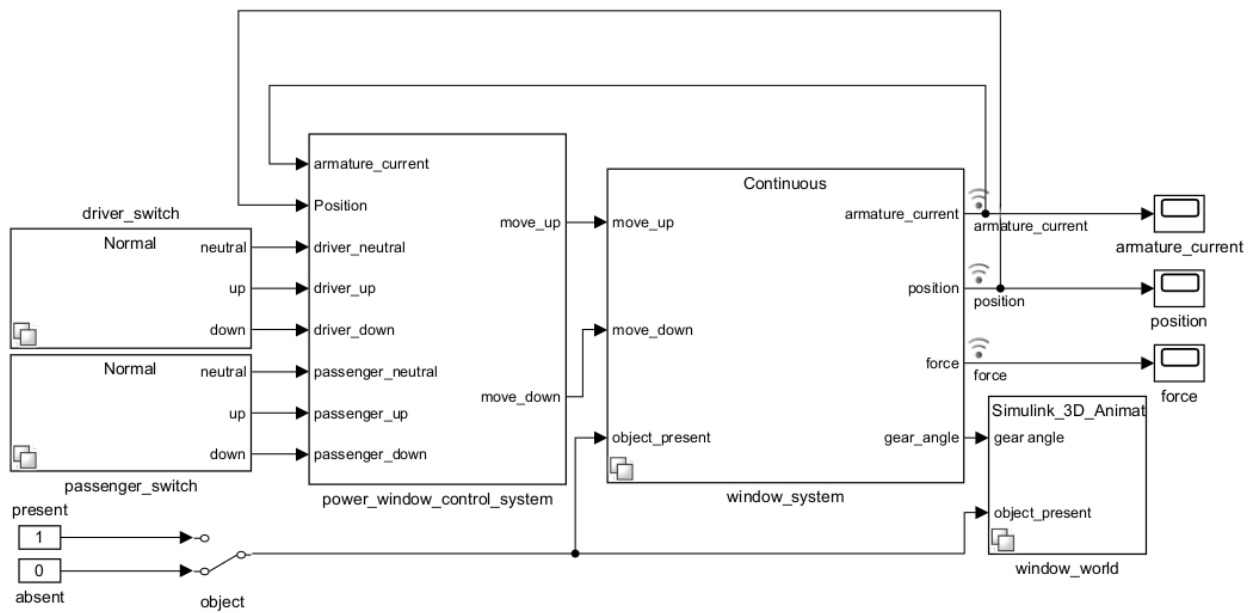
be the communication protocol implementations, too. The variation in *window\_world* is not addressed in Table 1, because all configuration sample scripts in the MATLAB/Simulink example implementation use the *Simulink\_3D\_Animation View* variant, none uses the *No\_View* submodel.

To allow only valid variant combinations, the value of *CV* is evaluated prior to simulation and mapped to specific control variables, called *variant control*, associated with the single variant subsystems. A variant choice is active, when the associated variant control evaluates to TRUE.

## 3 Implementation with the eSES/MB Approach

For remodeling of the power window example, the platform-independent and open source variability modeling tools *SESToPy* [7] and *SESMoPy* were used. These Python-based tools are developed by the research group Computational Engineering and Automation (CEA) at Hochschule Wismar. Both tools and the infrastructure they are used with are described in detail in [8].

A family of systems, which in this context means all possible variants, can be defined within a System Entity Structure (SES) using *SESToPy*. An SES is represented by a directed acyclic graph with an amount of entity nodes, descriptive nodes and attributes. For usage with model generation, entity nodes are linked to basic models organized in a Model Base (MB). Attributes of an entity node correspond to the parameters of the belonging model component. The available three kinds of descriptive nodes specify the relationship between entities. Aspect nodes are used to define the composition of entities, multi-aspect nodes are a special kind of as-



**Figure 1:** Overall Simulink model structure according to The MathWorks [5].

pect nodes, where all component entities are of the same type. The third descriptive node type, the specialization node, describes the taxonomy of an entity.

Descriptive nodes can be seen as variation points of an SES. Associated with the descriptive nodes, there are rules which need to be evaluated when deriving one specific system variant. Each specific system variant comprises of a system structure and a parameter configuration.

The process of deriving a system variant from an SES is called *pruning* and the result is a Pruned Entity Structure (PES). The PES still is a directed acyclic graph like the SES, but without any variation points. Applying the *flattening* method to a PES, all inner nodes are removed to obtain a Flattened Pruned Entity Structure (FPES). In conjunction with an MB, a fully configured and executable model can be generated from an FPES using the modelbuilder tool SESMoPy.

First step for remodeling the power window example was to identify the basic models which then needed to be organized in an MB. As the MB for the implementation of this example application the basic models were structured in four libraries. In the libraries, pre-configured blocks or submodels can be stored to reduce parametrization effort when defining the SES.

The library *LibSimple* contains basic models which are blocks copied directly from Simulink's block library to allow preconfiguration and to make the MB independent from Simulink versions. The other three libraries *LibSwitches*, *LibCtrl*, and *LibWindowSys* contain more complex models and can be seen as user-defined libraries. Then all configuration variants were coded in an SES tree according to the structure of The MathWorks' 150%-model. Figure 2 shows the SES tree modeled in SESToPy.

The entire example and all variants are covered except the 3D-animation variation in *window\_world*. The SES was developed step by step making use of SESToPy's capability to combine several SES trees with the *merge* method [8]. The variation points are expressed by the specialization nodes *DriverSwitch-SPEC*, *PassengerSwitch-SPEC*, *DOE-SPEC*, and *WS-SPEC*. For each specialization node, a specialization rule is defined. During pruning the rules are evaluated and it is decided, which of the child nodes will be part of resulting PES. How models are connected is defined with the coupling attribute at aspect and multi-aspect nodes. Since couplings can be set dynamically here, names and number of input and output ports are variable.

Tree	Type	MB
PowerWindow	Entity	
PowerWindow-DEC	Aspect	
DriverSwitch	Entity	
DriverSwitch-SPEC	Spec	
Normal	Entity	'LibSwitches/Normal'
CP	Entity	'LibSwitches/Communication_Protocol'
PassengerSwitch	Entity	
PassengerSwitch-SPEC	Spec	
Normal	Entity	'LibSwitches/Normal'
CP	Entity	'LibSwitches/Communication_Protocol'
CtrlSys	Entity	
PWCS-DEC	Aspect	
RT-all-PWCS	Entity	'LibCtrl/Rate_Transitions'
DOE	Entity	
DOE-SPEC	Spec	
RA-CP	Entity	'LibCtrl/RA_CP_DOE'
Visu	Entity	'LibCtrl/Visu_DOE'
Cont	Entity	'LibCtrl/Continuous_DOE'
PE	Entity	'LibCtrl/PowerEffects_DOE'
Val-D-P-State	Entity	
Val-D-P-State-MASP	Maspect	
State-Val	Entity	'LibCtrl/StateValidation'
Ctrl	Entity	'LibCtrl/control'
Pulse-Gen	Entity	'LibCtrl/10ms'
WindowSys	Entity	
WS-SPEC	Spec	
Cont-WS	Entity	'LibWindowSys/Continuous'
PE-WS	Entity	'LibWindowSys/PowerEffects'
RA-WS	Entity	'LibWindowSys/RealisticArmature'
ManualSwitch	Entity	'LibSimple/Manual_Switch'
W-Object	Entity	'LibSimple/Constant'
Wo-Object	Entity	'LibSimple/Constant'
Output-Force	Entity	'LibSimple/Out'
Output-Position	Entity	'LibSimple/Out'
Output-Armaturecurrent	Entity	'LibSimple/Out'
Terminator-Gear-Angle	Entity	'LibSimple/Terminator'

Figure 2: SES tree of the power window control system family in SESToPy.

In analogy to the control variable *CV* and the variant control variables in The MathWorks' 150%-model, three SES variables are used. The SES variables are *driver\_MODE*, *detect\_O\_E*, and *window\_system*. Ranges of the SES variables and combinations among them are restricted by defining semantic conditions. Thus, only valid variants can be generated, i.e. the SES can be pruned only to a valid PES. Figure 3 shows the example of one possible PES. This PES corresponds to the Simulink variant, where *CV*=1. After flattening, model generation from the resulting FPES was finally successfully done with SESMoPy.

## 4 Conclusion

Both approaches offer the possibility to model and simulate variability systems. A significant difference is that with the Variant Manager interfaces of submodels are static, while the eSES/MB approach allows to define variable interfaces and couplings. Regarding the modeling effort the approaches do not differ consid-

Tree	Type	MB
PowerWindow	Entity	
PowerWindow-DEC	Aspect	
Normal_DriverSwitch	Entity	'LibSwitches/Normal'
Normal_PassengerSwitch	Entity	'LibSwitches/Normal'
CtrlSys	Entity	
PWCS-DEC	Aspect	
RT-all-PWCS	Entity	'LibCtrl/Rate_Transitions'
Cont_DOE	Entity	'LibCtrl/Continuous_DOE'
Val-D-P-State	Entity	
Val-D-P-State-DEC	Aspect	
State-Val_1	Entity	'LibCtrl/StateValidation'
State-Val_2	Entity	'LibCtrl/StateValidation'
Ctrl	Entity	'LibCtrl/control'
Pulse-Gen	Entity	'LibCtrl/10ms'
Cont-WS_WindowSys	Entity	'LibWindowSys/Continuous'
ManualSwitch	Entity	'LibSimple/Manual_Switch'
W-Object	Entity	'LibSimple/Constant'
Wo-Object	Entity	'LibSimple/Constant'
Output-Force	Entity	'LibSimple/Out'
Output-Position	Entity	'LibSimple/Out'
Output-Armaturecurrent	Entity	'LibSimple/Out'
Terminator-Gear-Angle	Entity	'LibSimple/Terminator'

Figure 3: Resulting PES for *driver\_MODE*=1, *detect\_O\_E*=1, and *window\_system*=1.

erably, but modeling with Simulink's Variant Manager can be seen as a bottom-up procedure while modeling with the eSES/MB approach is rather top-down. The eSES/MB approach gives more clarity during the modeling process, because the overall structure of the model can be captured with one sight. If one uses Simulink's *Model Explorer* to determine the structure, one cannot see, that and where a model contains variant subsystems until one selects a variant subsystem block. The *Variant Manager* offers a view, where the overall structure is displayed, but e.g. block properties cannot be seen then. Information about the model is distributed over several tools, which may confuse new users. A survey among our students came to the result, that eSES/MB is a lot easier to get started with. Reusability of models is ensured for both approaches but may differ in the effort. The maintainability is closely associated with the reusability. Admittedly, a final comparison is not possible on the basis of just one example. According to the available findings, the eSES/MB approach appears to be easier in use for beginners.

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# Comparison of Prediction Models for Delays of Freight Trains by Using Data Mining and Machine Learning Methods

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**Abstract.** On the one hand, having a tight schedule is desirable and very cost-efficient for freight transport companies. On the other hand, a tight schedule increases the impact of delays and cancellations. Furthermore, the prediction of delays is extremely complex, because they depend on many factors of influence. To address these issues, this work will show an approach to forecast delays of freight trains by using data mining and machine learning methods. For this purpose, an international freight transport company in rail traffic provided us with a huge amount of historical data of freight train runs. In order to get a suitable prediction model, we apply a knowledge discovery in databases (KDD) process, which contains the steps data selection, data preprocessing, data transformation, data mining and interpretation/evaluation. After the data selection and data preprocessing step we transform categorical features via one-hot encoding as well as via embedding with various embedding sizes. Furthermore, we apply a data transformation method for cyclical features like weekday. In the actual data mining process, we use the preprocessed historical data to perform a regression analysis, which forecasts the delays of freight trains, and compare several regression models like decision tree, random forest, extra trees and gradient boosting regression. An adequate prediction model will be integrated into an agent-based model, which tests the robustness of optimized locomotive schedules for freight trains.

