Simulation-Based Decision Support for the Logistic System of the German Armed Forces

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ABSTRACT

Modeling and simulation contribute to the digitalization of logistics of German Armed Forces logistics and must present factors such as flexibility and robustness to identify risks and weaknesses in the logistics chain. ESG, as a military technology company in Germany with many years of military experience, we are presenting successful simulation and analysis projects (e.g., "Forecasting the operational capability of the German air force using the example of the Eurofighter" or "Simulation-based analysis of the medical rescue chain") and suggests further directions for action, such as simulation-based analysis for optimal concepts for additive production or autonomous systems in military supply chains. It can be checked and optimized for robustness and sustainability by using logistic simulation for the military supply chain. This method of data-based decision support (tool AnyLogic, guideline for simulation-based analysis in the Bundeswehr and model documentation). It focuses on a critical question such as "How is it highly probable that the material operational readiness of the system developed for the future under certain parameters/factors/ influences and what improves the performance of the system?" offers various advantages, as presented in this lecture.

1.0 INTRODUCTION

Foreseeing consequences, weighing options, and finally deciding is the challenge that decision-makers in companies, politics, and administrators face every day. Complex procedures, highly networked processes, and opaque framework conditions make it increasingly difficult to maintain an overview. A simulation, in general, is the virtual reproduction of an entire system (or part of it) to experiment and finally analyze it. It enables the analysis of a system by experimenting with a virtual replication of the system. The data and results obtained from the model calculations allow conclusions to apply to the existing system. Experiments offer the possibility of observing the model in different and artificially created scenarios and investigating its behaviors. The resulting findings can finally be evaluated, analyzed, and transferred to reality. In this paper, we present different studies of the German armed forces' military rescue and supply chain as an example of a simulation to aid decision-making. After presenting some theoretical background and our process for model development, we detail our projects and the generated results. Finally, we discuss the implications for the results and provide an outlook for future work.

Simulations are successfully applied in numerous industries. Well-known examples are weather and climate calculations, flight simulators, or medical simulations, such as the current forecast models for the spread of COVID-19 (Banks, 1998). Simulations are also prominently used in logistics, for example, in the planning of production facilities and production lines, in operation and use of fleet systems or storage facilities, and transport and capacity planning (Lars Mönch, 2011). There are hardly any limits to the use of simulations. Almost every procedure, every process can be modeled and reproduced with the help of the appropriate method.

Nevertheless, simulations should only ever be developed for meaningful questions, such as, "How is a system likely to behave with certain parameters, factors, and influences," and should not be regarded as the solution to all problems. The use of simulation has been established for several decades in production and logistics processes. The same approaches can be used as a problem-solving method for armed forces as well.

2.0 DEVELOPMENT AND USAGE

Various characteristics of the underlying system can classify simulations. Our projects considered systems evolving through time and change by events (discrete event or process-based simulation) combined with entities in a system that act autonomously but interacted with each other (Agent-Based Simulation). Depending on time and events, these entities adopt different states that can be tracked throughout the simulation run but never change continuously. The agents' behavior could be deterministic or incidental, which can be modeled via stochastic distributions (AnyLogic, 2018).

2.1 Process for Development of Simulation Models

For our simulation studies, approaches derive from the "Arbeitsgemeinschaft Simulation working group" (ASIM) process model (Rabe, S.Spiekermann, and Wenzel, 2007). With the help of the extended process model, our studies are structured into various phases (compare Figure 2-1). We eventually could answer the given project questions in an iterative process in conjunction with the model owner. All project validation was through an Independent Verification & Validation agent. (SAAD et al., 2015).

