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System Configuration to Enhance Co-Simulation for Decision Support

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Abstract

The development of complex ecosystems in the mobility domain and beyond require comprehensive support by simulation and virtual engineering methodologies. This work contributes to the field of co-simulation and its application for decision support for complex infrastructure decisions by the example of planning public charging infrastructure for electric mobility in Germany. Therefore, a hybrid co-simulation system is developed which serves as the field of application and foundation for the further work towards advances in handling and usage of complex simulation systems.

Setting up a framework which embeds the co-simulation system into a framework that accounts for multi-criteria decision support, the arising challenges in system configuration as well as result analysis and interpretation are addressed. The focus lies on user guidance, traceability and a high degree of automation. A distinction is made between five levels for system configuration spanning the range from the definition of top-level goals to an executable simulation run while ensuring user guidance and traceability. In accordance with the system configuration, the aggregation and post-processing of the results are mapped towards the levels of system configuration following the inverted path.

Within the system configuration, the advance compared to the state-of-the-art of system handling comprises the traceability over multiple abstraction layers, the consistent parametrisation of a heterogeneous system of multiple models by using Natural Language Processing (NLP), automated parameter transformation and the integrated usage of future structured scenarios. Thereby, the value of simulation results for complex decision making is enhanced, as the comparability between different simulation configurations and runs is ensured, the derivation of the desired scope for simulation is integrated and the uncertainty of future developments is considered by structured scenarios. With the help of expert interviews the range of foreseeable users, the practical applicability and comprehensibility of the proposed system configuration is proved.

Zusammenfassung

Die aktuelle Entwicklung komplexer Ökosysteme im Bereich der Mobilität und darüber hinaus erfordert eine umfassende Unterstützung durch Methoden der Simulation und des Virtual Engineering. Diese Arbeit leistet einen Beitrag zum Forschungsfeld der Co-Simulation und deren Anwendung zur Entscheidungsunterstützung für komplexe Infrastrukturentscheidungen am Beispiel der Planung öffentlicher Ladeinfrastruktur für Elektromobilität in Deutschland. Dazu wird zunächst ein hybrides Co-Simulationssystem entwickelt, welches im weiteren Verlauf als Anwendungsfeld und Grundlage zur Weiterentwicklung der Handhabung und Nutzung komplexer Simulationssysteme dient.

Durch den Aufbau eines Frameworks, welches das entwickelte Co-Simulationssystem in einen Rahmen weiterer Funktionalitäten einbettet, der die multikriterielle Entscheidungsunterstützung berücksichtigt, werden die entstehenden Herausforderungen bei der Systemkonfiguration sowie der Ergebnisanalyse adressiert. Der Fokus liegt dabei auf Benutzerführung, Nachvollziehbarkeit und einem hohen Automatisierungsgrad. Für die Systemkonfiguration werden fünf Ebenen unterschieden, welche den Bogen von der Definition von Top-Level-Zielen bis hin zu einem ausführbaren Simulationslauf spannen und dabei Benutzerführung, Durchgängigkeit und Nachvollziehbarkeit gewährleisten. Entsprechend der Ebenen der Systemkonfiguration wird die Aggregation und Nutzung der Ergebnisse auf die Ebenen der Systemkonfiguration in umgekehrter Reihenfolge abgebildet.

Innerhalb der Systemkonfiguration besteht der Beitrag, über den Stand der Technik hinaus, in der Nachvollziehbarkeit über mehrere Abstraktionsebenen, der konsistenten Parametrisierung eines heterogenen Modellverbundes durch den Einsatz von Natural Language Processing (NLP), der automatisierten Parametertransformation und der integrierten Nutzung von strukturierten Szenarien, welche zukünftige Entwicklungen abbilden. Dadurch werden der Wertbeitrag von Simulation und deren Ergebnisse für komplexe Entscheidungsfindungen erhöht, da die Vergleichbarkeit zwischen verschiedenen Simulationskonfigurationen und -läufen gewährleistet ist, die Ableitung des erforderlichen Simulationsumfangs integriert ist und die Unsicherheit zukünftiger Entwicklungen durch strukturierte Szenarien berücksichtigt wird. Durch Experteninterviews im Kreis der adressierten Nutzer wird die praktische Anwendbarkeit und Nachvollziehbarkeit der Arbeiten nachgewiesen.

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List of Algorithms

List of Symbols

a	Vector Representing Text
b	Vector Representing Text
B	Billion
c	Classes
i	Index of Sentence
K	Thousand
M	Million
n	Amount of Sentences to be Analysed
p	Data Properties
°	Degree
€	Euro
§	Paragraph (Legal)
$	US-Dollar
θ	Angel for Similarity

List of Acronyms

2D	Two Dimensional
3D	Three Dimensional
AC	Alternating Current
ACoRTA	Advanced Co-Simulation Methods for Real-Time Applications
ACOSAR	Advanced Co-simulation Open System Architecture
ADAS	Advanced Driver Assistance Systems
API	Application Programming Interface
AV	Autonomous Vehicle
BERT	Bidirectional Encoder Representations from Transformers
BEV	Battery Electric Vehicle
CAPEX	Capital Expenditure
CASE	Connected Autonomous Shared and Electric
CHAdeMO	CHArge de MOve
CO_2	Carbon Dioxide
cos	Cosine
CPO	Charge Point Operator
CPS	Cyber-Physical Systems
CPV	Charge Power of a Vehicle
CS	Co-Simulation
CSV	Comma Separated Value
CT	Continuous Time
CV	Connected Vehicle
DESTECS	Design Support and Tooling for Embedded Control Software
DC	Direct Current
DMU	Digital Mock Up
DE	Discrete Event
DSE	Design Space Exploration
DSS	Decision Support System
E	Electric
EA	Evolutionary Algorithm
EF	Experimental Frame
EGM	Energy Grid Model
EnWG	Energiewirtschaftsgesetz (German Energy Sector Law)
EU	European Union
EV	Electric Vehicle
F1	Harmonic Mean of the Precision and Recall
FCEV	Fuel Cell Electric Vehicle
FMI	Functional Mock-up Interface
FMU	Functional Mock-up Unit
FSA	Flexible System Architecture

GHG	Greenhouse Gas
GUI	Graphical User Interface
HiL	Hardware-in-the-loop
HLA	High-Level Architecture
IEC	International Electrotechnical Commission
ind	Individuals
INTO-CPS	Integrated Tool Chain for Model-Based Design for Cyber-Physical Systems
IP	Intellectual Property
ISO	International Organization for Standardization
IT/C	Incremental Testing/Certification
kg	Kilogram
KPI	Key Performance Indicator
kW	Kilowatt
kWh	Kilowatt Hours
LUC	Charging Use Case (in German: Lade-Use-Case)
MB	Mobility Behaviour
MCDA	Multi-Criteria Decision Analysis
MCDM	Multi-Criteria Decision Making
MiD	Mobilität in Deutschland (Mobility in Germany)
MiL	Model-in-the-Loop
MILP	Mixed Integer Linear Programming
MobiVoc	Open Mobility Vocabulary
MW	Megawatt
MWh	Megawatt Hour
NLP	Natural Language Processing
NOW	Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie (National Organization Hydrogen and Fuel Cell Technology)
NSGA-II	Non-Dominated Sorting Genetic Algorithm-II
OCPP	Open Charge Point Protocol
OEM	Original Equipment Manufacturer
OOV	Out of Vocabulary
OPEX	Operational Expenditure
OSM	OpenStreetMap
OWL	Web Ontology Language
PHEVs	Plug-in Hybrid Electric Vehicles
PV	Photovoltaic
RDF	Resource Description Framework
RegioStar	Regionalstatistische Raumtypologie (Regional Statistical Area Typology)
RT	Real Time
RTI	Runtime Infrastructure