## Introduction

The planning of train schedules is an extremely complex task, because of the many possibilities to schedule routes and locomotives.

However, it is the daily work of freight transport companies in rail traffic. In order to reduce costs, the locomotive schedule should be as tight as possible. But a tight schedule increases the impact of delays and cancellations, especially if there are no available backup resources like traction units. Therefore, a well-balanced ratio between a tight and robust schedule is desirable. To address these issues, this work will show an approach to forecast delays of freight trains by using data mining and machine learning methods. For this purpose, an international freight transport company in rail traffic provided us with a huge amount of historical data of freight and passenger train runs. Furthermore, we apply a knowledge discovery in databases (KDD) process and compare several regression models as well as data transformation methods, in order to receive a suitable prediction model for delays of freight trains. Finally, an adequate prediction model will be integrated into an agent-based model, which tests the robustness of optimized locomotive schedules for freight trains [1].

## 1 The KDD Process

A knowledge discovery in databases (KDD) process is a nontrivial procedure to identify valid, novel and potentially useful patterns in data [2]. This process contains the five steps data selection, data preprocessing, data transformation, data mining and interpretation/evaluation [3]. To create a prediction model for delays of freight trains, we use the huge amount of historical data of freight train runs and follow the sequence of the KDD process.

### 1.1 Data selection

The data selection step includes understanding of the application domain and the relevant prior knowledge, selecting appropriate data as well as the identification of the application goal [2].

For this purpose, we cooperate closely with the international freight transport company in rail traffic. The identified application goal is the prediction of the target value “delay\_ank”, which is the delay at the arrival station. Furthermore, we used SQL queries to extract appropriate features from the database of the freight transport company.

Feature name	Description
<b>abfsstelle_id</b>	Station ID of the departure station
<b>ankbsstelle_id</b>	Station ID of the arrival station
<b>planabfahrt</b>	Planned departure time
<b>planankunft</b>	Planned arrival time
<b>lon_abf</b>	Longitude of the departure station
<b>lat_abf</b>	Latitude of the departure station
<b>lon_ank</b>	Longitude of the arrival station
<b>lat_ank</b>	Latitude of the arrival station
<b>border_abf</b>	Indicates if dep. stat. lies on the border
<b>border_ank</b>	Indicates if arrival stat. lies on the border
<b>region_abf</b>	Region of the departure station
<b>region_ank</b>	Region of the arrival station
<b>meter</b>	Distance between two stations
<b>tz</b>	Indicates the position of the traction unit
<b>reihe</b>	Series of the traction unit
<b>ordnr</b>	ID inside the series of the traction unit
<b>produktname</b>	Indicates the type of the train operation
<b>delay_abf</b>	Delay at the departure time
<b>altitude_diff</b>	Difference betw. altitudes of two stations

Table 1: Chosen features for the further KDD process and their descriptions.

For the feature “altitude\_diff”, we used the open elevation public API to receive the altitudes of the stations and we calculated their altitude differential.

The chosen features for the further KDD process are shown in Table 1. To investigate the correlations between the chosen numerical features and the target value “delay\_ank”, we use a correlation matrix (Figure 1).

As expected, there exists a strong correlation between delay at the departure station and delay at the arrival station. In order to get more information about the importance of the other chosen numerical features, we apply the random forest method without the feature “delay\_abf” (Figure 2).

### 1.2 Data preprocessing

Data preprocessing, also called data cleaning includes strategies for handling missing data fields and if appropriate removing noise to obtain consistent data [4].

The huge amount of historical data of freight train runs are real data including missing and wrong entries.

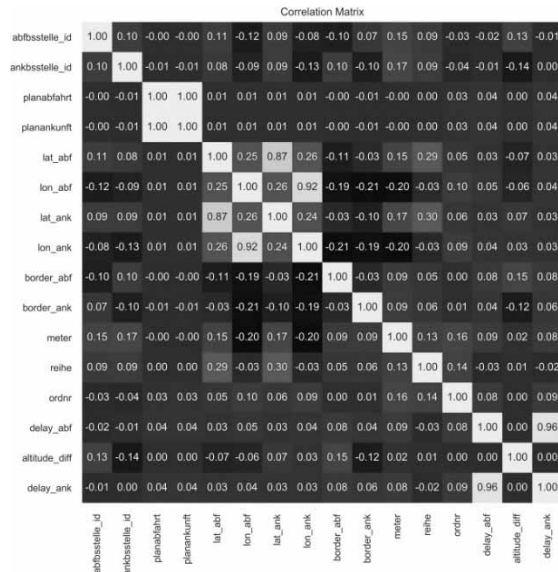


Figure 1: Correlation matrix, which shows the correlations between the chosen numerical features and the target value “delay\_ank”.

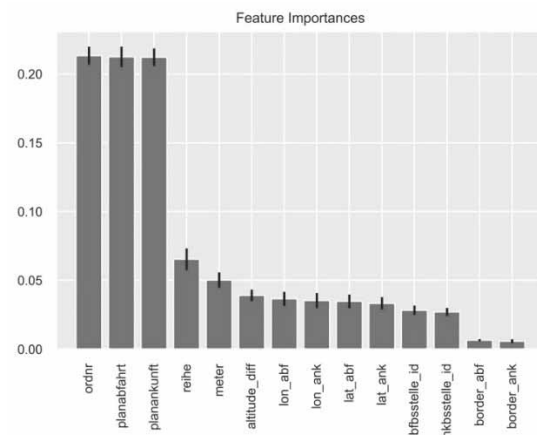


Figure 2: Feature importances of the chosen numerical features without the feature “delay\_abf” in descending order of importance.

Some wrong entries were easy to adjust, like swapped geographic coordinates. But for example, samples including planned arrival time before planned departure time or no distance between two different stations couldn't be adjusted that easily. For the further steps of the KDD process we don't consider samples with missing or wrong entries, which we couldn't replace or adjust.

### 1.3 Data transformation

In this step, we transform the nominal features “abfsstelle\_id”, “ankbsstelle\_id”, “region\_abf”, “region\_ank”, “tz”, “reihe”, “ordnr” and “produktname”, to use them for the data mining process and to increase the accuracy of the prediction model. For this purpose, we

apply the data transformation method one-hot encoding, which creates for each possible value of a nominal feature a new dummy feature and returns a quite sparse array. But each of the nominal features “abfsstelle\_id”, “ankbsstelle\_id”, “reihe” and “ordnr” contains several hundred possible values.

In order to reduce the number of dimensions to represent these nominal features, we use an embedding with various embedding sizes, which is a further data transformation method. The embedding learns to map each possible value of a nominal feature into a vector with the length of a given embedding size [5, 6].

Furthermore, we used the features “planabfahrt” and “planankunft” to extract the cyclical features day of the year “jahrestag”, weekday “wochentag” and minute of the day “tagmin” for the planned departure and arrival time.

In order to further increase the accuracy of the prediction model, we transform these cyclical features by using a sine and cosine transformation [7].

#### 1.4 Data mining

The actual data mining process includes selecting an adequate model, for example classification, clustering or regression, and choosing the data-mining algorithm(s) to find patterns of interest and finally to achieve the application goal [8]. Because our target value “delay\_ank” is a continuous numerical value, we chose a regression analysis and split the prepared data into training and test data. With the training data, we train a dummy regressor model, decision trees, random forests, extra trees and gradient boosting regression models.

For the comparison of prediction models, we apply the test data and evaluate for each regression model as well as different data transformation methods the mean squared error between the prediction and the target value “delay\_ank”. We use the dummy regressor which always predicts the mean of the training targets as a baseline to compare the mean squared errors.

#### 1.5 Interpretation and evaluation

This step consists of interpreting the found patterns, evaluating the prediction models and acting on the discovered knowledge. Proper interpretation of data mining results requires a high degree of domain knowledge. For this reason, we cooperate closely with experts of the freight transport company to interpret the results. For the theoretical evaluation of the prediction models, we used 2-fold cross-validation.

## 2 Results

Table 2 shows the comparison of the mean squared errors of the different regression models and the data transformation methods one-hot encoding as well as

embedding by using three different embedding sizes. The prediction model with the highest accuracy is the gradient boosting regression model with the embedding and embedding sizes 25 or 50.

Regression model	One-hot	Emb. 10	Emb. 25	Emb. 50
<b>DummyRegressor</b>	8329	8329	8329	8329
<b>Decision tree</b>	1119	1462	1363	1504
<b>Random forest</b>	696	683	690	696
<b>Extra trees</b>	749	684	692	695
<b>Gradient boosting</b>	643	632	629	629

Table 2: Comparison of different regression models and data transformation methods.

## 3 Conclusion and Outlook

This work has shown a comparison of prediction models for delay of freight trains by using data mining and machine learning methods. For further work, we will use the gradient boosting regression model with the embedding and embedding size 25. We will integrate an adequate prediction model into an agent-based model [1] to test the robustness of optimized locomotive schedules for freight trains.

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# ARGESIM Benchmarks on Modelling Approaches and Simulation Implementations – Development, Classification and Basis for Simulation Education

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**Abstract.** ARGESIM, a non-profit association for information and publication on simulation, started in 1990 in co-operation with EUROSIM, the Federation of European Simulation Societies, the series 'ARGESIM Comparison of Simulation Software' in the journal Simulation Notes Europe (SNE). The comparisons have been developed successfully towards the 'ARGESIM Benchmarks for Modelling Approaches and Simulation Implementations', with up to now 24 benchmarks defined, and up to now 350 benchmark solutions, benchmark reports, or benchmark studies published in SNE Simulation Notes Europe.

Interestingly, it turned out, that along with the various benchmark publications in SNE, the benchmarks are used as examples, case studies, and lab work in simulation education in academia.

This contribution sketches the development of the benchmarks and introduces a new classification of the benchmarks with respect to system type, model approach, and required experiments with the model(s). In the following, main emphasis is the investigation of the benchmarks as source and basis for simulation education, together with a classification of the up to now defined benchmarks with respect to their suitability in education – from simulation methodology view, and from simulation application view. The contribution concludes with an overview table on benchmark data: definition date, number of solutions, type classification, and classification for educational use.

## Introduction

The ARGESIM *Benchmarks for Modelling Approaches and Simulation Implementations* are a success story in the simulation community. With up to now 24 benchmarks defined, and up to now 350 benchmark solutions, benchmark reports, or benchmark studies published in SNE, the scientific membership journal of EUROSIM, the Federation of European Simulation Societies, the benchmarks publications have become a forum for information exchange on modelling approaches, simulation implementations, and features of simulation systems.

Interestingly, it turned out, that along with the various benchmark publications in SNE, the benchmarks are used as examples, case studies, and lab work in simulation education in academia – one emphasis of this contribution.

The first section lists the benchmarks defined up to now and describes the development from simulation software comparison to comparative studies on modelling approaches and simulation implementations, along with the development of the type of benchmark publications in SNE.

The second section discusses the impact of the benchmarks for simulation education generally, following the observed practice of use of the benchmarks as examples, case studies and lab work in simulation education in academia. Furthermore, the section introduces the new SNE publication type *Educational Benchmark Note*, for benchmark publications with primarily educational purpose and underlines the need for review of the benchmarks for educational use and classification of this educational use. The third section deals with the second emphasis of this contribution – the classification of the benchmarks with respect to system type, special modelling aspects, and required experiments.

The fourth section inspects in detail the benchmarks with respect to education use and combines a classification for education use with the new benchmark type classification. The section finishes with an overview table on benchmark data: definition date, number of solutions, type classification, and classification for educational use.

The fifth section sketches briefly the simulation software used in benchmarks contributions, and reviews shortly the context with the benchmark development. The last section is a short *Call for Benchmark Contributions*.

## 1 Benchmark Development

ARGESIM, a non-profit association for information and publication on simulation, started in 1990 in co-operation with EUROSIM, the Federation of European Simulation Societies, the series *ARGESIM Comparison of Simulation Software* in the journal *Simulation Notes Europe* (SNE). The comparisons have been developed successfully towards the *ARGESIM Benchmarks for Modelling Approaches and Simulation Implementations*, with various publication in SNE, and publications in other journals and conference proceedings.