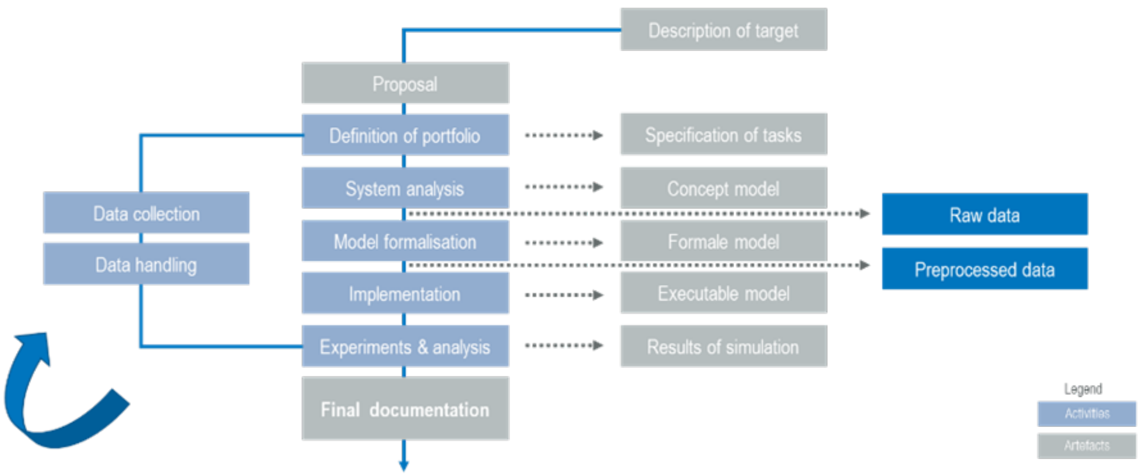

Figure 2-1: Process for model development.

All models developed for the simulation implementation were documented according to the "Guideline of Model Documentation" of ITIS GmbH as required from the model owner for all developed simulations. The process starts with the description of the target for the future simulation models and the associated analyses. Therefore, the document **Sponsor Needs (SN)** is created. It contains the user requirements and acceptance criteria, which are often formulated by concrete questions for the system to be modeled. The document is part of the preliminary project phase and is often prepared before the award procedure if the simulation development happens externally and is part of the proposal documents. With the project start, the phase of **Structured Problem Description (SPD)** starts. Here, the model owner and developer jointly agree on the concrete objective, the questions to be answered, the actual system section to be modeled, further model requirements such as I/O- structure and model behavior. In addition, assumptions and model limits are already formulated, and the experimental framework is also defined. Once all project participants are clear about the objectives, an intensive phase of system analysis follows. System documentation and historical data are analyzed, which later also serves as input for the future model. In addition, workshops are held with the Subject Matter Experts of the existing system, which help to record the actual processes. The result of this phase is the **Conceptual Model (CM)**. It describes the abstract behavior of the actual system and serves as the basis for the model implementation. It contains at least a description of the general model, the breakdown in sub-models, and the identification of reusable components. The following steps in the modeling and simulation process are model implementation. The **Formal Model (FM)** translates the CM. The object structures and interconnections are formally documented with the help of class diagrams. Within a tailoring process, the CM and FM can be combined into one document. The actual implementation results in the **executable model (EM)**. It consists of one or more executable simulations which run on suitable servers and are programmed in the specified language and simulation frameworks. The related document describes the simulation environment, the software description, documentation of the developed model, and the simulation infrastructure. The implemented simulation model needs to be validated. For this purpose, experiments can be computed, and the results can be compared to actual data. All executed experiments are based on a scenario defined by the model owner and communicated via a formal scenario description.

After the completed validation process, the experimental simulation framework can answer the questions and issues the model owner already asked at the start of model development. It is essential to understand that the entire process is iterative. If further questions arise during the use of the model, the model must be designed to be expandable and changeable.

2.2 Architecture of Simulation Systems

In order to be able to work with a simulation, additional system components are required in addition to the actual model. These are shown in Figure 2-2.