SBERT	Sentence Bidirectional Encoder Representations from Transformers
SGAM	Smart Grid Architecture Model
SiL	Software-in-the-loop
SM	Shared Mobility
SOC	State of Charge
SSP	System Structure and Parameterization
SysML	System Modeling Language
UML	Unified Modelling Language
V2G	Vehicle-to-Grid
V2X	Vehicle-to-X
VDE	Verband der Elektrotechnik Elektronik Informationstechnik e. V. (Association of Electrical, Electronic & Information Technologies)
XiL	X-in-the-Loop
XML	Extensible Markup Language

1. Introduction

The mobility is undergoing significant changes for the last decade and is expected to change even accelerated in the upcoming years. The drivers for these changes are manifold: The user behaviour is changing due to urbanisation and awareness for the environmental impact of one's decisions. Technologically, a trend towards electrification of the individual mobility, not only limited to cars, but also towards bikes and scooters is observable.

The acronym CASE for connected, automated, shared and ecological mobility summarizes the trends and thereby the framework for the development of future mobility. Although there is consensus on the need to further develop the existing mobility ecosystem, the challenge is to realise the ideas in practise. Besides the diverging interests and high required invests, there are also remaining methodological challenges to analyse the interdependencies between different stakeholders and measures under uncertainty. This leads to a gap between concrete decisions to be made and a high variety of options which can be barely assessed holistically.

A concrete example is the development of charging infrastructure for electric mobility. In contrast to fuel-driven vehicles, the infrastructure to "refuel" electric vehicles needs to be build by consideration of further dependencies and options. At first, there are private as well as public options, the technology development accelerates towards longer ranges and shorter charging time and the prices and availability of electricity become unforeseeable. When setting up the future charging infrastructure, all the thinkable scenarios have to be considered, but synthesized into concrete action in the end.

Real-world experiments, e. g. in a research project can contribute to an understanding of the interdependencies, but are time-consuming and costly. Moreover, the large-scale perspective as well as comparing different configurations with each other is difficult to reach in real world. Therefore, simulation is a feasible methodology to overcome time and cost restrictions by applying a framework that accounts for flexibility in terms of modelled stakeholders while ensuring an efficient and traceable process. This can be reached by automation along the simulation tool chain and calls for consideration of requirements for decision support, namely comparability, concreteness and results that are suitable for further analysis. Co-simulation as the approach to build up a simulation system as the coupling of multiple submodels enables the necessary flexibility regarding considered stakeholders in the context of mobility development. Moreover, this approach allows to model the different stakeholders in individually feasible modelling tools and in parallel, to reuse existing models for different questions.

In the past, co-simulation has been established as a methodology, e. g. for the virtual development of vehicles, and in this course, the development of standardized model interfaces has been pursued. While coupling algorithms solving the most pressuring numeric issues have been tackled, the holistic view on co-simulation systems accounting for their flexibility and efficient use in divergent domains is still a major field of research.

1.1. Scientific Contribution and Methodology

This thesis contributes to the development and agile use of co-simulation systems in the context of decision support for future mobility. By the example of charging infrastructure, a framework is set up which brings three major improvements in comparison to existing co-simulation solutions: Structured derivation of simulation configurations, central parametrisation for simulation runs and a high degree of automation in handling.

From the need of supporting decision making for future mobility and in particular, its infrastructure development, a framework is developed which brings together different submodels, scenarios to be analysed and domain-specific knowledge to automate necessary processes. Thereby, comparability between multiple simulation configurations is ensured and comprehensive decision support by the example of planning public charging infrastructure in Germany is enabled.

The addressed challenges compared to the state-of-the-art comprise the traceability within the usage of simulation systems, the enabling of decision support in a structured and comparable manner as well as the stakeholder cooperation and user guidance along the simulation system's handling.

Proposing a system configuration with five levels of abstraction, the composition and derivation of a suitable simulation system for a decision problem from real-world is enabled in collaboration of multiple stakeholders and their corresponding degree of detailing. Starting with the definition of top-level Key Performance Indicators (KPIs), qualitative interdependencies to be analysed in simulation are defined. Subsequently, the simulation scope is defined with the corresponding models representing the defined interdependencies. This step marks the transition between abstract definition of the simulation's goals and content towards the configuration of a suitable and executable simulation system.

In the following step, the model decomposition is conducted by analysing the models' individual parameter and variables, comparing those to each other and setting up the connections between inputs and outputs. Finally, in the step of model parametrisation all values required for simulation and optimisation are set accordingly until an executable simulation system is reached. In analogy to the steps of system configuration, the aggregation and further analysis of the results is mapped to the same five levels of abstraction.

Within the system configuration, a high degree of automation is pursued which calls for the development of artefacts that account for traceability, automation and user guidance and have been implemented into a front end for demonstration. First, central parametrisation enables the systematic parameter variation considering all connected submodels with their parameters and variables. Thereby, it becomes possible to run different scenarios with the same models and to apply those scenarios to different model configurations; both is enabled by the usage of Natural Language Processing (NLP).

In the context of charging infrastructure, this step enables the consideration of relevant stakeholders for a specific question. Furthermore, different models of the same stakeholders can be compared with each other by applying the same scenarios and analysing the results regarding overlapping and differences.

Second, the automated model replacement and integration allows to reconfigure the system in a flexible manner. As explained in the example above, the reconfiguration in terms of included submodels is highly important in the context of planning charging infrastructure. Thereby, an automation of this process facilitates the handling of the simulation system and enables the efficient application e. g. to different cities.

Although a full automation of the prior-described steps is only feasible inside certain boundaries, the underlying framework is of high interest also for related fields such as virtual prototyping. Therefore, this contribution advances the state-of-the art for co-simulation systems regarding flexibility and usability for fields of application without fully detailed a-priori definitions.

Most of the here-presented work has been published before at conferences and in papers which based on collaboration with other researchers. The feedback from the review processes as well as discussions on conferences or internally at ITK Engineering, the industry sponsor of this thesis, contributed to the research outcome. Additional support was conducted by student work and thesis which helped in particular with the implementation and literature research. The student work is available on request from the author.