ARGESIM started in 1990 the series *Comparison of Simulation Software* with modelling and simulation tasks based on relatively simple, easily comprehensible processes. In the beginning, simulationists were invited to prepare a *comparison solution* to be published in SNE as one-page solution.

### 1.1 Comparison and benchmark definitions

Along with development of system simulation, also the comparisons of simulation software developed further on towards benchmarks for modelling approaches and simulation implementations.

This development can be seen in definitions and solutions published from 1990 to 2018 in 95 SNE issues: 23 definitions (some revised), and about 350 publications with solutions. The following list of comparisons and benchmarks shows also the broad variety of simulation applications:

- C01 Lithium-Cluster Dynamics, SNE 0(1), 1990
- C02 Flexible Assembly System, SNE 1(1), 1991
- C03 Generalized Class-E Amplifier, SNE 1(2), 1991
- C04 Dining Philosophers I, SNE 1(3), 1991
- C05 Two State Model, SNE 2(1), 1992
- C06 Emergency Department SNE 2(3), 1992

- C07 Constrained Pendulum, SNE 3(1), 1993
- CP1 Parallel Simulation Techniques, SNE 4(1), 1994
- C08 Canal-and-Lock System, SNE 6(1), 1996
- C09 Fuzzy Control of a Two Tank System, SNE 6(2), 1996, revised SNE 16(3), 2006
- C10 Dining Philosophers II, SNE 6(3), 1996
- C11 SCARA Robot, SNE 8(1), 1998
- C12 Collision of Spheres, SNE 9(3), 1999
- C13 Crane Crab and Embedded Control, SNE 11(1), 2001; rev. SNE 17(1), 2007
- C14 Supply Chain, SNE 11(2-3), 2001
- C15 Clearance Identification, SNE 12(2-3), 2002
- C16 Restaurant Business Dynamics, SNE 14(1), 2004
- C17 SIR Type Epidemic with CA and ODEs, SNE 14(2-3), 2004; revised SNE 25(2), (2015)
- C18 Neural Networks vs. Transfer Functions, SNE 15(1), 2005
- C19 Pollution in Groundwater Flow, SNE 15(2-3), 2005, revised SNE 16(3-4), 2006
- CP2 Parallel & Distributed Simulation, SNE 16(2), 2006
- C20 Complex Assembly System, SNE 21(3-4), 2011
- C21 State Events and Structural-dynamic Systems, SNE 26(2), 2016
- C22 Non-standard Queuing Policies, planned 2019

For details, see [www.sne-journal.org/benchmarks/](http://www.sne-journal.org/benchmarks/)

### 1.2 From comparisons to benchmarks

In 2006, a re-organisation of the comparisons has been started [1], as the investigation of features of simulation systems went into the background, and the emphasis tended towards outline of modelling approaches and implementation techniques. The comparisons developed towards *Benchmarks for Modelling Approaches and Simulation Implementations*. The general changes are:

- Revised definitions: SNE is publishing revised definitions of previous comparisons, updating models and tasks in order to continue them as benchmark.
- Extended solution documentation: SNE allows two (or more) pages for solutions of classic benchmarks.
- Extended benchmarks: SNE introduces extended benchmarks, comparing modelling and simulation paradigms, or dealing with more complex models and experiments – as with benchmarks C12, C19, CP2, C20, C21, and C22.

The benchmark publications now may have different content, structure, emphasis, and length. Modellers and simulationists are invited to take the challenge to prepare, realise and submit a:

- *Benchmark Solution* with concise description of model implementation and experimentation tasks (two pages SNE), or a
- *Benchmark Report* with sufficient detailed description of model implementation with variants and adequate experiment formulations (four to six pages SNE), or a
- *Benchmark Study* presenting e.g. different / alternative / comparative modelling approaches and sketching analysis variants or supplemental model experiments (six to ten pages SNE).

## 2 Benchmarks and Simulation Education

Interestingly, during some archival work in 2017 and 2018, it turned out, that along with the various benchmark publications in SNE, the benchmarks are used as examples, case studies, and lab work in simulation education in academia.

As consequence, SNE invites authors to submit their benchmark publication also with educational impact, from sketching educational aspects, until a documented teaching template for the process under investigation (see also first announcement in SNE 28(4), [1]). Benchmark reports and benchmark studies become also a *SNE Educational Note*:

- *Educational Benchmark Report* with sufficient detailed description of model implementation with variants and adequate experiment formulations and with educational impact (four to six pages SNE), or a
- *Educational Benchmark Study* presenting e.g. different /alternative / comparative modelling approaches and sketching analysis variants or supplemental model experiments on an educational basis suitable for use in teaching (six to twelve pages SNE).

### 2.1 Benchmarks and types of SNE Notes

Generally, SNE publishes peer reviewed contributions on developments and trends in modelling and simulation in various areas and in application and theory, with main topics being simulation overall aspects and interdisciplinarity. Benchmark publications are seen as classical scientific publication, and categorized within the SNE publication types as *Benchmark Note* (BN).

As benchmark publications with educational impact may be also seen as *Educational Note* (EN), SNE is extending its publication type specification from 2018 on:

- *Technical Note* (TN) – scientific publication on specific topics in modelling and simulation, 6 – 10 pages
- *Short Note* (SN) – recent development on specific topics, short case study, max. 6 pages
- *Education Note* (EN) – modelling and simulation in / for education and e-learning, 6 - 8 pages
- *Software Note* (SW) – specific implementation with scientific analysis, max. 6 pages
- *Project Note* (PN) – Intermediate or final report or summary on a simulation project, 6 – 10 pages
- *Benchmark Note* (BN) – Documentation of a realized ARGESIM Benchmark as *Benchmark Solution*, 2 pages  
*Benchmark Report*, 4 – 6 pages  
*Benchmark Study*, 6 – 10 pages
- *Educational Benchmark Note* (BNE) – Documentation of a realized ARGESIM benchmark suited for educations as *Educational Benchmark Report*, 4 – 6 pages, or as, *Educational Benchmark Study*, 6 – 10 pages
- *Overview Note* (ON) – State-of-the-Art report in a specific area, only upon invitation – up to 14 pages

The SNE publication type can be also seen in the header frame as picture, and within the DOI of the publication, for instance the *Educational Benchmark Note* [2] in SNE 28(4) ([2], DOI: 10.11128/sne.28.bne12.10452, and this contribution itself with DOI: 10.11128/sne.29.bn.10453.

As another consequence of the observed educational use, the recent benchmark and the planned new benchmarks integrate educational aspects already in the definition – with equations, tasks, and background.

## 3 Benchmark Classification

There have been some attempts to classify the benchmarks and the solutions sent in. The classifications tested ranged from a rough classification of the definition to a detailed classification of the techniques presented in the solutions sent in.

From beginning on, comparisons were roughly classified as continuous comparison, or as discrete comparison. On the other side, around 2002, for the one-page comparison solutions a detailed classification for the techniques used in each task was developed and stored in a database to be accessed from the old SNE website ([3]).

And the two-page solutions, started in 2006, requested in the last paragraph an author-defined classification of approach and software- basis.

It turned out that the development of techniques very often overrun the detailed classification based on a certain status of an implemented method, and the author-defined classifications were sometimes not really significant and meaningful. As consequence the *SNE Editorial Office* decided to introduce a new classification only for the benchmark definitions: i) type of the underlying dynamic system and generic modelling approach, ii) type(s) of additional modelling aspects to be considered, and iii) required experiments with the model(s).

This recent benchmark classification makes use of abbreviated keywords:

- one-letter classification key **X** for the general type of the dynamic system and generic modelling approach,
- two-letter classification key **YY** for special modelling aspects to be considered or to be used alternatively,
- and three-letter keys **ZZZ** for the experiments necessary or suggested for the analysis of the model(s).

While in the early days of benchmarks only either continuous or discrete benchmarks were defined, the new classification introduces five general types, given in Table 1 (multiple classifications possible).

The general classification implies a modelling approach by ODEs, by PDEs, by event description, by process description, or by algorithmic description. The classification with special modelling aspects – listed in Table 2 – describes special modelling aspects to be considered, or special modelling approaches (to be used or suggested for comparison), etc.

Type	Abb.	Comment
Continuous	C	ODE/PDE-type model
Discrete	D	Model type Event, Process
Algorithmic	A	Model type Generic Discrete
Hybrid	H	Continuous model with discrete intervention
Structural-dynamic	S	State-dependent change of continuous and discrete models

Table 1: Benchmark classification – general type with one-letter keys.

Simulation of dynamic systems generally involves time domain analysis – the basic experiments required for all benchmarks; but also, steady state, analytical or symbolic

analysis may be useful. The experiment classification – given in Table 3 – denotes also the more complex experiment tasks.

Type	Key	Comment
Stiffness	ST	Stiff System
Spatial	SP	Additional spatial dynamics
State Events	SE	State event description
Implicit	IM	Implicit model description
Time Events	TE	Time event description
Scheduling	SC	Scheduling control in model
Concurrency	CC	Concurrent events
Control	CO	Model with control (tasks)
Fuzzy	FZ	Fuzzy control or system
Data	DA	Complex modelling data
Physical Approach	PM	Modelica-type approaches
AB-Models	AB	Agent-based modelling
Transfer Function	TF	Transfer function modelling
Neural Nets	NN	Modelling with / as NN
SD Models	SD	System Dynamics modelling
Cellular Automata	CA	Modelling with / as CA
Petri Net	PN	Petri net modelling / analysis
Compartment	CP	Compartment modelling

Table 2: Benchmark classification – special modelling aspects with two-letter keys.

Type	Abb.	Comment
Time Domain	TDA	time domain analysis
Parameter	PAR	parameter study
Steady State	SST	steady state analysis
Optimization	OPT	parameters/function optimization
Analytics	ANA	analytical analysis
Sensitivity	SEN	sensitivity analysis
Symbolics	SYM	Symbolical analysis
Identification	IDT	model identification by data
Numerics	NUM	handling of numerical problems
Boundary	BVP	boundary value solution
Validation	VAL	model/implementation validation
Comparisons	CPM	model alternatives comparison o
Statistics	STA	statistically driven experiments
Conditions	CON	condition-dependent experiments
Presentation	PRE	advanced result presentation
Model Parts	MOP	model parts at experiment level
Model Control	MOC	control of models (sequence)

Table 3: Benchmark classification – experiment classification with three-letter keys.



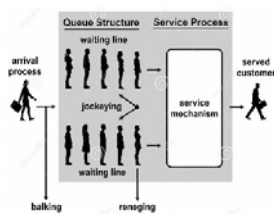
## 4 Educational Impact of the Benchmarks

The early benchmarks (comparisons) concentrated mainly on features of simulation systems, so that an educational aspect can be mainly found in implementation. The more recent comparisons and benchmarks, and especially the extended benchmarks since 2006 investigate also modelling approaches, so that the benchmarks may suit also for educational purposes in modelling.

In the following the up to now defined comparisons and benchmarks are briefly sketched and investigated with respect to their suitability for educational purposes, which allows selection of a benchmark for certain educational use. The educational impact presents itself in modelling, in implementation, or in the application, and depends on the educational level. Therefore the *SNE Editorial Office* has suggested an educational classification **E** for the benchmarks in modelling **M**, implementation **I** and application **A** with the rating **V** – very suitable, **S** – suitable, **U** – useful, and for the educational **E** level **L** the suggestion beginners **B**, and practitioners **P**. A three-letter key, with a hyphen to distinguish from the benchmark content classification, compiles then the educational classification, e.g. **EM-U**, **EI-V**, **EA-S**, **EL-P**.

The new three-step classification: general type – special modelling aspects – types of required experiments – is added to the following short presentation of benchmarks from the most recent one in 2019 the first one in 1990. The summarizing Table 4 list all benchmarks with content classification, educational classification, *SNE* definition, and number of contributions sent in.