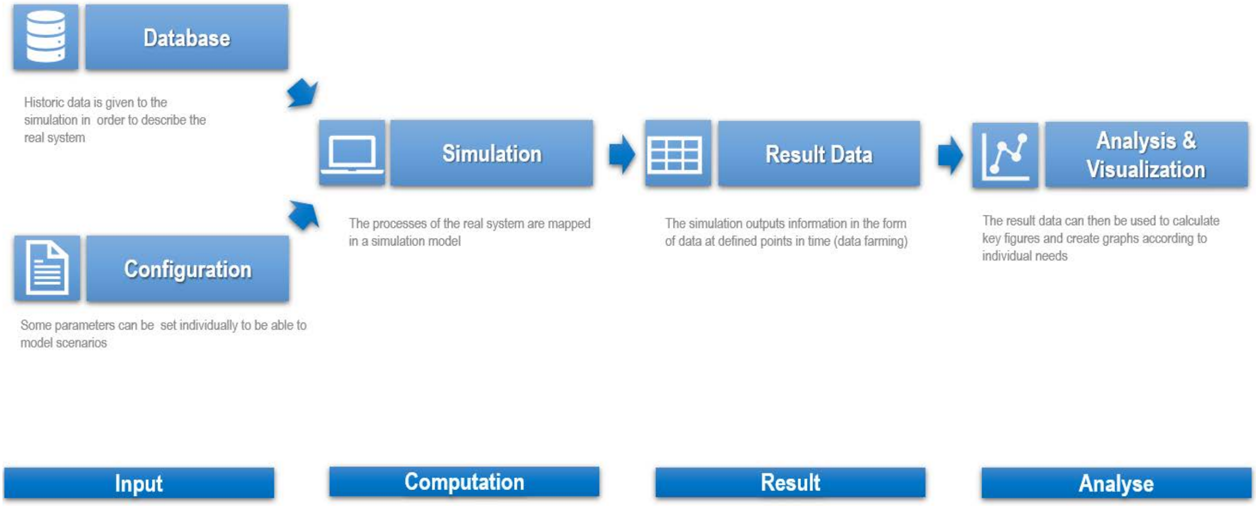

Figure 2-2: System architecture

In many simulation projects, model users and developers are not the same people. Because of that, it is helpful to separate the executable model from the input model. At first, the input is based on historical and actual data usually stored in a database (file-based storage is also possible but not recommended). These data are necessary to fit the generic simulation model to the existing system. The second input is manually configurable parameters. They allow the configuration of the whole simulation independently from the developer of the executable model. Via those parameters, different scenarios can be simulated, always starting at the same historic point defined in the database. But there is a second advantage of the separation of input and executable model, which is especially useful in the Armed Forces. The model implementation can take place independent from the access to classified data as fake data with the same structure that can be used for implementation.

While computation, the simulation generates output data depending on the specified output parameters. This concept is called data farming. Here, the previously validated simulation model is used as a data generator. The data covers a large or even complete spectrum of the model or system behavior (Feldkamp et al., 2017). The simulation output can be stored in different user-specific formats. Usually, this includes MS EXCEL or CSV files, but the data can also be written directly to a database. The generation of added value from the simulation data must be analyzed and visualized using suitable analysis tools.

2.3 Decision making with Simulations

First, it is essential to recognize that simulation itself can and should make decisions. Simulations are intended solely as a support tool for making information-based and predictive decisions. With their help, statements are compiled about the behavior of a natural system. For example, developing a critical figure over time is helpful to data generated by the simulation. The decision-maker must constantly make a qualitative evaluation of the simulation result. The decision-maker is also responsible for interpreting the results of the simulation and using the knowledge gained to prioritize the alternative actions or decision options and make the final decision. Simulations can support the decision-maker precisely at the points where he reaches his limits: Namely, based on historical data, taking into account the actual processes taking place and considering randomly occurring events, trends can be depicted, and future developments can be predicted. Simulations, therefore, enable the decision-maker to gain insight into interrelationships, trends, and interactions that he would not be able to recognize without technical support. However, the final decision is always made by the human being.

3.0 MILITARY RESCUE & SUPPLY CHAINS – CASE STUDIES FOR THE BUNDESWEHR

In our studies and research projects for the Bundeswehr together with the University of the Armed Forces Munich, we evaluated different concepts, e.g., resource planning for the medical service to provide an orientation and collection point for researches of the estimation of required qualitative and quantitative capabilities or the prognosis for a flying weapon system the EUROFIGHTER.

A closer look at those projects is examined based on the theoretical introduction about simulation development and architecture.

3.1 Logistic Simulation to Support Military Rescue Chains

The objective of the study was to find possible solutions for national and multinational planning of sustainable medical service capabilities and procedures from a national point of view, based on the framework conditions and associated challenges, both in operations as sole capability guarantor and in cooperation with allied (or friendly) nations based on the national medical service capability elements. For this purpose, the capabilities of the medical service elements of the rescue chain currently planned for an operation are analyzed with the help of a parameterizable, valid simulation model, considering their essential performance characteristics, the current operational principles, and procedures of the German medical service. The Bundeswehr, ESG, and partners have developed a holistic approach to test the medical military rescue chain (process focus) for robustness and sustainability.