Having motivated the work and stated the contribution, the research questions are elaborated in the following. With the overall goal of contributing to the usage of co-simulation for decision making, the use case of planning public charging infrastructure is investigated and a suitable simulation and optimisation system is developed. In the following, the arising challenges for co-simulation in the context of infrastructure decision making are analysed and a framework to embed the simulation is developed. To solve the analysed challenges, a traceable handling of simulation systems is developed and the user guidance and support within system configuration, execution and analysis are derived. This leads to the following four research questions that are tackled in this work:

1. How can decision support by co-simulation be reached by the example of public charging infrastructure?
2. Where do the challenges for co-simulation in context of infrastructure lie?
3. How is a traceable handling of simulation possible?
4. How can the user be guided and supported during the simulation system configuration process?

1.2. Structure of Thesis

The structure is synthesized in Figure 1. Hereafter in Section 2, the work is embedded into current research trends and demands to motivate the chosen niche within virtual engineering and simulation . Subsequently, the state of the art and related work is summarized in Section 3. This comprises simulation and modelling techniques in general and work related to co-simulation in particular. Relevant terms are introduced as well as literature approaches towards standardization and automation in the context of simulation systems. It follows the introduction of simulation for decision support and of the field of application in this work: Charging infrastructure for electric mobility.

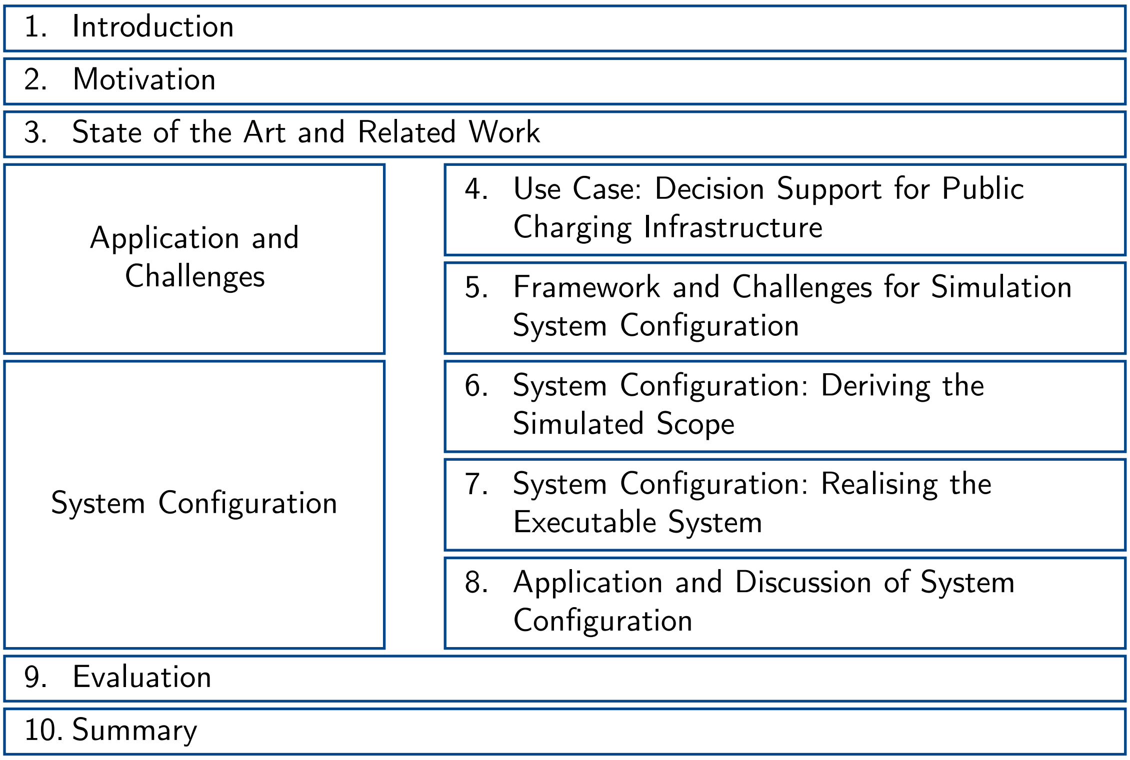


Figure 1: Structure of thesis

In Section 4 the simulation and optimisation system to plan public charging infrastructure for electric mobility in Germany is explained. Therefore, the considered perspectives with Electric Vehicle (EV) drivers, Charge Point Operator (CPO) and the electrical grid are elaborated as individual models, complemented by the analysed scenarios for its future development. This simulation system is embedded into an optimisation framework to enable the aimed decision support. Thereby, the reader of this thesis gets a detailed understanding of the practical application for the here-presented tool chain development.

Chapter 5 describes the developed framework and functionality to realise the aimed decision support by simulation in the context of charging infrastructure. The focus is set on the challenges for mainly automated central and consistent parametrisation when replacing a submodel in the simulation system. Further points of discussion are the challenges during runtime and the simulation post-processing towards the aimed decision support. In the following Sections 6 and 7, the five levels of abstraction are introduced as the core artefact within this work accounting for the structured, traceable and guided usage of simulation for decision support to tackle the challenges elaborated in the prior Chapter 5. Thereafter, in 8 the application of the introduced system configuration is demonstrated towards the challenges of reusability, model replacement, traceability and decision support. The evaluation of this work in Section 9 is divided into the technical aspects of methodological limits and plausibility check on the one side, and expert interviews as well as the application to further fields of interest on the other. In the last Section 10 the work of this dissertation is summarized and the scientific contribution is outlined based on the prior-given details. The thesis finishes with an outlook on future work. The mapping of the research questions to the chapters is summarized in Figure 2.