### C22 Non-standard Queuing Policies



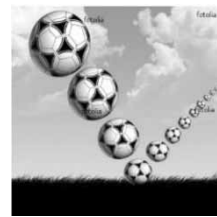
#### Classification C22

- System: **D**
- Modelling: **TE, SC, CC**
- Experiments: **TDE, PAR, SST, STA**
- Education: **EM-V, EI-V, EA-S, EL-B**

The benchmark *C22 Non-standard Queuing Policies* studies three non-standard queues with practical relevance: the renegeing queue, where entities leave a queue after a given waiting time, the jockeying queue, where entities can switch to another shorter queue, and the classing queue, where at certain time entities with a given attribute ("class") are called to the front of the queue.

Challenges are a proper modelling approach and a suitable implementation, especially in case of concurrency, and the evaluation of the dynamic behaviour. On the one side, this benchmark is a challenge for discrete simulation systems, and on the other side this benchmark is very suited for education of beginners in modelling and implementation area.

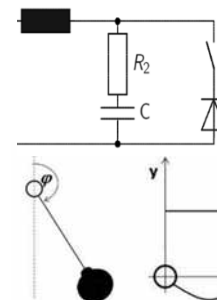
### C21 State Events and Structural-dynamic Systems



#### C21 Classification

- System: **H, C, S**
- Modelling: **SE, IM, PM**
- Experiments: **TDA, PAR, BVP, NUM, MOC**
- Education: **EM-V, EI-S, EA-S, EL-B, EL-P**

In benchmark *C21 State Events and Structural-dynamic Systems*, three case studies compare modelling and implementation of state events in dynamic systems, up to structural-dynamic systems. The first case study, the almost classical bouncing ball dynamics investigates different kinds of bounce modelling and implementation with associated events.

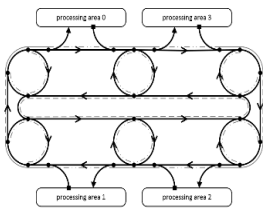


In the second case study, a switching RLC circuit, different diode models result in simple switching state events or in DAE systems which may need index reduction.

The third case study is structural-dynamic by itself: the rotating pendulum with free falling phase changes dynamics from swinging to falling (and vice versa) – switching between different degrees of freedom.

This benchmark addresses on the one side the features of simulation systems for describing and implementing hybrid and structural-dynamic systems, on the other side all three case studies are coming along with educational aspects for simulation methodology, implementation, and application. In application, the benchmark addresses mechanical engineering and electrical engineering, in methodology and implementation the benchmark deals with appropriate description and handling of hybrid and structural-dynamic systems. Depending on the case studies, the benchmark is suited for all educational levels in simulation.

## C20 Complex Production System



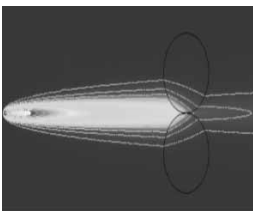
### C20 Classification

- System: **D**
- Modelling: **SC, TE, CC**
- Experiments: **TDA, PAR, STA**
- Education: **EM-U, EI-S, EA-U, EL-P**

Benchmark **C20 Complex Production System** is intended to be used as a foundation for analyzing manufacturing control systems, by comparing different simulation techniques and/or control algorithms regarding complexity and dynamics. The benchmark is based on two dimensions, defining a total of twelve different scenarios that differ in their complexity and dynamic behavior.

This benchmark is a challenging one for expert users in discrete process simulation and for discrete simulation systems – educational aspects can be found at implementation level.

## C19 Pollution in Groundwater Flow with Spatially Distributed Modelling



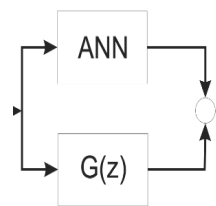
### C19 Classification

- System: **C**
- Modelling: **SP, CO, CA**
- Experiments: **TDA, SST, PAR, CPM**
- Education: **EM-V, EI-S, EA-U, EL-P**

Benchmark **C19 Pollution in Groundwater Flow with Spatially Distributed Modelling** analyses a homogeneous ground water body with a singular pollution source and with facilities for reduction of contamination, based on the transport equation. Tasks require steady state analysis, spatial calculation of unregulated pollution spread, and modelling and control of facilities (pumps) for decontamination. The benchmark addresses quite different modelling approaches and solution techniques, from classical discretization methods via FEM to alternatives techniques like cellular automata, Monte-Carlo methods and Random Walk.

The recent revised definition emphasizes on modelling methods for distributed systems, and is a very suitable case study for introduction into instationary distributed diffusion processes – with educational aspects for comparative modelling and simulation implementation.

## C18 Identification of Nonlinear Dynamics – Neural Networks versus Transfer Functions



### C18 Classification

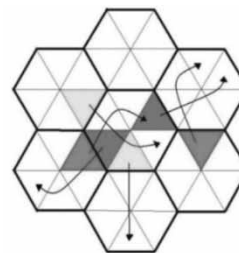
- System: **C, D, H**
- Modelling: **NN, CO, DA, TF**
- Experiments: **TDA, VAL, IDT**
- Education: **EM-V, EI-S, EA-U, EL-B**

Benchmark **C18 Identification of Nonlinear Dynamics – Neural Networks versus Transfer Functions** studies alternative approaches for identification of the nonlinear dynamical relation between muscle force and muscle-belly thickening.

Classical discrete transfer function models and as alternatives discrete transfer function models with neural net models in parallel, and extended neural net models are to be compared with respect to accuracy and efficiency. Two data sets, measured on the same muscle type, are available for identification procedures and for validation purposes (download available).

The comparative approaches invite for educational use in modelling of nonlinear dynamics and in introduction to neural nets – independent on the application area physiology. Another educational aspect is use of appropriate discrete transfer functions and error correction by neural network compensation.

## C17 SIR-type Epidemic with CA and ODEs



### C17 Classification

- System: **C, D**
- Modelling: **SP, CA, TE**
- Experiments: **TDA, PAR, IDT, CPM**
- Education: **EM-V, EI-S, EA-S, EL-B, EL-P**

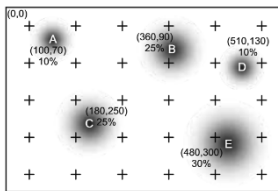
Benchmark **C17 Modelling and Simulation of a SIR-type Epidemic with Cellular Automata and Ordinary Differential Equations** investigates a classical population model for the spread of infection diseases (SIR model) and an inhomogeneous spatial approach using cellular automata.

The benchmark puts emphasis on identification of parameters based on an abstract time discrete conceptual model.

Tasks include validation and analysis of identification, investigation on the impact of different spatial dynamics, and simulation scenarios for confining epidemic outbreaks that involve state-dependent interventions (vaccinations).

This benchmark is suited for educational purpose in various ways. In modelling, macroscopic and microscopic approaches can be compared, and modelling with advanced cellular automata can be studied. In implementation, discrete processes are to be formulated properly for comparative investigations. In application – spread of disease and vaccination – the benchmark is a powerful basis for testing different vaccination strategies.

### C16 Restaurant Business Dynamics



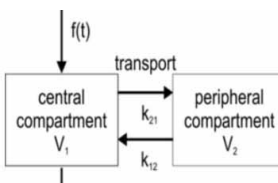
#### C16 Classification

- System: **A, D**
- Modelling: **TE, SC, AB**,
- Experiments: **TDA, PAR, OPT**
- Education: **EM-V, EI-V, EA-U, EL-B**

Benchmark *C16 Restaurant Business Dynamics* addresses modelling, simulation and optimization of a discrete dynamic system. The business system under examination is restaurant operating: depending on financial results (from guests living in the neighbourhood), restaurants open branches in an adequate surrounding or close down. Strategic parameters are tax rate and structural distance to new branch restaurants - to be investigated and optimized in an adequate discrete (stochastically influenced) model (process model, agent-based model, statistical analysis, event model...).

This benchmark addresses not only the simulation community, it is an interesting calculation task for everybody, and allows various approaches, e.g. also generic algorithmic ones. Consequently, the benchmark is a basis for various education areas, also suited for spreadsheet calculation.

### C15 Clearance Identification



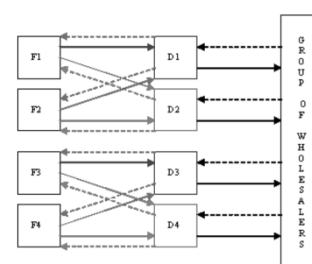
#### C15 Classification

- System: **C**
- Modelling: **CP, DA**
- Experiments: **TDA, IDT, STA, SEN, VAL**
- Education: **EM-S, EI-S, EA-S, EL-B**

The Benchmark *C15 Clearance Identification* is based on the dynamics of renal clearance. The benchmark puts emphasis on identification of a compartmental model for the clearance using real-world measurement protocols, and on statistical model parameter analysis based on artificial protocols.

This benchmark allows to study different identification approaches for a linear dynamic system, e.g. use of sensitivity functions or use of analytical solutions, and to handle artificial data protocols for extended experiments – a useful basis for teaching of both topics, independent on the physiological background.

### C14 Supply Chain Management



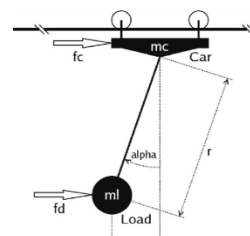
#### C14 Classification

- System: **A, D**
- Modelling: **TE, AB**
- Experiments: **TDA, PAR, STA**
- Education: **EM-S, EI-S, EA-S, EL-B**

Benchmark *C14 Supply Chain Management* is based on a simplified supply chain (four factories, four distributors, a group of wholesalers, and twelve products). The benchmark concentrates on discrete modelling of the process, especially on the order flow, and on implementation of different order strategies.

This benchmark is a classical case study for supply chain modelling, showing also the bullwhip effect dependent on the order strategies – an interesting topic for basic education in production and logistics. The implementation does not really need a simulation system, classical recursive calculations can manage all tasks, so that the benchmark is open as educational case study in many areas.

### C13 Crane with Complex Embedded Control



#### C13 Classification

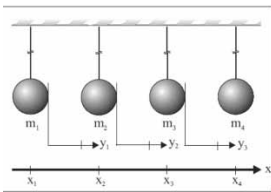
- System: **C, H**
- Modelling: **CO, SE**
- Experiments: **TDA, PAR, MOP, CPM, MOC, CON**
- Education: **EM-S, EI-S, EA-S, EL-P**

Benchmark *C13 Crane with Complex Embedded Control* is based on modelling and digital control of a crane crab. The discrete control is designed by means of a state space observer, and by state space control.

On modelling level, setup and handling of implicit nonlinear model descriptions are investigated, and nonlinear model and linear model (linearized model) are compared. On simulation level, simulation results for nonlinear and linear dynamics without feedback control are to be compared, and two time-domain scenarios for the fully controlled nonlinear system with disturbances are investigated.

The revised definition of this benchmark underlines the educational impacts: on model level, comparison of models and integration of discrete elements are to be investigated, and on experiment level formulation of state-dependent interventions. And finally, yet importantly, the benchmark is a case study for control application: digital observer control with security interventions.

### C12 Collision Processes in Rows of Spheres



#### C12 Classification

- System: **C, D**
- Modelling: **SE, TE, PM**
- Experiments: **TDA, NUM, PAR, CPM, STA**
- Education: **EM-S, EI-V, EA-V, EL-B**

Benchmark **C12 Collision Processes in Rows of Spheres** is based on a continuous mechanical model with collision events, but mainly concentrates on discrete events within the movement of the spheres – on the collision of the spheres. The benchmark tries to analyse the phenomena of collisions, from elastic to plastic, or inelastic, resp. The tasks of the benchmark – the experiments to be performed with the model – require determination of collision sequences depending on the collision type (between elastic and inelastic), boundary value problems for initial hits, analysis of the number of collisions and of final velocities of the spheres, and stochastic analysis for stochastically modelled collisions strength. The primarily given equations are linear and can be solved analytically, so that collision times are known in advance – and an event-oriented approach is possible. But more realistic nonlinear equations require full state event handling.