Within an Operational Scenario Description (OSD), the Bundeswehr specified the structures and sequences of a scenario to be considered, which served as the basis for the modeling. The required simulation model was parameterizable and was operated by trained personnel of the Bundeswehr. This approach enabled the investigation of current and future operational concepts and made the model development independent from restricted data which had to be used as input.

For the simulation study, we employ an approach derived from the ASIM process model (Rabe, S.Spiekermann und Wenzel 2007). With the help of the extended process model, the study is structured into various phases (compare Figure 2-1). In an iterative process in conjunction with the customer, we can eventually answer the given project questions. The Military Rescue Chain is designed with the help of three sub-models: "Patient Arrival," "Transport," and "Treatment" (Figure 3-1). The underlying part of the existing system is identified for each sub-model, and all in- and output parameters are linked. Each sub-model is defined with an independent structure and behavior model. Additionally, all connections to the other sub-models are identified.

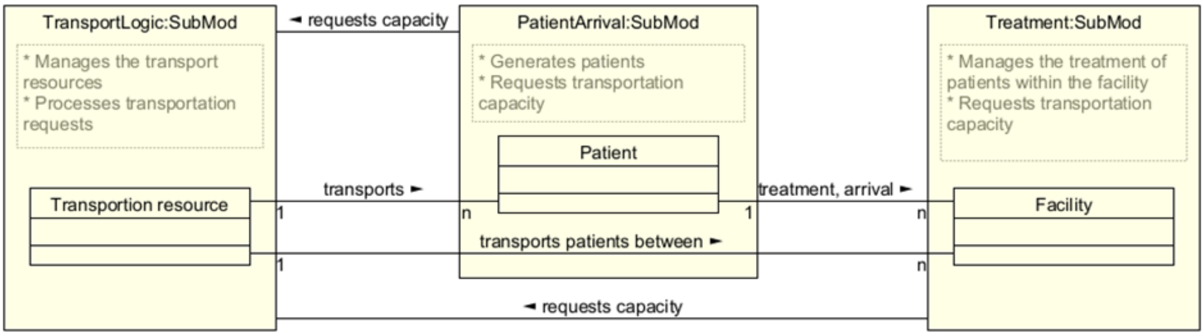

Figure 3-1: Developed sub-models designed with UML class diagrams

The executable model is implemented with the help of AnyLogic and Java. The model developed represents the rescue chain in a simplified, conservatively estimated form to obtain strong statements on the one hand and at the same time reduce the model's susceptibility to error. In principle, the model is designed to represent the capabilities of the treatment facilities in an ideal-typical and optimistic way. Accordingly, breakdowns of the rescue chain and identified bottlenecks are expected to be even more significant.

A separate visualization as part of the AnyLogic model was developed for validation purposes. The visualization realized with AnyLogic is shown in Figure 3-2.