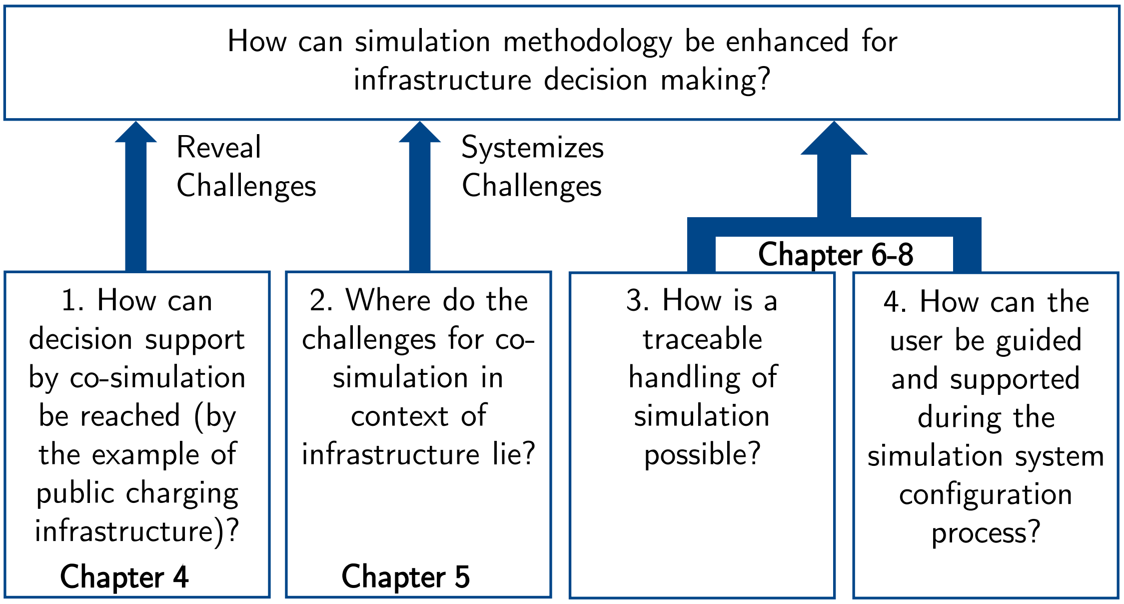


Figure 2: Mapping of research questions to chapters

2. Motivation

In this chapter, the motivation for the work at hand is elaborated. According to the prior introduction, the need for simulation techniques and methods is already high and further increasing in the mobility sector. This section focuses on the big picture of the field of research, existing challenges and already foreseeable developments comprising the four elements as illustrated in Figure 3.

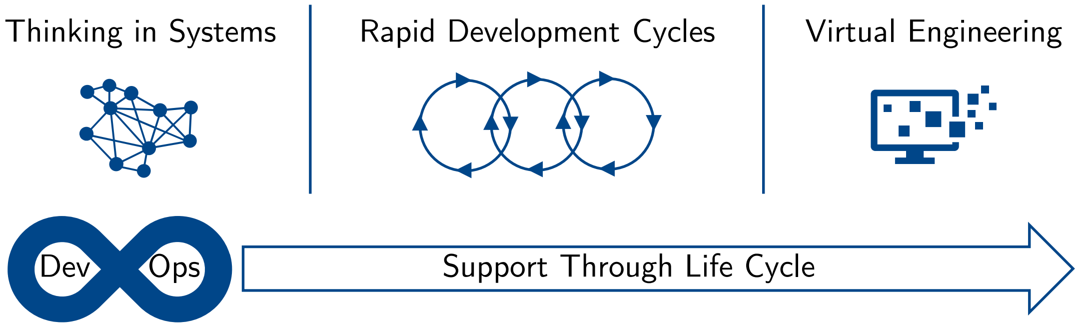


Figure 3: Motivation and big picture

2.1. Thinking in Systems

Former development processes have mainly concentrated on stand-alone products with a set of specific characteristics. The core value of such products is defined by its characteristic and customer value from an isolated point of view. Examples in the mobility domain can be found with the car development in the last decades of the last century: New car generations distinguished themselves from their predecessors by increased driving performance, reliability and better safety systems [1].

Recent and foreseeable future developments have to be seen as a contrast to that. With the market penetration of smartphones, the transition of cars to the class of connected devices accelerated. Software components interacting with the environment gained higher importance and tend to define the user experience significantly. [1]

This development is even accelerated by the shift to electric mobility as the recharging requires planning due to the unsteady availability of charging points in terms of location and time. Therefore, an up-to-date Battery Electric Vehicle (BEV) does not only provide its customer value by its own characteristics, but additionally and with a major share by its interaction with the environment and ecosystem that it takes part in. [2]

Ecosystems in general can be defined as systems spanning over a domain with multiple subsystems and components that interact with each other. By the interaction, the value of the individual parts - so-called subsystems - is increased and services are enabled that require several parts. E. g. the latest BEV and the latest wallbox are hardware-focused subsystems of the ecosystem electric mobility. Subsystems can be either hardware, but also software or a combination of both. For such an ecosystem approach, the configuration of interfaces and the harmonization between multiple involved parties play an important role. [3], [4]

Another strong example for ecosystems in the mobility domain is the offer of micro mobility solutions. To offer e. g. an Electric (E)-scooter service in a city, it is much more needed than only the physical E-scooters: First, maintenance and the batteries' recharge have to be ensured and therefore coordinated. Second, information about the fleet regarding e. g. individual positions and status have to be continuously collected and analysed. Third and possibly most important, the user interface, most likely realised via smartphone application, needs to be implemented. Thereby, the users reserve, unlock and pay their rides. Conclusively, the whole usage is steered via app and the scooters themselves as hardware play a relative minor role for the user experience of micro mobility. [3]

With the two examples of charging infrastructure and E-scooter micro mobility, the interdependencies between stakeholders become apparent. When introducing the examples above, the core artefacts and relations have been described. In the following, their embedding in real world is elaborated. For electric mobility, the car manufacturer and the user of the electric car have been already introduced. When analysing the charging infrastructure, their manufacturer and operator have to be added on the first view. To supply the energy, the electrical grid and its operator are further stakeholders. The communication as well as the payment are typically conducted app-based via internet. Regarding the number and location of public charging points, the politics as well as the city planners are relevant. This stakeholder analysis could be even further elaborated, e. g. on other mobility options, which demonstrates the need for the definition of boundaries.

For the E-scooter service, the interplay with other mobility options is even more in focus - multimodal mobility e. g. combining public transport with micro mobility for the last mile combines large scale transport with mobility to individual destinations. In this case, the overall mobility provision with the offer of public transport and E-scooters depend on the characteristics and development of each other.

When setting up the E-scooter offer, the existing public transport should be analysed. On routes with low-frequency public transport or unattractive connections, mobility alternatives will be more likely used. Moreover, daily commuting tend to lead to a high demand in one direction in the morning and vice versa in the afternoon. This shall be considered for the location and quantity of scooters in the network.

On the other side, the setup of a micro mobility offer may influence the use of public transport. On the one hand, for routes with a low passenger volume, their replacement by other offers might become considerable. On the other hand, the attraction of public transport offers can be increased by additional micro mobility services as users have better options for their individual last mile.

Therefore, the strengthening of micro mobility can increase the demand for public transport on certain routes while decreasing the demand on other routes in parallel. Such contradictory effects reveal the challenges in system thinking and analysis. Also it calls for the refinement and re-analysis of interdependencies over time.

The examples above also show the importance of new subsystems and offers into the existing system, e. g. the mobility system. Public transport as well as street and electricity infrastructure already exist and possibilities for changes are limited there. Furthermore, with regard to the ongoing usage of conventional existing offers, the transition to e. g. a different mode of driving or commuting, is fluent. Therefore, the transition is also part of the system's dynamic and evolvement and has to be considered as a lively part of the system. [3]

With the introduction of a new subsystem, its interfaces to all related subsystems have to be considered. Also the subsystem's introduction might lead to changed interdependencies between already existing subsystems which calls for further refinements. These necessities shall be reflected in the development process and supporting tools.

Finally, even the thinking in systems has to be limited at some extent. It remains a uncertainty in some degree as influences and interdependencies or at least their exact strength cannot be determined and analysed. Furthermore, the higher the level of detailing, the higher the complexity of the system's analysis. Therefore, the thinking in system has to be limited according to the available resources and in particular, the scope of the system's consideration within the task at hand.