This benchmark is a classical educational benchmark: demonstration of basic mechanical phenomena, various implementation possibilities because of simple linear equations, and statistically driven experiments – mainly for beginners. Interestingly, all implementations have to compensate numerical problems caused by too small slopes for determining the collisions.

### C11 SCARA Robot



#### C11 Classification

- System: **C, H, S**
- Modelling: **IM, SE, CO, PM**
- Experiments: **TDA, PAR, CPM, NUM**
- Education: **EM-V, EI-V, EA-V, EL-B, EL-P**

Benchmark **C12 SCARA Robot** investigates movement and control of SCARA robot (Selective Compliance Assembly Robot Arm).

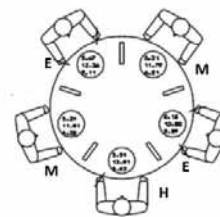
This robot type has two vertical revolute joints and one vertical prismatic joint. The axes of all three joints are vertical. The equations of motion follow the typical implicit form: mass matrix times accelerations equal to generalized forces. A DC-motor (ODE model with current limitations) with PD-control drives the specific movement of the robot (point-to-point control).

Challenge for implementation is the implicit model description, whereby handling requires a-priori manual resolving to an explicit state space, or numerical resolving in implementation, or use of a DAE-solver; solution may also make use of physical modelling approaches which decrease the modelling effort, but which need special care for in case of state-dependent changes.

As further challenge, the benchmark requires modelling and implementation of a collision avoidance – which requires state event handling and model change (depending on implementation).

The educational aspects of this benchmark are multifaceted: an introduction to robot modelling and control, a guideline for implementing implicit models and state event handling, and a test for the capabilities of physical modelling environments as Modelica, and some more. Interestingly, also spreadsheet calculation allows an implementation of this comparison.

### C10 Dining Philosophers II



#### C10 Classification

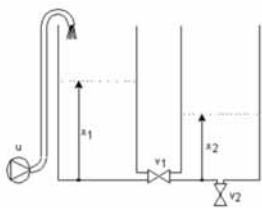
- System: **D, A**
- Modelling: **TE, SC, AB, PN**
- Experiments: **TDA, SST, PAR, STA, NUM, CON**
- Education: **EM-V, EI-V, EA-V, EL-B, EL-P**

Benchmark **C10 Dining Philosophers II** is a successor of the very general fourth benchmark **C4 Dining Philosophers**. The Dining Philosophers' problem is relatively easy to describe, but the philosophers' behaviour may cause interesting problems, including especially concurrent access and deadlock situations: Five philosophers are sitting around a large round table, each with a bowl of Chinese food in front of him. Between periods of meditation, they may start eating whenever they want to, with their bowls being filled frequently. However, there are only five chopsticks available, one each to the left of each bowl - and for eating Chinese food one needs two chopsticks.

This process offers a wide range of modelling approaches and simulation case studies – as foreseen for the original benchmark **C4 Dining Philosophers**. This benchmark **C10 Dining Philosophers II** provides better specifications for result comparisons: i) modular and / or object-oriented model descriptions, ii) investigation of simultaneous access to resources, and iii) detection of deadlocks. For this purpose, the philosophers must follow suitably settled strategies for changing the status of meditating and eating.

This definition implicitly describes also the educational impact: modelling and simulation of concurrent events, investigation of system status as deadlock or reachability. This benchmark addresses not only the simulation community, it is an interesting calculation task for everybody, and allows various approaches, e.g. also generic algorithmic ones. Consequently, the benchmark is a basis for various education areas, also suited for spreadsheet calculation.

### C09 Fuzzy Control of a Two Tank System



#### C09 Classification

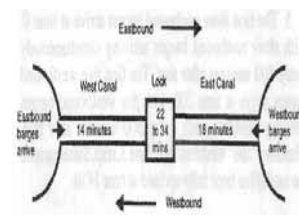
- System: **C, H**
- Modelling: **FC, CO, PM**
- Experiments: **TDA, CPM, NUM, PRE**
- Education: **EM-U, EI-S, EA-U, EL-B**

Benchmark **C09 Fuzzy Control of a Two Tank System** is a tribute to the method of fuzzy control. A two-tank system in a specific configuration is characterized by non-linear balancing ODEs, including characteristics of the liquid (laminar, turbulent, friction). Two fuzzy controllers (one using singletons) should be implemented as discrete systems.

The benchmark requires implementation of the fuzzy controllers and 3-D visualisation and various use of the fuzzy controllers for control of the two-tank system

From educational viewpoint, the benchmark introduces to fuzzy control and its implementation in continuous systems. The two-tank system could be described by physical modelling.

### C08 Canal-and-Lock System



#### C08 Classification

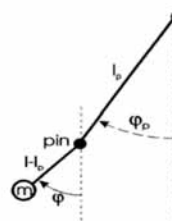
- System: **D, A**
- Modelling: **TE, SC, DA**
- Experiments: **TDA, STA, VAL**
- Education: **EM-U, EI-V, EA-U, EL-B**

Benchmark **C8 Canal-and-Lock System** investigates a canal-and-lock system used by barges moving from one waterway to another. The system is composed of a west canal, a lock, and an east canal. Barges can move through the system in only one direction at a time. The policy for operating the system is to let a up to maximal number barges proceed through the system in the eastbound direction, and vice versa. This ideal uniform east-to-west cycle and west-to-east cycle is 'disturbed' by less arriving barges, delayed barges, not available barges at cycle change, and differences in lock operation depending on the direction. For proper operation complex rules for the frequent exception cases must be followed.

While the systems can be modelled by simple process modelling, these complex rules are the modelling challenge in this benchmark. Task are the validation of the model (of the implementation of the complex rules) by given and solved scenarios, and statistical capacity analysis including variance reduction techniques.

This benchmark shows educational aspects for condition implementation in process modelling, and generally for conditional event modelling (as the benchmark can also be solved in a classical programming environment). On experiment level, variance reduction techniques can be trained.

### C07 Constrained Pendulum



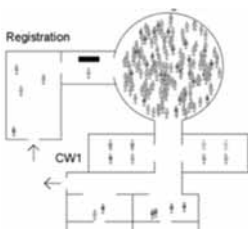
#### C07 Classification

- System: **C, H, S**
- Modelling: **SE, PM**
- Experiments: **TDA, PAR, CPM, BVP, MOP, MOC**
- Education: **EM-V, EI-V, EA-S, EL-B**

Benchmark **C07 *Constrained Pendulum*** comes from classical mechanics. The physical pendulum hits a pin - a state event, whereby length and angular velocity change discontinuously. Tasks are proper description of the hit (and release) event, either by switching constructs or by structural-dynamic model approaches, comparison of linear and nonlinear model dynamics, parameter studies, and boundary value calculations.

This benchmark is of high educational interest, as various techniques can be used for the necessary model change, and a proper state space transformation results in much easier hit- and release-events. There is also a clever way around the boundary value problem.

### C06 Emergency Department – Follow-up Treatment



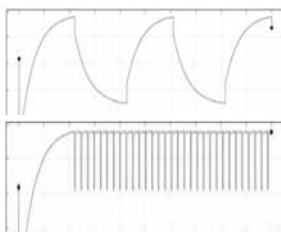
#### C06 Classification

- System: **D**
- Modelling: **TE, SC, DA**
- Experiments: **TDA, SST, STA, CON**
- Education: **EM-S, EI-S, EA-S, EL-B**

The Benchmark **C06 *Emergency Department - Follow-up Treatment*** discusses modelling approaches and strategic computer experiments for a small health care unit (post-treatment in a casualty department). The challenge for classical process-oriented modelling - with wards as stations and patients as entities - is a state-dependent change of available doctors, so that either more complex control strategies are needed, or other approaches may be meaningful. The descriptive parameters for the model - statistical distributions - are based on real-world data of the health care unit.

The benchmark represents a classical introductory case study into process modelling or advanced techniques and is well suited for education in modelling and simulation.

### C05 Two State Model



#### C05 Classification

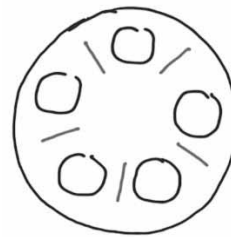
- System: **C, H**
- Modelling: **SE**
- Experiments: **TDA, ANA, NUM, SYM**
- Education: **EM-S, EI-S, EA-U, EL-B**

Benchmark **C05 *Two State Model*** deals with discontinuities in dynamic systems. While the solution itself is continuous, the derivatives may have jumps, depending on thresholds for the states. Basis is a linear stiff system with two states, where parameters in the derivative function switch depending on threshold values for the state - resulting in rare switching or in high frequency switching. In any case, the switching time instants must be detected with high accuracy.

The task requires parameter variations resulting in drastically increasing number of switching, and validation of certain switching time instants with data from analytical solutions, and investigations on dependence of solutions on relative accuracy.

For education, this benchmark is suitable for getting knowledge in handling state events and mastering numerical and accuracy problems caused by stiff systems. Furthermore, numerical and analytical solutions can be compared, also for validation.

### C04 Dining Philosophers



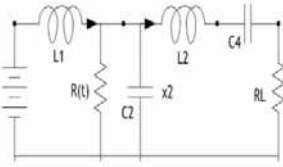
#### C04 Classification

- System: **D, A**
- Modelling: **TE, CC, SC, AB, PN**
- Experiments: **TDA, SST, STA, PAR, ANA, SYM**
- Education: **EM-V, EI-V, EA-V, EL-B, EL-P**

Benchmark **C04 *Dining Philosophers*** is a very general benchmark. The Dining Philosophers' problem is relatively easy to describe, but the philosophers' behaviour may cause interesting problems, including especially concurrent access and deadlock situations: Five philosophers are sitting around a large round table, each with a bowl of Chinese food in front. Between periods of meditation, they may start eating whenever they want to, with their bowls being filled frequently. However, there are only five chopsticks available, one each to the left of each bowl - and for eating Chinese food one needs two chopsticks.

This process offers a wide range of modelling approaches, analysis techniques, and simulation studies. The benchmark does not fix certain task to be performed with a model of this process - any kind of contribution with classical and alternative modelling technique, any kind of analysis technique (from numeric to symbolic), and any kind of strategy case study is welcome. This variety makes this benchmark generally very suitable for education purposes.

### C03 Generalized Class-E Amplifier

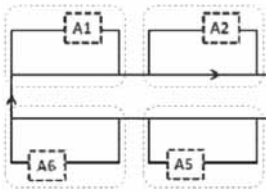


#### C03 Classification

- System: **C, H**
- Modelling: **TE, ST, PM**
- Experiments: **TDA, PAR, ANA, NUM, BVP**
- Education: **EM-U, EI-S, EA-U, EL-B**

The Benchmark **C03 Generalized Class-E Amplifier** is based on the classical model of a class-E amplifier, consisting of two capacitors, two inductors, and two resistors mixed in serial and in parallel. Tasks are general parameter studies, steady state analysis, special parameter analysis for a switching resistor, and a boundary value problem. This benchmark offers education purposes in physical modelling for electrical engineering, and analysis techniques (numerical and analytical),

### C02 Flexible Assembly System



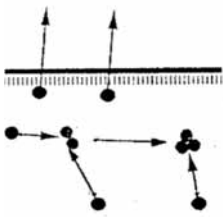
#### Classification C02

- System: **D**
- Modelling: **TE, SC**
- Experiments: **TDE, STA**
- Education: **EM-U, EI-U, EA-S, EL-B**

Benchmark **C02 Flexible Assembly System** is the first discrete comparison defined in SNE. Based on a relatively simple process model with six stations around a circular transport belt, the task is to define and combine submodels and to describe control strategies for the workflow of pallets travelling around the belt.

Originally defined for checking the features of discrete simulators for the sketched tasks, the relatively simple model is case study for introduction to discrete process modelling, or to event-based process modelling and to simulation of production systems – a suitable basis for education for simulation novices in this area.