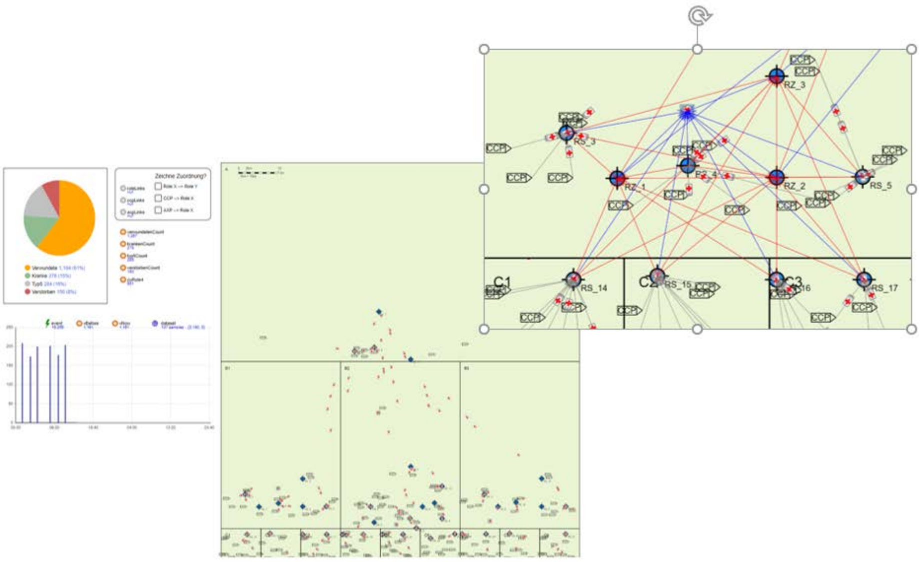

Figure 3-2: Developed sub-models designed with UML class diagrams

The simulation output was processed into a Java output model that streamed results into MS EXCEL files. The designed output model captured every state change from all simulated entities. A developed post-processing algorithm analyzed the resulting simulation data and calculated, e.g., the number of considered entities, which share the same state at the same simulation time. Additionally, the algorithm was able to combine the output of any number of simulation runs. A dashboard for visualization was developed with the help of Python. The visualizations were based on the summarized data generated from the post-processing algorithm. The visualization can answer general questions about the allocation of the treatment and transportation resources. Additionally, the arrival can be analyzed. 3-3 shows a screenshot of the developed dashboard.

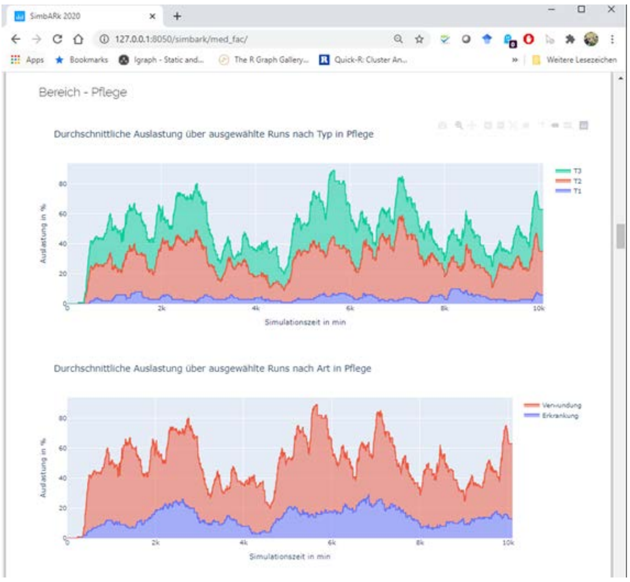

Figure 3-3: Screenshot of AnyLogic visualization

The developed simulation model allowed a detailed investigation of the medical rescue and supply chains. Additionally, the accomplished study shows a variety of questions regarding the security of supply and the sustainability of military logistic chains that can be addressed with the help of simulation. The following list summarizes a few examples of questions that can be addressed with the help of the simulation:

- Can I provide the required capabilities with the upper limit of troops robustly and sustainably?
- Which logistical services are required, and what is their scope?
- Are the resources (material and personnel) enough for the operation, and what do I need (e.g., means of transport, storage space, spare parts, consumable goods, medical equipment, maintenance resources, parking areas, energy, and media requirements their dependencies)?
- Which means of transport, resources, drivers are available and ready for deployment at a given time and location?
- Which services/capabilities must be externally procured or establish a reserve to fulfill the mission (e.g., from other nations / armed forces or industry)?

3.2 Prognose for a Flying Weapon System

The study's objectives were to evaluate the effects of different measures on the material operational capability of a flying weapon system (here on the example of the EUROFIGHTER) via a simulation-based approach. Two main goals were defined:

1. Development of a blueprint for the predictive capability to control a weapon system utilization process (flight and maintenance) in the air dimension