2.2. Rapid Development Cycles

During the last decade, the acceleration of development cycles could be observed. Driven by software and expanding technological possibilities, the development cycles of hardware also accelerated. Advancements in either hardware or software require adoptions on the other side to benefit on a system-level from the progress that has been made. A further driver for increased innovation cycles can be found in the consumer habits and sales perspective. To meet the market demand and expectations, frequent new releases are required, e. g. a smartphone generation per year seems to be the established cycle. [4]

In accordance with the fast cycles of development, the size of revisions and improvement form a contradictory impact to the accelerated development. While the accelerated development tend to lead to more technical progress compared to former times, the faster cycles lead to smaller differences between successive generations. Independent of the progress made between generations, the development phases have to be undergone and the testing effort rises due to the increased number of products and product generations. [5]

Despite the relatively small differences between product generations, the integration and testing effort rises significantly due to an increasing number of interfaces and interdependencies. This tendency applies for all levels of testing, reaching from software component tests to the integration of combined software hardware products into an ecosystem. When analysing a system composed of three subsystems, e. g. a smartphone, a tablet and a smartwatch, the number of is up to six (3!). If the involved subsystems is six, the number of unidirectional connections can reach up to 720 (6!), when considering two generations for each product.

A further trend emerges with pursuing multiple parallel development strings to meet the rapid development cycles. With parallel developments, it is no longer sufficient to orchestrate subsystems and their interplay, but also processes and different phases of development. When releasing e. g. yearly a new smartphone generation but the development cycle for major innovation is longer, several development projects have to be executed in parallel. Consequently, projects are in different stages and have to be coordinated across teams and organizations, e.g. for cooperation with suppliers. [6] Either employees are associated with a project and work in cross-functional teams or teams of specialists deal with multiple parallel projects. Additional complexity results from international collaboration and division of labour as well as different local requirements, e. g. the available grid voltage level. In each case, the development processes and the used artefacts shall account for structure, easy usage and traceability as the complexity increases.

Bringing together the above-explained aspects of system thinking and rapid development cycles, the compatibility of subsystems from different generations arises as a challenge. Taking the example of electric mobility, the new generation of a vehicle shall be compatible with the wall boxes and the app-based steering which are already in the market. Moreover, the vehicle shall be also prepared to collaborate with future software releases and newly launched wallboxes. Therefore, the question of downwards and upwards compatibility of components and subsystems must be considered. This comprises aspects of communication, functionality and resources.

First, the aspect of communication has been discussed above with the connections to be developed and tested. Second, the functionality has to be evaluated that certain subsystems provide when they are combined in an ecosystem. Therefore, the specification of the desired interaction is needed, followed by the required test cases to ensure the correct execution.

This procedure mainly applies for downwards compatibility when the one side is already released and the other side is currently under development.

In contrast, the aspects of available resources focuses on the upwards compatibility. E. g. the computing unit for vehicle-to-X (V2X) communication which allows the communication of the vehicle with surrounding infrastructure, could be nowadays considered in the development process to have the system ready for this future application. Therefore, computing power in the current vehicle development has to be designed beyond concrete demands from today. Additionally, communication interfaces have to be available future-ready, but also safe and secure nowadays to prevent misuse. [7]

Finally, the future integration of new features has to be prepared. Those which are nowadays foreseeable or already in the development process can be integrated in a roadmap. As an example could serve a wallbox that is currently in the development and is planned to be released a year after a new model of an electric vehicle. On the other side, the described V2X usage depends on the availability of the ecosystem of general infrastructure and cannot be planned bindingly. Therefore, the system can be prepared to a certain extent by designing powerful hardware and preparing interfaces. Those have to be well-documented with a high degree of traceability for its future finishing in a further development cycle.

Conclusively, the rapid development cycles poses challenges especially for systems with multiple subsystems and interfaces. Moreover, they require parallelism in development processes which implies challenges for the processes and teams working in the development. Aspects of downwards and upwards compatibility have to be given priority due to multiple available versions and their interplay in an ecosystem. Therefore, sophisticated support by tools is required to account for a structured evaluation of relevant variants.

2.3. Virtual Engineering

The rapid development cycles described above in Subsection 2.2 reveal the challenges that compatibility must be ensured and that parallel development projects exist parallel to each other, but in different stages [5]. The field of virtual engineering aims to support research and development tasks by modelling and simulation, typically prior or in addition to real-world tests. In the context at hand, the wallbox as a hardware artefact and its belonging software could be both part of a virtual engineering process.

Virtual engineering itself aims to facilitate, accelerate and specify the development process. Achieved goals by extensive virtual engineering could be either an accelerated development process, an improved quality in the development leading to a better product or the reduction of costs because of virtual experiments instead of real-world experiments. Therefore, the role of virtual engineering is supportive in a sense that the application of virtual engineering helps to take decisions in the development process on a profound base. [5]

Conclusively, there is an overlapping with the field of decision support as both aim to prepare decision-taking by providing data, quantitative analysis and somehow optimised solutions. [5]

In the beginning virtual engineering starts with an abstract model with is then later refined as more information is available and requirements are further specified within the development process. Models can either represent single components, like the software of the wall-box or could also represent the combined hardware and software of the wall-box.

The decision on how the models are composed and aggregated is a decision which has to be taken with regard to the current but also future use of the models. It can also depend on the level of detailing which is currently required. E. g. the detailed modelling of the wallbox regarding its hardware and software functionalities is of interest to test its compatibility with a certain BEV. Therefore, a detailed modelling approach is feasible. On the other side, in the context of grid integration, the power demand curve of the wallbox might be sufficient and further software characteristics could be neglected. Such trade-off can be summarized with model decomposition and level of abstraction. Both can vary over time within the development process which calls again for traceability of versions and decisions and an facilitated process to compose the needed virtual system.

Having introduced the aim and several challenges for virtual engineering, the different artefacts are introduced that may take part in such a virtual system. Models have been already introduced, but further distinctions are made. For development, the use of two-Dimensional (2D) physical models is most common. For visualization purposes or specific requirements, three-Dimensional (3D) models are also feasible, e. g. for user experience tests. [5] An example could be the 3D model of the wallbox's hardware to virtually demonstrate its design to possible customers and get feedback in an early stage of development. A possible existing 2D model could serve as a base to develop the 3D model and the received feedback might be played back into the 2D model. This example demonstrates how not only virtual artefacts from different components or subsystems interact, but also artefacts representing the same component.

Further artefacts comprise, beside others, software and hardware which is coupled with virtual artefacts such as models. The so-created systems are called Software-in-the-Loop (SiL), Hardware-in-the-Loop (HiL), or more general X-in-the-Loop (XiL). The software or hardware is tested in the currently available version and its usual environment is simulated partially via models or additionally by further software and hardware artefacts. This is also part of virtual engineering, as the emulation of the environment is at least partially virtual. [5]

The benefits of combining virtual elements with available hardware and software artefacts leads to the opportunity to combine subsystems or components from different stages in development. Thereby, it supports the accelerated development and accounts for the increased interdependencies that occur in ecosystems.