### C01 Lithium-Cluster Dynamics



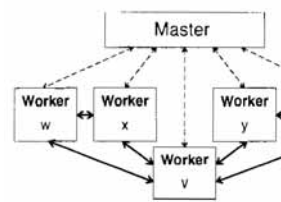
#### C01 Classification

- System: **C**
- Modelling: **ST, CP**
- Experiments: **TDA, SST, PAR, NUM**
- Education: **EM-S, EI-S, EA-S, EL-B**

The Benchmark **C01 Lithium Cluster Dynamics**, the first benchmark in SNE, is taken from solid state physics. A balance model describes formation and decay of defect aggregates in alkali halides, produced by electron bombardment. The nonlinear ODE model consists of three states (defect aggregates) and is very stiff.

Tasks are simulation of the stiff system comparing ODE solvers, a parameter study for a critical decay parameter, and steady state calculation. Emphasis of educational aspects is simulation of stiff systems, and steady state analysis.

### CP1 Parallel Simulation Techniques



#### Classification CP1

- System: **C**
- Modelling:
- Experiments: **TDE, NUM, CPM, MOP**
- Education: **EM-U, EI-S, EA-U, EL-B**

Benchmark **CP1 Parallel Simulation Techniques** deals with parallel simulation techniques. Three testcases investigate effort and benefit of parallelization of time domain for continuous models.

The first case is a parallel parameter variation of the damping factor of the classical oscillation. The ODEs for the oscillation are not coupled, the ODE solver work independently in parallel. The second case study are five strongly coupled predator-prey models. Almost all of the ten ODEs are coupled with each other, so that any kind of parallelisation of the model shows a strongly coupled structure. The third case study requires only a weak coupling: discretizing the PDE for the swinging rope by the method of lines, results in weakly coupled ODEs, where one line ODE is coupled only with the neighbouring lines. This weak coupling remains also if lines are grouped together. Tasks of this benchmark is the investigation of parallelisation variants for time domain analysis, qualitatively and quantitatively in comparison with the non-parallel simulation.

This benchmark has been set up in 1994, where the simulation community was experimenting with parallelisation, at times where parallel hardware was exotic, and software for parallelisation needed special knowledge. Nowadays simulation environments make use of the parallel hardware in modern PCs automatically, so that the primary aims of the benchmark almost have lost relevance. But this benchmark is still a proper case study for introduction into the area, so it still has impact on educational level.

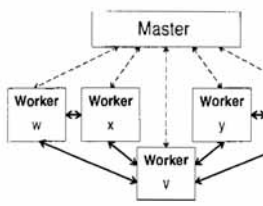
Benchmark	Type Classification			Definition in SNE	# Sol.	Education Classification			
	Gen. Type	Modeling Aspects	Experiment			Mod.	Impl.	Appl.	Level
C22 Non-standard Queuing Policies	D	TE, SC, CC	TDE, PAR, SST, STA	SNE 29(3) 2019		EM-V	EI-V	EA-S	EL-B
C21 State Events and Structural-dynamic Systems	H, C, S	SE, IM, PM	TDA, PAR, BVP, NUM, MOC	SNE 26(2), 2016	3	EM-V	EI-S	EA-S	EL-B, EL-P
C20 Complex Assembly System	D	SC, TE, CC	TDA, PAR, STA	SNE 21(3-4) 2011	1	EM-U	EI-S	EA-U	EL-P
C19 Pollution in Groundwater Flow	C	SP, CO, CA	TDA, SST, PAR, CPM	SNE 16(3-4), 2006, R	3	EM-V	EI-S	EA-U	EL-P
C18 Neural Networks vs. Transfer Functions,	C, D, H	NN, CO, DA, TF	TDA, VAL, IDT	SNE 15(1), 2005	4	EM-V	EI-S	EA-U	EL-B
C17 SIR-type Epidemic with CA and ODEs	C, D	SP, CA, TE	TDA, PAR, IDT, CPM	SNE 15(2), 2015, R	6	EM-V	EI-S	EA-S	EL-B EL-P
C16 Restaurant Business Dynamics	A, D	TE, SC, AB	TDA, PAR, OPT	SNE 14(1), 2004	10	EM-V	EI-V	EA-U	EL-B
C15 Clearance Identification	C	CP, DA	TDA, IDT, STA, SEN, VAL	SNE 12(2-3), 2002	7	EM-S	EI-S	EA-S	EL-B
C14 Supply Chain Management	A, D	TE, AB	TDA, PAR, STA	SNE 11(2-3), 2001	8	EM-S	EI-S	EA-S	EL-B
C13 Crane Crab and Embedded Control	C, H	CO, SE	TDA, PAR, MOP, CPM, MOC, CON	SNE 17(1), 2007, R	12	EM-S	EI-S	EA-S	EL-P
C12 Collision of Spheres	C, D	SE, TE, PM	TDA, NUM, PAR, CPM, STA	SNE 9(3), 1999	16	EM-S	EI-V	EA-V	EL-B
C11 SCARA Robot	C, H, S	IM, SE, CO, PM	TDA, PAR, NUM, CPM	SNE 8(1), 1998	12	EM-S	EI-V	EA-V	EL-B EL-P
C10 Dining Philosophers II	D, A	TE, SC, AB, PN	TDA, SST, PAR, STA, NUM, CON	SNE 6(3), 1996	23	EM-S	EI-V	EA-V	EL-B EL-P
C09 Fuzzy Control of a Two-Tank System	C, H, D	FC, CO, PM	TDA, CPM, NUM, PRE	SNE 6(3), 2006	21	EM-U	EI-S	EA-U	EL-B
C08 Canal-and-Lock System	D, A	TE, SC, DA	TDA, STA, VAL	SNE 6(1), 1996	9	EM-U	EI-V	EA-U	EL-B
C07 Constrained Pendulum	C, H, S	SE, PM	TDA, PAR, CPM, BVP, MOP, MOC	SNE 3(1), 1993	43	EM-V	EI-V	EA-S	EL-B
C06 Emergency Department	D	TE, SC, DA	TDA, SST, STA, CON	SNE 2(3), 1992	20	EM-S	EI-S	EA-S	EL-B
C05 Two State Model	C, H	SE	TDA, ANA, NUM, SYM	SNE 2(1), 1992	20	EM-S	EI-S	EA-U	EL-B
C04 Dining Philosophers I	D, A	TE, SC, AB, PN	TDA, SST, STA, PAR, ANA, SYM	SNE 1(3), 1991	19	EM-V	EI-V	EA-V	EL-B EL-P
C03 Generalized Class-E Amplifier	C, H	TE, ST, PM	TDA, PAR, ANA, NUM, BVP	SNE 1(2), 1991	31	EM-U	EI-S	EA-U	EL-B
C02 Flexible Assembly System	D	TE, SC	TDE, STA	SNE 1(1), 1991	38	EM-U	EI-U	EA-S	EL-B
C01 Lithium-Cluster Dynamics	C	ST, CP	TDA, SST, PAR, NUM	SNE 0(1), 1990	38	EM-S	EI-S	EA-S	EL-B
CP2 Parallel & Distributed Simulation	C, D		TDE, NUM, CPM, MOP	SNE 16(2), 2006	1	EM-U	EI-S	EA-S	EL-B
CP1 Parallel Simulation Techniques	C		TDE, NUM, CPM, MOP	SNE 4(1), 1994	12	EM-U	EI-S	EA-U	EL-B

**Table 4:** ARGESIM Benchmarks: Definition date (R – revised definition), number of solutions, and classificationS:

**Education E:** in modelling **M** - implementation **I** - application **A**: **V** – very suitable, **S** – suitable, **U** – useful; Level **L**: beginner **B** – practitioner **P**  
**General Type:** Continuous **C** - Discrete **D** - Algorithmic **A** - Hybrid **H** - Structural-dynamic **S**  
**Modeling Aspects:** Stiffness **ST** - Spatial **SP** - State Events **SE** - Implicit **IM** - Time Events **TE** - Scheduling **SC** - Concurrency **CC** - Control **CO** - Fuzzy **FZ** - Data **DA** - Physical Model. **PM** - AB-Models **AB** - Transfer Function **TF** - Neural Nets **NN** - SD Models **SD** - Cellular Automata **CA** - Petri Net **PN** - Compartment **CP**  
**Experiment:** Time Domain **TDA** - Parameter **PAR** - Steady State **SST** - Optimization **OPT** - Analytics **ANA** - Sensitivity **SEN** - Symbolics **SYM** - Identification **IDT** - Numerics **NUM** - Boundary **BVP** - Validation **VAL** - Comparisons **CPM** - Statistics **STA** - Conditions **CON** - Presentation **PRE** - Model Parts **MOP** - Model Control **MOC**



## CP2 Parallel & Distributed Simulation



### Classification CP1

- System: C, D
- Modelling:
- Experiments: TDE, NUM, CPM, MOP
- Education: EM-U, EI-S, EA-S, EL-B, EL-P

Benchmark CP2 *Parallel & Distributed Simulation* updates and extends the previous ARGESIM Benchmark CP1 Parallel Simulation Techniques. Three test cases, a Monte-Carlo study, a Lattice Boltzmann Simulation, and a PDE-based Simulation investigate effort and benefit of parallelization of time domain for continuous models.

The first test case is the Monte-Carlo for the damping parameter of a classical oscillation. The ODEs for the oscillation are not coupled, the ODE solver work independently in parallel.

The second case study addresses the lattice Boltzmann method (LBM) for fluid flows, which is widespread in parallel simulation domains today. The method is derived from lattice gas cellular automata in which space, time, particle velocity and particle occupation state are all discrete. The case study is based on the famous cavity flow problem published by Hou et al in J. Comput. Phys. 118 (1995), where the behaviour of an incompressible fluid in a square enclosure, driven by a constant stream on the top boundary is examined. The task is to simulate the cavity flow with lattice size 257 x 257 for a number of 350.000 iterations – testing different parallelisation approaches for the flow dynamics.

The third case study is based on the PDE for a swinging string with fixed length, fixed at both ends, excited at the beginning. Discretising the space equidistant and replacing the partial differential quotient by a central difference quotient, a set of weakly coupled ODEs replaces the PDE. Also, an analytical solution (approximation) can be calculated because of the linearity of the discretized system. A classical separation approach can be used for calculating the solution (this yields with given initial and boundary conditions a solution with a Fourier series).

Nowadays simulation environments make use of the parallel hardware in modern PCs automatically, so that the primarily aims of the benchmark almost have lost relevance. But parts of this benchmark have an educational impact at modelling level, e.g. the different approaches for the swinging string PDE, and the introduction to Lattice-Boltzmann simulation.

## 5 Benchmarks and Software

In the early days, the benchmarks – at that time called *Comparison of Simulation Software* – primarily aimed for investigation of features of simulation software. Aim was to get benchmark contributions from as many as possible different simulation software systems. And indeed, solutions sent in presented quite different simulation software.

Along with the development of the *Comparison of Simulation Software* towards the *Benchmarks for Modelling Approaches and Simulation Implementations* also the development of simulation software underlined the shift of the emphasis of the benchmarks: more benchmarks contributions using the same usually general simulation environment, but using different approaches; and less benchmark contributions using a very specific simulation environment.

The recent benchmark contributions indicate a preference for general simulation environments and general calculation systems. So, it is not astonishing, that most frequently used software systems for benchmark contributions are MATLAB, Simulink, and AnyLogic. And very recently, contributions using Python – and also not surprisingly – contributions with EXCEL (with extensions) were submitted. Contributions using special simulation software are becoming a minority, and the number of contributions using a specific modelling environment (e.g. Modelica, System Dynamics, ..) or simulating in a general numerical calculation environment is growing.