2. Development of initial action items to improve the material operational capability of the EUROFIGHTER.

For this purpose, the flight and maintenance processes of the German EUROFIGHTER fleet were modeled and analyzed with the help of a parameterizable, valid simulation model. The ASIM process model (Figure 1-1) was also used here as in the other study. Before the project started, the future model owner designed a detailed OSD and statement of work describing the questions the simulation model should answer. During several workshops with the SMEs (Subject Matter Experts) of the weapon system, the processes of the flight operation and the maintenance were recorded, and different KPIs and parameter values (for example, the duration of one flight or inspection) that could not be computed from historical data, but were needed for the simulation model were elaborated. All requirements and questions that should be answered via data analytics and simulation methods were defined by the model owner in the Sponsor Needs and provided a list of acceptance criteria. On that basis, the conceptual, formal, and finally, executable model could be developed within half a year. Similar to the simulation of the rescue chain, the EUROFIGHTER model is divided into several sub-models (Figure 3-4). In this case, these sub-models were called levels. On the highest level, the simulation splits into two process lines: operation and maintenance. The degree of detail grows across the levels (maximum level is 5) until the whole process lines are illustrated.

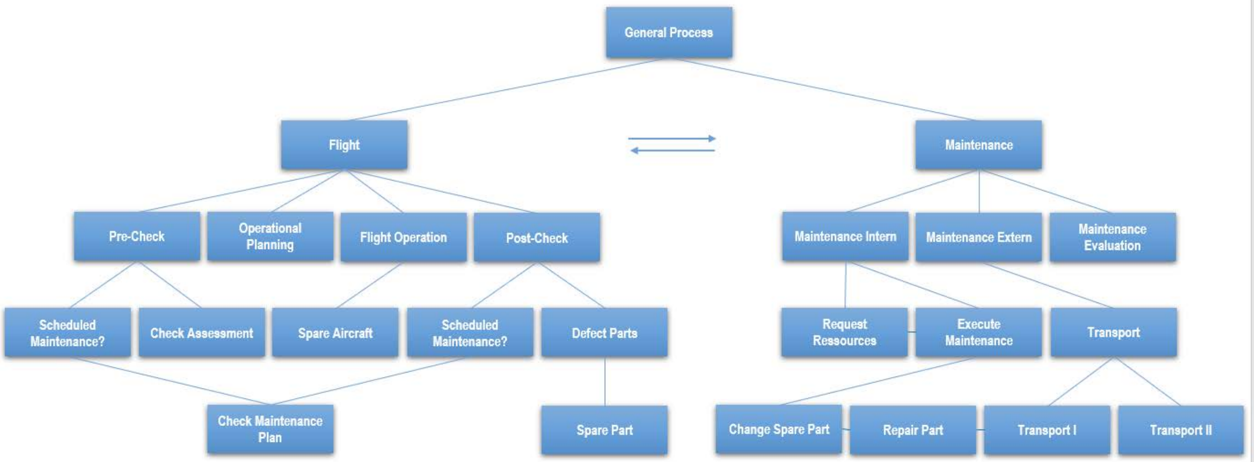

Figure 3-4: Levels (Sub-Models) of the modeled processes

Analog to the conceptual models, these levels are implemented in the executable model in a process-based way. The model is implemented with the help of AnyLogic and Java as well (Figure 3-5).

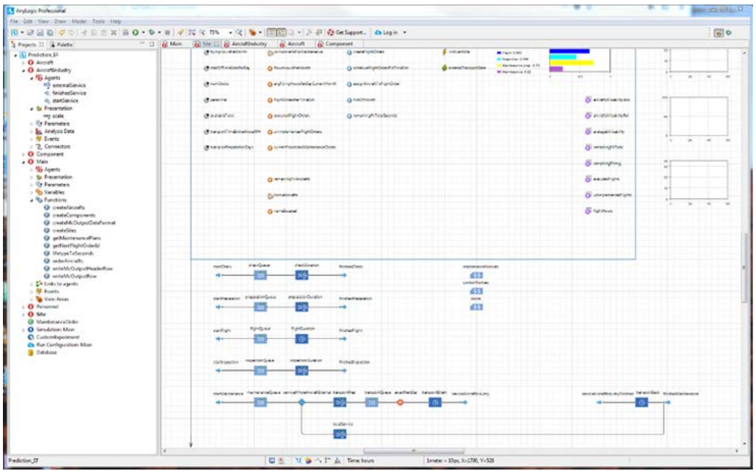

Figure 3-5: AnyLogic Implementation

The simulation is manually parameterizable by the model user and based on historical fleet data. Unlike the simulation rescue chain model, there is a third input file, the Monte-Carlo input. The simulation is designed as a Monte Carlo experiment. This means that certain variables within the simulation are modeled as (pseudo-) random. The simulation must run multiple iterations per experiment to adequately account for the variability (which comes from the random modeling) to obtain meaningful results.