Also the scope of the system under test and the operational environment can be varied with less effort or to an extend that is not feasible in real-world. E. g. the changes in user behaviour of public transport and E-bikes could be analysed not only in the authorized sandbox, but with only one specific target customer behaviour which is extracted from real-world and largely-scaled for virtual engineering. A further example is the testing of e. g. autonomous public transport options that have not yet been fully released to public, but can be virtually tested on public roads.

An important part of virtual engineering is the traceability of configurations and results. The results of multiple simulation runs can be only evaluated against each other if the conducted experiment in virtual engineering is described holistically. Besides common facts from real-world experiments such as environmental conditions or the time observed, aspects like data and model versions must be logged in a suitable manner.

2.4. Support Throughout Life Cycle

In the prior Subsection 2.3, the idea and requirements for virtual engineering have been explained referred to different stages in the development. A further aspect to be considered in the context of virtual engineering is the continuous improvement and integration in later stages. Not only newly developed artefacts have to account for compatibility, but also the subsystem under development shall be prepared for its reintegration, adoption and further changes. [6]

Thinking in systems leads to the common situation to start on a brown field environment which is usually considered by the requirements in the development as long as the requirements are already known. Requirements which appear due to other developments during development stage have been discussed in Subsection 2.2. The stages after the development of a subsystem until its end of life are the focus of this subsection. It is elaborated which challenges appear and how they do affect the development stage and what is needed to overcome these challenges.

Extending the above-introduced example of public transport and E-scooters, the subsystem of E-bikes is integrated into the existing mobility ecosystem. Since the integration of a new subsystem has been discussed by the example of adding E-scooters to public transport, the focus here lies on the analysis of how the existing ecosystem (public transport and E-scooters) shall be prepared during the E-bike establishment. Thereby, the challenges and adoptions to be made can be understood for the support throughout life cycle.

Whereas a free-floating approach for the E-scooters has been introduced which means waiving of fixed locations to collect the E-scooters, such a station-based approach is pursued with the E-bike subsystem. Therefore, stations are required where users either want to depart or arrive by E-bike, for which the stations of public transport could provide the initial set of options.

This example demonstrate that the construction of public transport stations shall account for further extensions and micro-mobility offers, even when they are not concretely planned, but foreseeable. Consequently, reserves in terms of space and additionally, available power connections are recommended.

On the software level, the mobile application for the usage and payment of the E-scooters could be prepared regarding code and interfaces for the later integration of the E-bike offer. Thereby, the mobility offers appear as an integrated ecosystem and the entry barrier for such an additional service is lowered. Also in maintenance and support during the operation phase, synergies are revealed: Technical and customer support for the mobile application as well as the vehicles themselves could be bundled by one service provider. Therefore, the support team must be educational- and equipment-wise enhanced. Daily operations like the route of a technician might be changed and the break-even point for a support offer may vary.

Customer behaviour might change due to the new offer. The E-bike offer can either lead to a reduced demand for public transport and the E-scooters or to an increased demand because of the improved ecosystem. Consequently, the manifold interdependencies cover aspects of software, operation as well as business-case-wise. Such system behaviour requires an a-priori quantitative analysis of the changes and the availability of interfaces within the existing subsystems.

This need leads to the transition of virtual artefacts from the development phase to their state in the operation phase which calls for traceability, reuse-ability and modularity. Several use cases do appear here. First, the reasonability and validity of the virtual artefacts, mainly models, from the development phase can be evaluated. Thereby, not only single models or subsystems shall be evaluated, but the system behaviour and interdependencies in particular. During the evaluation, not only the effects with are modelled shall be analysed, but also a data-driven approach might reveal unknown or unpredictable effects and relations, e. g. of a change in usage of public transport at a certain station. The validated and possibly refined models can be then reused as demonstrated by the example of adding E-bikes as a micro-mobility offer to existing E-scooters. [3]

Second, the virtual artefacts from the development phase can serve as the base for a digital twin. Either real-time data can be routed through according interfaces in the existing models or the knowledge from operation can be indirectly integrated by modelling the somehow abstracted knowledge from data analysis. Therefore, interfaces for data must be available and the traceability of functionalities as well as changes shall be ensured for an efficient handling. The digital twin can be then used to reveal potential in operation phase and to gain knowledge for thinkable extensions or similar projects. [8]

For such similar projects, single artefacts, e. g. the the user behaviour for E-scooters, as well as the whole virtual system might be taken for further analysis which leads to the need of modularity. This requirement interacts with traceability and defined interfaces which have been described above.

A further application of the development artefacts is identified in the transition from a sandbox to a large-scale project. In the example of a mobility ecosystem, the extension of the public transport by E-scooters could be limited to a neighbourhood at first. For this application, the initialization shall be also supported by simulation to reach a realistic setup that meets the user demand. Even a sandbox shall be limited in its risks by purpose, the feasible setup is a must to gain the experience to judge on its real-world applicability. For the further usage of the virtual artefacts and the gained knowledge for large-scale applications, requirements for reuse, traceability and reconfiguration must be considered.

In this chapter, the motivation for the work at hand has been elaborated. It comprises aspects of an enhanced thinking in systems, increasing speed in development with methods of virtual engineering, and the continuous support, improvement and refinement throughout the life cycles of artefacts, subsystems and systems. Thus, it has become evident that methodological advancement is required for analysing interdependencies and systems in the development phase. Thereby, large-scale decisions in ecosystems e. g. in infrastructure development, can be taken with a decreased level of uncertainty. Moreover, aspects from different perspectives become more relevant as the degree of integration and interaction increases nowadays. Therefore, systems and their artefacts have to be reconsidered and possibly enhanced throughout their life cycle. In the following chapter, the related state of the art is presented towards systems and virtual engineering, decision support, along side with the background for the exemplary application in this work.

3. State of the Art and Related Work

In this section the relevant state of the art for this work is synthesized. First, the relevant aspects and terms from modelling, simulation and co-simulation are introduced, followed by the required fundamentals of systems engineering. Afterwards, the field of ontology matching is introduced which is required for the NLP application. Furthermore, the fundamentals for the field of application in this work, charging infrastructure for electric mobility, are introduced complemented by the necessary aspects of design space exploration and decision support. Finally, the thesis at hand is embedded into comparable work.