## 6 Benchmark Contribution - Call

Since 2018, benchmark contributions in SNE may have different content, structure, emphasis, and length – benchmark solutions, benchmark report, or benchmark study; additionally, educational aspects can be emphasis of a contribution. And furthermore, authors are free to add and modify modelling and simulation tasks of a benchmark, or to concentrate only on a part of a benchmark and extend this part. Modellers and simulationists are invited to take the challenge to prepare, realise and submit a benchmark contribution to SNE.

For details, see [www.sne-journal.org/benchmarks/](http://www.sne-journal.org/benchmarks/)

### References

- [1] Breitenecker F, Körner A, Ecker H. Educational Use of the ARGESIM Benchmarks of Modelling Approaches and Simulation Implementations. *Simulation Notes Europe SNE* 28(4), 2018, 215-218. DOI: 10.11128/sne.28.bne.10453)
- [2] Kolozsvari Z, Lienbacher L, et al. Time- and Event-oriented Spreadsheet Modelling of ARGESIM Benchmark C12 'Collision Processes in Rows of Spheres'. *Simulation Notes Europe SNE* 28(4), 2018, 205-214. DOI: 10.11128/sne.28.bne12.10452)
- [3] Breitenecker F. ARGESIM Benchmarks on Modelling and Simulation: Revised Definitions, Extended Solutions, and Supplemental Information. *SNE* 16(3-4), 57-58, 2006.



# SNE Simulation News

## EUROSIM Data and Quick Info



## EUROSIM 2019

10<sup>th</sup> EUROSIM Congress on Modelling and Simulation

La Rioja, Logroño, Spain, July 1 – 5, 2019

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## EUROSIM Federation of European Simulation Societies

**General Information.** EUROSIM, the Federation of European Simulation Societies, was set up in 1989. The purpose of EUROSIM is to provide a European forum for simulation societies and groups to promote advancement of modelling and simulation in industry, research, and development. → [www.eurosim.info](http://www.eurosim.info)

**Member Societies.** EUROSIM members may be national simulation societies and regional or international societies and groups dealing with modelling and simulation. At present EUROSIM has *Full Members* and *Observer Members*, and member candidates.

<b>ASIM</b>	Arbeitsgemeinschaft Simulation <i>Austria, Germany, Switzerland</i>
<b>CEA-SMSG</b>	Spanish Modelling and Simulation Group <i>Spain</i>
<b>CSSS</b>	Czech and Slovak Simulation Society <i>Czech Republic, Slovak Republic</i>
<b>DBSS</b>	Dutch Benelux Simulation Society <i>Belgium, Netherlands</i>
<b>KA-SIM</b>	Kosovo Simulation Society, <i>Kosovo</i>
<b>LIOPHANT</b>	LIOPHANT Simulation Club <i>Italy &amp; International</i>
<b>LSS</b>	Latvian Simulation Society; <i>Latvia</i>
<b>PSCS</b>	Polish Society for Computer Simulation <i>Poland</i>
<b>MIMOS</b>	Italian Modelling and Simulation Association, <i>Italy, Observer Member</i>
<b>NSSM</b>	Russian National Simulation Society <i>Russian Federation</i>
<b>ROMSIM</b>	Romanian Society for Modelling and Simulation, <i>Romania, Observer Member</i>
<b>SIMS</b>	Simulation Society of Scandinavia <i>Denmark, Finland, Norway, Sweden</i>
<b>SLOSIM</b>	Slovenian Simulation Society <i>Slovenia</i>
<b>UKSIM</b>	United Kingdom Simulation Society <i>UK, Ireland</i>
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<b>FRANCO-SIM</b>	<i>Société Francophone de Simulation Belgium, France</i>
<b>HSS</b>	<i>Hungarian Simulation Society; Hungary</i>
<b>ISCS</b>	<i>Italian Society for Computer Simulation Italy</i>

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**EUROSIM Congress.** EUROSIM is running the triennial conference series EUROSIM Congress. The congress is organised by one of the EUROSIM societies.

**EUROSIM 2019, the 10th EUROSIM Congress,** will be organised by CEA-SMSG, the Spanish Simulation Society, in La Rioja, Logroño, Spain, July 1 – 5, 2019.

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**ASIM**  
**German Simulation Society**  
**Arbeitsgemeinschaft Simulation**

ASIM (Arbeitsgemeinschaft Simulation) is the association for simulation in the German speaking area, servicing mainly Germany, Switzerland and Austria. ASIM was founded in 1981 and has now about 400 individual members (including associated), and 90 institutional or industrial members.

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- ASIM Int. Conference 'Simulation in Production and Logistics' – biannual
- ASIM 'Symposium Simulation Technique' – biannual
- MATHMOD Int. Vienna Conference on Mathematical Modelling – triennial

Furthermore, ASIM is co-sponsor of WSC – Winter Simulation Conference, of SCS conferences *SpringSim* and *SummerSim*, and of *I3M* and *Simutech* conference series.

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## CEA-SMSG – Spanish Modelling and Simulation Group

CEA is the Spanish Society on Automation and Control and it is the national member of IFAC (International Federation of Automatic Control) in Spain. Since 1968 CEA-IFAC looks after the development of the Automation in Spain, in its different issues: automatic control, robotics, *SIMULATION*, etc. The association is divided into national thematic groups, one of which is centered on Modeling, Simulation and Optimization, constituting the CEA Spanish Modeling and Simulation Group (CEA-SMSG). It looks after the development of the Modelling and Simulation (M&S) in Spain, working basically on all the issues concerning the use of M&S techniques as essential engineering tools for decision-making and optimization.

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Last data update February 2018



## CSSS – Czech and Slovak Simulation Society

CSSS -The *Czech and Slovak Simulation Society* has about 150 members working in Czech and Slovak national scientific and technical societies (*Czech Society for Applied Cybernetics and Informatics, Slovak Society for Applied Cybernetics and Informatics*). CSSS main objectives are: development of education and training in the field of modelling and simulation, organising professional workshops and conferences, disseminating information about modelling and simulation activities in Europe. Since 1992, CSSS is full member of EUROSIM.

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## DBSS – Dutch Benelux Simulation Society

The *Dutch Benelux Simulation Society* (DBSS) was founded in July 1986 in order to create an organisation of simulation professionals within the Dutch language area. DBSS has actively promoted creation of similar organisations in other language areas. DBSS is a member of EUROSIM and works in close cooperation with its members and with affiliated societies.

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*Last data update June 2016*



## LIOPHANT Simulation

Liophant Simulation is a non-profit association born in order to be a trait-d'union among simulation developers and users; Liophant is devoted to promote and diffuse the simulation techniques and methodologies; the Association promotes exchange of students, sabbatical years, organization of International Conferences, courses and internships focused on M&S applications.

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*Last data update June 2016*

## LSS – Latvian Simulation Society

The Latvian Simulation Society (LSS) has been founded in 1990 as the first professional simulation organisation in the field of Modelling and simulation in the post-Soviet area. Its members represent the main simulation centres in Latvia, including both academic and industrial sectors.

→ [briedis.itl.rtu.lv/imb/](http://briedis.itl.rtu.lv/imb/)

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*Last data update June 2016*



## KA-SIM Kosovo Simulation Society

Kosova Association for Modeling and Simulation (KA-SIM, founded in 2009), is part of Kosova Association of Control, Automation and Systems Engineering (KA-CASE). KA-CASE was registered in 2006 as non Profit Organization and since 2009 is National Member of IFAC – International Federation of Automatic Control. KA-SIM joined EUROSIM as Observer Member in 2011. In 2016, KA-SIM became full member.

KA-SIM has about 50 members, and is organizing the international conference series International Conference in Business, Technology and Innovation, in November, in Durrhës, Albania, and IFAC Simulation Workshops in Pristina.

→ [www.ubt-uni.net/ka-case](http://www.ubt-uni.net/ka-case)

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*Last data update December 2016*

## MIMOS – Italian Modelling and Simulation Association

MIMOS (Movimento Italiano Modellazione e Simulazione – Italian Modelling and Simulation Association) is the Italian association grouping companies, professionals, universities, and research institutions working in the field of modelling, simulation, virtual reality and 3D, with the aim of enhancing the culture of ‘virtuality’ in Italy, in every application area.

MIMOS became EUROSIM Observer Member in 2016 and EUROSIM Full Member in September 2018.

→ [www.mimos.it](http://www.mimos.it)

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*Last data update December 2016*

## NSSM – National Society for Simulation Modelling (Russia)

NSSM - The Russian National Simulation Society (Национальное Общество Имитационного Моделирования – НОИМ) was officially registered in Russian Federation on February 11, 2011. In February 2012 NSS has been accepted as an observer member of EUROSIM, and in 2015 NSSM has become full member.

→ [www.simulation.su](http://www.simulation.su)

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*Last data update February 2018*

## PSCS – Polish Society for Computer Simulation

PSCS was founded in 1993 in Warsaw. PSCS is a scientific, non-profit association of members from universities, research institutes and industry in Poland with common interests in variety of methods of computer simulations and its applications. At present PSCS counts 257 members.



→ [www.eurosim.info](http://www.eurosim.info), [www.ptsk.pl/](http://www.ptsk.pl/)

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*Last data update December 2013*

## SIMS – Scandinavian Simulation Society

SIMS is the *Scandinavian Simulation Society* with members from the five Nordic countries Denmark, Finland, Iceland, Norway and Sweden. The SIMS history goes back to 1959. SIMS practical matters are taken care of by the SIMS board consisting of two representatives from each Nordic country (Iceland one board member).

**SIMS Structure.** SIMS is organised as federation of regional societies. There are **FinSim** (Finnish Simulation Forum), **MoSis** (Society for Modelling and Simulation in Sweden), **DKSIM** (Dansk Simuleringsforening) and **NFA** (Norsk Forening for Automatisering).

→ [www.scansims.org](http://www.scansims.org)

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*Last data update February 2018*



## SLOSIM – Slovenian Society for Simulation and Modelling

SLOSIM - Slovenian Society for Simulation and Modelling was established in 1994 and became the full member of EUROSIM in 1996. Currently it has 90 members from both Slovenian universities, institutes, and industry. It promotes modelling and simulation approaches to problem solving in industrial as well as in academic environments by establishing communication and cooperation among corresponding teams.

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*Last data update December 2018*

## UKSIM - United Kingdom Simulation Society

The UK Simulation Society is very active in organizing conferences, meetings and workshops. UKSim holds its annual conference in the March-April period. In recent years the conference has always been held at Emmanuel College, Cambridge. The Asia Modelling and Simulation Section (AMSS) of UKSim holds 4-5 conferences per year including the EMS (European Modelling Symposium), an event mainly aimed at young researchers, organized each year by UKSim in different European cities. Membership of the UK Simulation Society is free to participants of any of our conferences and their co-authors.

→ [uksim.info](http://uksim.info)

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*Last data update March 2016*

## EUROSIM Observer Members

### ROMSIM – Romanian Modelling and Simulation Society

ROMSIM has been founded in 1990 as a non-profit society, devoted to theoretical and applied aspects of modelling and simulation of systems. ROMSIM currently has about 100 members from Romania and Moldavia.

→ [www.eurosim.info](http://www.eurosim.info) ([www.ici.ro/romsim](http://www.ici.ro/romsim))

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*Last data update June 2017*

## MEMBER CANDIDATES

### Albanian SIMULATION Society

At the Department of Statistics and Applied Informatics, Faculty of Economy, University of Tirana, Prof. Dr. Kozeta Sevrani at present is setting up an Albanian Simulation Society. Kozeta Sevrani, professor of Computer Science and Management Information Systems, and head of the Department of Mathematics, Statistics and Applied Informatic, has attended the a EUROSIM board meeting in Vienna Feb. 2016.

There she has presented simulation activities in Albania and the new simulation society.

The society – constitution and bylaws are being worked out – will be involved in different international and local simulation projects, and will be engaged in the organisation of the conference series ISTI – Information Systems and Technology. The society intends to become a EUROSIM Observer Member.