As running complex simulation experiments in parallel require lots of computing capacity, a computer cluster in the data centre of the German air force was established to which we could connect via GenuScreen to ensure safe data handling for classified data. The job scheduler Slurm was used to control the experiments on the cluster. It organizes the distribution of the computations on the available hardware resources. The software R was used for the analysis and visualization of the output data. The whole software architecture of the simulation model is shown in Figures 3-6.

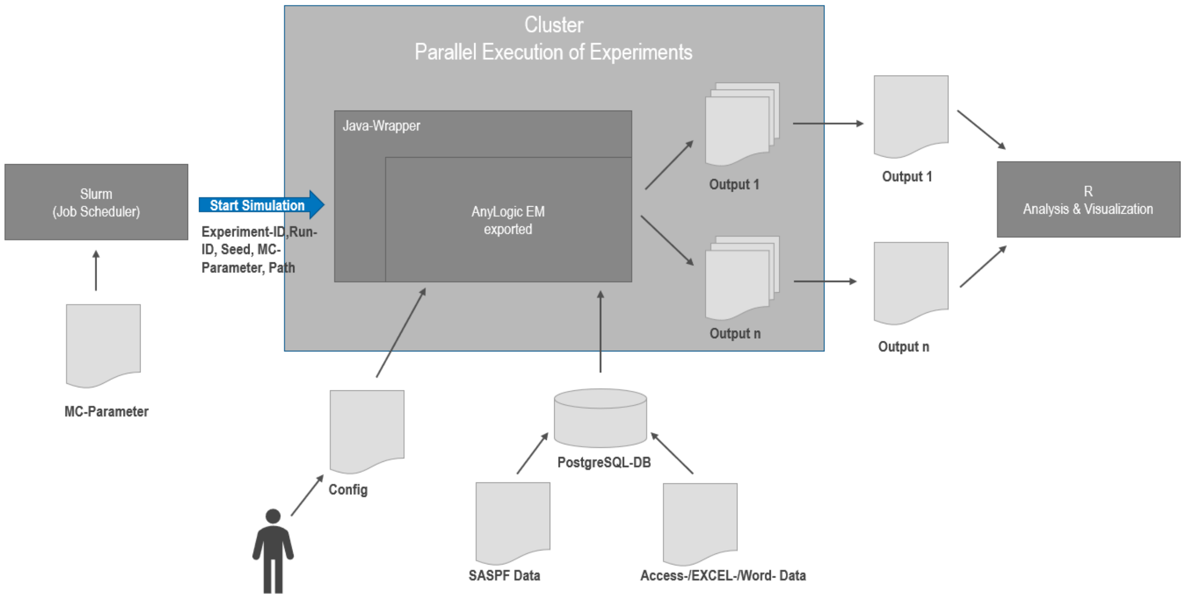

Figure 3-6: Software architecture for the Monte-Carlo experiments on the cluster

Together with the model owner, the output figures which should be evaluated were defined. They include the number of available aircraft per day, the number of produced flight hours per day, the number of aircraft in maintenance, and the utilized resources like docks or staff per hour. Furthermore, the states (e.g., flight, maintenance, check) per aircraft were tracked. With this artificially generated data (data farming approach), analysis and visualization were computed with automated scripts in the software R. The generated graphics were used to validate the model and discuss and interpret them with the SMEs to define measures and action items to improve the operational capability of the fleet.

The results and reports were presented in the German Ministry of Defence, and the study was given a positive result. It showed that it is possible to create a digital twin of a weapon system fleet via a simulation-based approach and that the implemented logic can also be used for other systems. Furthermore, six action items could be derived from the simulation experiments. They were transferred to the responsible units for review.