3.1. Co-Simulation

The history of co-simulation leads back to the late 1970s. In the early 90s, system design was applied to co-simulation and its application for concurrent engineering (and therefore faster development) raised. In the 2010s the concept of Digital Twin came up as a further development of the Digital Mock Up (DMU) concept spanning not only the design and assembly phases of the system, but additionally the maintenance phase. This goes along with the recent path to increased virtualization during the system's life cycle. [9]

The objective for co-simulation is the accurate reproduction of the behaviour of the system under study. The simulation unit is broken down into the solver, the model and the input approximation. The model represents the system under study based on the modeller's knowledge. A solver approximates the behaviour of the model and the input approximation is used by the solver to approximate the model's inputs over time. Further down the line, the model is broken down into the concepts of input, state, output and parameter. The orchestrator as a coordinating unit initializes the participating simulation units with feasible values, sets inputs and gets outputs and is responsible for the simulation progression over time. [10]

Co-simulation is an important tool for collaboration among different disciplines, as it allows to combine multiple simulation techniques and specialised software to one simulation system. Thereby, complex interdependencies between subsystems can be evaluated while specialised tools account for simulative accuracy. In this work the remaining research needs are identified with coupling of simulation units accounting for modularity, stability, accuracy and correctness. In general, the integration of models to systems are limited due to different specialized tools in use and the protection of Intellectual Property (IP). [11]

Co-simulation comprises theory and techniques to setup a system of coupled simulation composed by multiple black box mock-ups of simulators. Thereby, virtual mock-ups of solutions can be integrated, tested and compared without revealing IP. This is one motivation for the development of the Functional Mock-up Interface (FMI) standard. [11] Co-simulation is separated from other types of simulation by the multiple participating models which are solved by multiple solvers [12]. Co-simulation is defined as the combination of distributed modelling and distributed simulation [13]. Whereas parallel simulation is referred to as the usage of multiple processors or cores of a computing system, the term distributed simulation describes the usage of multiple computers at (possibly) different locations for a simulation [14].

A co-simulation scenario is here defined as a set of information that is required for obtaining a correct co-simulation. It contains the input/output routing and the experimental frame. The composition of an orchestrator with a co-simulation scenario is a co-simulation unit which can be understood as the substitute of the real coupled system. The survey focuses on black box simulation units with limited knowledge about models and simulators. The importance of compositionality is stressed. [11]

According to the survey presented in [15], co-simulation's strength lie in the separate implementation of different sub-system in specialized tools and the support of cross-company cooperation. In contrast, the computational performance and robustness compared to monolithic simulation is lower and moreover, licenses for multiple simulation programs are required. [15]

The classification for the taxonomy presented in [11] are summarized in Figure 4. First, the class of non-functional requirements deals with groups concerns such as performance or accuracy. Second, simulation unit requirements, e. g. exposed information or causality, are named. Finally, framework requirements that contain features provided by the orchestrator are addressed while mandatory features are differed from optional ones. Thereby, the associated literature between 2011 and 2016 is classified. [11] The non-functional requirements for co-simulation comprise platform independence, open-source, extensibility, scalability and configuration reusability. [11]

3.1.1. Modelling Approaches

Modelling as the technique to virtually build a real system has been studied since the 1960s latest. Simulation can be then defined as the time-dependent observation of the model's behaviour. A model of a real system which characteristics are described by the help of state and evolution rules, is called dynamical system. The expression "simulation unit" describes something which produces a behaviour trace (output). A simulation is the behaviour trace or output from a simulation unit. [16] Multi-paradigm modelling deals with three orthogonal directions of research: multi-formalism modelling, model abstraction and meta-modelling. [17]

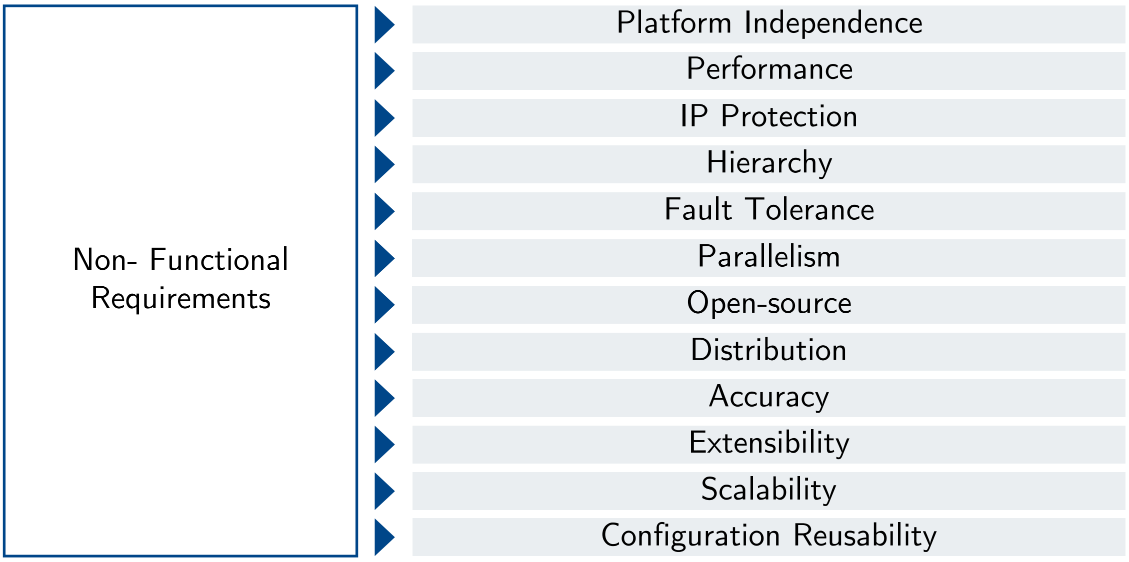
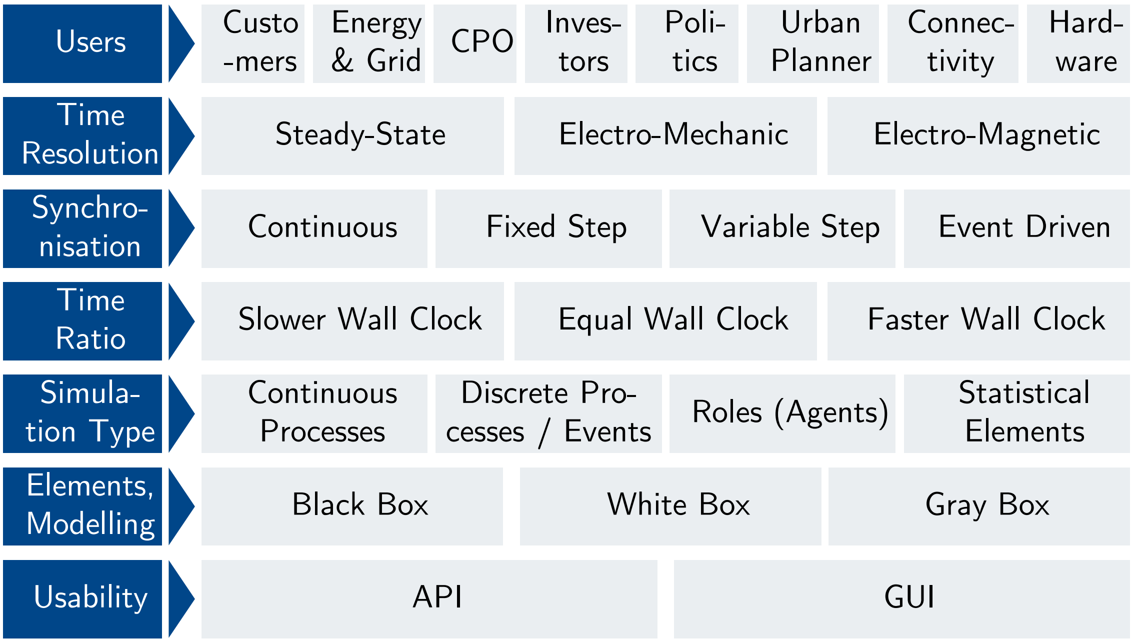