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*Last data update December 2016*

## Societies in Re-Organisation

The following societies are at present inactive or under re-organisation:

- CROSSIM  
*Croatian Society for Simulation Modelling*
- FRANCO-SIM – Société Francophone de Simulation
- HSS – Hungarian Simulation Society
- ISCS – Italian Society for Computer Simulation



## Association Simulation News



ARGESIM is a non-profit association generally aiming for dissemination of information on system simulation – from research via development to applications of system simulation. ARGESIM is closely co-operating with EUROSIM, the Federation of European Simulation Societies, and with ASIM, the German Simulation Society. ARGESIM is an 'outsourced' activity from the *Mathematical Modelling and Simulation Group* of TU Wien, there is also close co-operation with TU Wien (organisationally and personally).

→ [www.argesim.org](http://www.argesim.org)

✉ → [office@argesim.org](mailto:office@argesim.org)

✉ → ARGESIM/Math. Modelling & Simulation Group,  
Inst. of Analysis and Scientific Computing, TU Wien  
Wiedner Hauptstrasse 8-10, 1040 Vienna, Austria  
Attn. Prof. Dr. Felix Breitenecker

ARGESIM is following its aims and scope by the following activities and projects:

- Publication of the scientific journal *SNE – Simulation Notes Europe* (membership journal of EUROSIM, the *Federation of European Simulation Societies*) – [www.sne-journal.org](http://www.sne-journal.org)
- Organisation and Publication of the ARGESIM Benchmarks for *Modelling Approaches and Simulation Implementations*
- Publication of the series ARGESIM Reports for monographs in system simulation, and proceedings of simulation conferences and workshops
- Publication of the special series *FBS Simulation – Advances in Simulation / Fortschrittsberichte Simulation* - monographs in co-operation with ASIM, the German Simulation Society
- Organisation of the Conference Series MATHMOD Vienna (triennial, in co-operation with EUROSIM, ASIM, and TU Wien) – [www.mathmod.at](http://www.mathmod.at)
- Organisation of Seminars and Summerschools on Simulation
- Administration of ASIM (German Simulation Society) and administrative support for EUROSIM [www.eurosim.info](http://www.eurosim.info)
- Support of ERASMUS and CEEPUS activities in system simulation for TU Wien

ARGESIM is a registered non-profit association and a registered publisher: ARGESIM Publisher Vienna, root ISBN 978-3-901608-xx-y, root DOI 10.11128/z...zz.zz. Publication is open for ASIM and for EUROSIM Member Societies.

## SNE – Simulation Notes Europe

# SNE

The scientific journal *SNE – Simulation Notes Europe* provides an international, high-quality forum for presentation of new ideas and approaches in simulation – from modelling to experiment analysis, from implementation to verification, from validation to identification, from numerics to visualisation – in context of the simulation process. SNE puts special emphasis on the overall view in simulation, and on comparative investigations. Furthermore, SNE welcomes contributions on education in/for/with simulation.

SNE is also the forum for the ARGESIM Benchmarks on *Modelling Approaches and Simulation Implementations* publishing benchmarks definitions, solutions, reports and studies – including model sources via web.

→ [www.sne-journal.org](http://www.sne-journal.org),

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EiC Prof. Dr. Felix Breitenecker

SNE, primarily an electronic journal, follows an open access strategy, with free download in basic layout. SNE is the official membership journal of EUROSIM, the *Federation of European Simulation Societies*. Members of EUROSIM Societies are entitled to download SNE in high-quality, and to access additional sources of benchmark publications, model sources, etc. On the other hand, SNE offers EUROSIM Societies a publication forum for post-conference publication of the society's international conferences, and the possibility to compile thematic or event-based SNE Special Issues.

Simulationists are invited to submit contributions of any type – *Technical Note*, *Short Note*, *Project Note*, *Educational Note*, *Benchmark Note*, etc. via SNE's website:

# SNE SIMULATION NOTES EUROPE

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[www.eurosim2019.com](http://www.eurosim2019.com)



Presentation and Cfp. EUROSIM Congresses are the most important modelling and simulation events in Europe. For EUROSIM 2019, we are soliciting original submissions describing novel research and developments in the following (and related) areas of interest: Continuous, discrete (event) and hybrid modelling, simulation, identification and optimization approaches.

Two basic contribution motivations are expected: M&S Methods and Technologies and M&S Applications. Contributions from both technical and non-technical areas are welcome.

Congress Topics. The EUROSIM 2019 Congress will include invited talks, parallel, special and poster sessions, exhibition and versatile technical and social tours. The Congress topics of interest include, but are not limited to:

Intelligent Systems and Applications  
Hybrid and Soft Computing, Data & Semantic Mining  
Neural Networks, Fuzzy Systems & Evolutionary Computation  
Image, Speech & Signal Processing  
Systems Intelligence and Intelligence Systems  
Autonomous Systems  
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Manufacturing and Workflows  
Adaptive Dynamic Programming and Reinforcement Learning  
Mobile/Ad hoc Wireless networks, mobicast, sensor placement, target tracking  
Control of Intelligent Systems. Robotics, Cybernetics, Control Engineering, & Manufacturing  
Transport, Logistics, Harbour, Shipping and Marine Simulation

Registration	Early	Late (after June 10)
Regular Fee	445 €	495 €
Student Fee	200 €	250 €
Accompanying Persons	145 €	195 €

Important Dates

Submission Deadline	April 30, 2019
Acceptance Deadline	May 10, 2019
Final Submission Deadline	May 25, 2019

Congress Venue & Social Events. The Congress will be held in the City of Logroño, Capital of La Rioja (Spain) very well-known by the Rioja red wines. The main venue and the exhibition site is the University of La Rioja (UR), located on a modern campus in Logroño, capital of La Rioja, where 7500 students are registered. The UR is the only public university in this small, quiet region in Northern Spain.

La Rioja offers three main points of interest to its visitors:

- The wine and the cellars. La Rioja was the first region with qualified designation of origin and is a World reference for the red wines quality. Its wineries combine modernity with history and tradition, and the wine museum is the world's largest dedicated to this food. Wine is the centre of La Rioja's culture, economy and society.
- The monasteries, among which are Cañas, Valvanera, Santa Maria La Real, and of course the San Millán de la Cogolla monasteries (Suso and Yuso), cradle of the first words written in the Spanish language, included in UNESCO's World Heritage List in 1996 .
- The Santiago's Road, which for centuries has made constant and continuous the visit of pilgrims to the city, where they are always welcome. Logroño is one of the main cities of the main Santiago's road in Spain, known as the French route (Jaca, Pamplona, Logroño, Burgos, León, Astorga, Santiago).

In addition to these attractions of La Rioja, Logroño, its capital, with a historical helmet with four remarkable religious monuments (Santa María La Redonda, Santiago, San Bartolomé and Santa María de Palacio), is well known for Laurel Street, the most famous Street of *Tapas* in Spain.

Of course, social events will reflect these interest points, as can be verified in the Program.

Additionally, the situation in Logroño allows visits to wonderful environments less than 2 hours away (San Sebastian, Burgos, Bilbao, Zaragoza, Pamplona, etc.).





### Program & Scheduling

The Congress includes three days of work (Tuesday to Thursday) combined with cultural and social activities, a previous day of simulation courses and pre-reception (Monday), a day devoted to cultural and technical activities (Friday), and finally, as an extension, the possibility of a trip (Saturday) to the festivities of San Fermín in Pamplona. All this is detailed in the Programme:

#### Monday 1<sup>st</sup> July

Morning: Free courses on continuous and discrete events simulation.

Lunch and coffee breaks

Evening: Dinner and Rioja Wine Tasting Course



#### Tuesday 2<sup>nd</sup> July

Morning: Plenary sessions. Reception at the city hall.

Lunch and coffee breaks

Afternoon: Parallel sessions (optional visit to the Wine Museum for those who cannot visit it on Saturday)

Evening: Dinner in the old town



#### Wednesday 3<sup>rd</sup> July

Morning: Parallel sessions

Lunch and coffee breaks

Afternoon: Parallel sessions

Evening: Walk for the Santiago's road in the city to the Gala Dinner in a Winery (and visit to the winery)

#### Thursday 4<sup>th</sup> July

Morning: Parallel sessions

Lunch and coffee breaks

Afternoon: Parallel sessions

Evening: Guided visit to the old town and Dinner of typical tapas at bars of Laurel Street



#### Friday 5<sup>th</sup> July

Technical and Cultural visits, including the Wine Museum, Wineries (such as the famous Marques de Riscal, of architect Frank Gehry), and the well-known monasteries (Suso, Yuso, Cañas, Santa María La Real, San Millán, and Valvanera)



#### Saturday 6<sup>th</sup> July

As an extension of the activities, and taking advantage from the vicinity of Pamplona, the well-known city for the festivities of *San Fermín* and the bullfights for its streets during the festivities, immortalized by Hemingway, there will be an excursion to the event of the official beginning of the festivity, with "*el chupinazo*" (rocket announcer).

### EUROSIM 2019 LA RIOJA

10<sup>th</sup> Congress of the Federation of European Simulation Societies (Eurosím [www.eurosím.info](http://www.eurosím.info))

July 1 - 5, 2019, Logroño (La Rioja), Spain

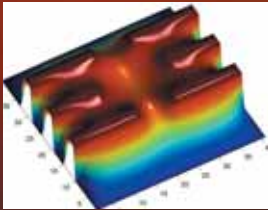
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# EUROSIM 2019

10<sup>th</sup> EUROSIM Congress on Modelling and Simulation

La Rioja, Logroño, Spain, July 1 – 5, 2019



EUROSIM Congresses are the most important modelling and simulation events in Europe. For EUROSIM 2019, we are soliciting original submissions describing novel research and developments in the following (and related) areas of interest: Continuous, discrete (event) and hybrid modelling, simulation, identification and optimization approaches. Two basic contribution motivations are expected: M&S Methods and Technologies and M&S Applications. Contributions from both technical and non-technical areas are welcome.

**Congress Topics** The EUROSIM 2019 Congress will include invited talks, parallel, special and poster sessions, exhibition and versatile technical and social tours. The Congress topics of interest include, but are not limited to:

Intelligent Systems and Applications	Bioinformatics, Medicine, Pharmacy and Bioengineering	Simulation Methodologies and Tools
Hybrid and Soft Computing	Water and Wastewater Treatment,	Parallel and Distributed
Data & Semantic Mining	Sludge Management and Biogas	Architectures and Systems
Neural Networks, Fuzzy Systems & Evolutionary Computation	Production	Operations Research
Image, Speech & Signal Processing	Condition monitoring, Mechatronics and maintenance	Discrete Event Systems
Systems Intelligence and Intelligence Systems	Automotive applications	Manufacturing and Workflows
Autonomous Systems	e-Science and e-Systems	Adaptive Dynamic Programming and Reinforcement Learning
Energy and Power Systems	Industry, Business, Management, Human Factors and Social Issues	Mobile/Ad hoc wireless networks, mobicast, sensor placement, target tracking
Mining and Metal Industry	Virtual Reality, Visualization, Computer Art and Games	Control of Intelligent Systems
Forest Industry	Internet Modelling, Semantic Web and Ontologies	Robotics, Cybernetics, Control Engineering, & Manufacturing
Buildings and Construction	Computational Finance & Economics	Transport, Logistics, Harbour, Shipping and Marine Simulation
Communication Systems		
Circuits, Sensors and Devices		
Security Modelling and Simulation		

**Congress Venue / Social Events** The Congress will be held in the City of Logroño, Capital of La Rioja, Northern Spain. The main venue and the exhibition site is the University of La Rioja (UR), located on a modern campus in Logroño, capital of La Rioja, where 7500 students are registered. The UR is the only University in this small, quiet region in Northern Spain. La Rioja is where the Monasteries of San Millán de la Cogolla, cradle of the first words written in the Spanish language, are situated, sites included in UNESCO's World Heritage List in 1996. Of course, social events will reflect this heritage – and the famous wines in la Rioja.

**Congress Team:** The Congress is organised by CAE CAE-SMSG, the Spanish simulation society, and Universidad de la Rioja.

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