The developed simulation models allowed a detailed investigation of the fleet's operational, maintenance, and supply chain. Additionally, the accomplished study shows a variety of questions regarding the security of supply and the sustainability of military logistic chains that can be addressed with the help of simulation. The following list summarizes a few examples of questions that can be addressed with the help of simulation:

- How does the number of operational or ready weapon systems develop over time?
- What is the impact of changing repair capacity in personnel, spare parts supplies, tools, and dock space?
- How many and which spare parts/ large equipment reserve should be planned for a specific mission?
- Can parts be used longer?

4.0 CONCLUSION: MODELLING IN THE MILITARY SECTOR

These and many other questions can be answered with modeling and simulation concerning the security of supply and sustainability of armed forces. Other approaches are conceivable for:

- Availability management of resources for exercises and operations: Which logistical services are required for this purpose, and to what extent, and where might there be bottlenecks?
- Capacity management for weapon systems: Are my weapon systems and capabilities sufficient to fulfill the core mission in all scheduled and unscheduled events - e.g., in the area of maintenance, and if not, what are the alternative options and what is the impact on my supply chain?
- Structure and procurement management: What are the consequences of potential structural decisions on military equipment and requirements, and how is the optimal procurement necessary to achieve this?
- Digital Military Supply Chain - Deployment of Autonomous Systems: What is the impact of autonomous and networked systems on the military supply chain?
- Impact of additive manufacturing in the military supply chain: What impact does 3D printing have on material readiness, and how must the military position itself optimally in the future (locally, in terms of content) to use this efficiently?

In general, the analyses of real-world systems with simulation help are very promising, especially in logistics. For example, complex, dynamic processes and dependencies can be tested against each other, and a valid and cost-efficient verification of concepts and processes can be easily achieved. Additionally, consequences and bottlenecks are known before. A realistic derivation of resource availability can be forecasted with the advances in digitalization and the corresponding collection of significant amounts of data, the generation of simulation models that can process these collected data. However, there are also weaknesses and threats that must be addressed. Figure 4-1 summarizes strengths, opportunities but also outlines weaknesses and threats in a SWOT-Analysis.

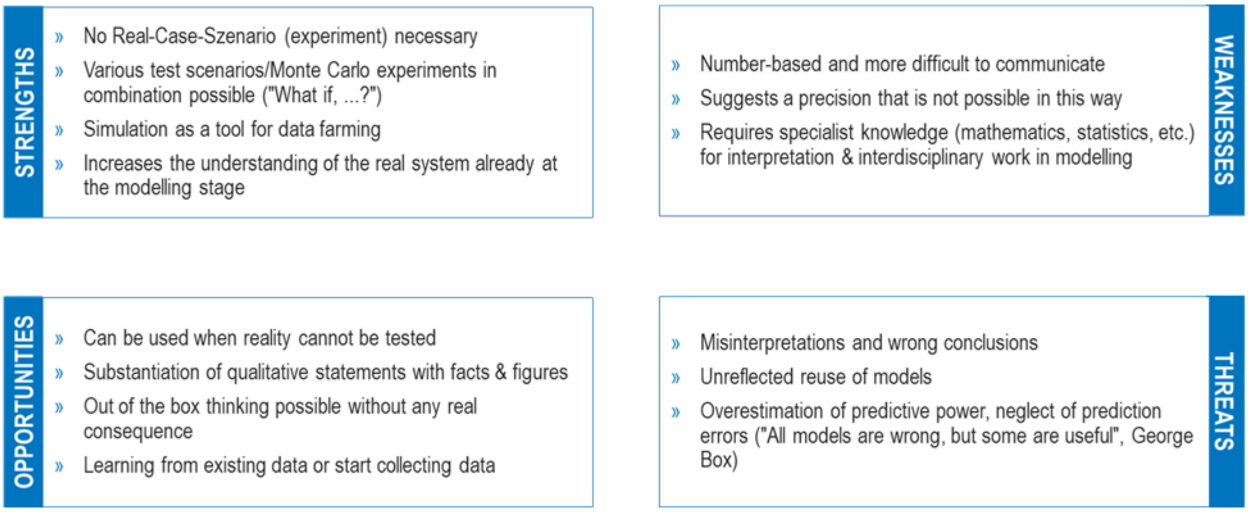

Figure 4-1: Strengths Weaknesses Opportunities Threats Overview

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