Figure 4: Classification of co-simulation according to [11]

In [17] the terms and their concepts are summarized as developed in [18], [19]. Real world entities show a wide range of behaviour depending on the context and aspects to be investigated. The base model is an abstract representation of an object's properties including its behaviour and aims to describe all object's facets. The system is a real world object that contains specific aspects of its behaviour. The Experimental Frame (EF) defines the system boundaries for experiments to be conducted. A model is defined as an abstract representation of a system for a prior-described EF. Experimentation can be regarded as an own system. Simulation is defined as a model in a certain formalism computing dynamic input and output behaviour which can either be symbolic or numerical. The abstraction level of models can be varied by degree of detailing or by different formalisms for description. Verification means the process to check the consistency of a simulation program and validation is the process of comparing experiment measurements with simulation results. [17], [20]

The term dynamical system is defined as a model of a real system which is characterized by a state and a notion of evolution rules. Simulation unit is defined as the composition of a simulator with a dynamical system and serves as a replacement of the real system. Multiple simulation units can be then coupled via their inputs and outputs. Thereby, a coupled system is reached which is called co-simulation. For the coordination an orchestrator is required which is called master algorithm within the FMI standard. [11] Agent-based modelling is established for (microscopic) modelling of traffic demand and flow. Each participant is characterized by a set of attributes, e. g. mobility options and home location. The system dynamics results from the accumulation and interaction of the individual behaviours. In parallel, a high resolution in time, space and behaviour can be studied. [21]



Users	Custo-mers	Energy & Grid	CPO	Inves-tors	Poli-tics	Urban Planner	Connec-tivity	Hard-ware
Time Resolution	Steady-State	Electro-Mechanic	Electro-Magnetic					
Synchro-nisation	Continuous	Fixed Step	Variable Step	Event Driven				
Time Ratio	Slower Wall Clock	Equal Wall Clock	Faster Wall Clock					
Simula-tion Type	Continuous Processes	Discrete Pro-cesses / Events	Roles (Agents)	Statistical Elements				
Elements, Modelling	Black Box	White Box	Gray Box					
Usability	API	GUI						

Figure 5: Morphological box for co-simulation in the context of connected mobility- and energy-systems

Discrete Event (DE) simulation is characterized by reactivity and transiency. The former summarizes the instant reaction to external stimuli and the latter the multiple states' changeability per time step. DE simulation units do not necessarily provide outputs at each time step if no event has occurred. DE co-simulation units comprise exclusively DE simulation units. [11]

Continuous Time (CT) simulation units have a state which advances continuously over time. Conclusively, a CT co-simulation consists of simulation units and orchestrators that all follow the CT approach. The micro-step size is the individual internally-used time between two steps in the model. The communication step size, also named as macro-step size, describes the time between the exchange of values of the simulation units in a co-simulation unit. The macro-step size is set for all simulation units within a co-simulation unit. [11]

Hybrid co-simulation describes the mixture of DE and CT simulation units. In [11] no formal definition for hybrid co-simulation scenarios is made, but there are regarded as a mix of characteristics and assumption of both, DE and CT, co-simulation scenarios. For coupling DE and CT simulation units, two approaches are pursued. First, the hybrid DE approach which wraps the CT units as DE simulation units and thus, orchestrates by a DE based approach. Second, the opposite by wrapping the DE units to become a CT unit and use a CT based orchestrator. [11] For the use case in this work a hybrid CT approach is chosen.

For orchestration algorithms, the Gauss-Seidel and the Jacobi approach are introduced. First, the Gauss-Seidel approach bases on the computation of the next interval of each simulation unit. Afterwards, they are asked to produce outputs which are then fed into the other units, before the next interval is computed. In contrast, in the Jacobi approach, the simulation units compute each interval in parallel and set their inputs at the end of the co-simulation step. [10] Adapters are used in co-simulation to overcome the gap between a specific simulation tool and a master algorithm in the absence of a standardized interface. [22]

3.1.2. Challenges and Ongoing Research

The identified challenges are clustered into four categories: Design Space Exploration (DSE), (XiL) co-simulation, Incremental Testing/Certification (IT/C), and Education. DSE requires a high level of simulation results' reliability as the results are usually assessed by non-experts. XiL describes a co-simulation with not incorporating exclusively simulation units, but either human operators, animation requirements, or physical subsystems. IT/C summarizes the application of co-simulation in the context of concurrent engineering activities with the refactoring of subsystems and frequent integration. Future research is derived concerning the formal guarantee of accuracy of simulation units' behaviour. Moreover, this individual prove shall be then extended on the co-simulation unit level. Education helps to exploit the theoretical potential of the methodology, e. g. by demonstrating the IP protection. [9]

Standards and common requirements for hybrid co-simulation are still pending. The work presented in [23] approaches this research gap and provides guidance for hybrid co-simulation with the FMI standard. More concrete, principles and formal notations are provided for test components. Additionally, a minimal set of test components and a set of test cases are provided. Thereby, a set of capabilities for hybrid co-simulation is provided, instead of a standard that defines requirements. [23]

A major challenge that arises in CT co-simulation units is the consistent initialization of simulators. The initial conditions are part of each individual simulation unit, but need to be set consistently in all simulators. The FMI standard includes a particular mode to identify a consistent initial state of all simulation units. [11]

Current research projects addressing co-simulation besides others comprise Advanced Co-Simulation Methods for Real-Time Applications (ACoRTA), Advanced Co-simulation Open System ARchitecture (ACOSAR), Design Support and Tooling for Embedded Control Software (DESTECS), and Integrated Tool chain for Model-Based Design for Cyber-Physical Systems (INTO-CPS) [11].

The project ACOSAR aims for a standardized integration of Real-Time (RT) and non-RT systems in parallel while pursuing a master-slave approach. The transfer of knowledge shall be enabled from the concept phase via Model-in-the-Loop (MiL) and SiL up to HiL application. On the other hand, the FMI standard only addresses the simulation model integration. [24]

Current challenges for co-simulation are two-fold: First, coupling of multiple entities and second, performance compared to monolithic systems. The work in this thesis concentrates on the former. Strong coupling describes the approach that the equations and algorithms of different models are integrated into a monolith. This is limited to applications where the models' content is revealed and accessible. In contrast, weak-coupling is defined as separate models being coupled via information exchange with inputs and outputs that are exchanged as specified communication points. Co-simulation systems belong to the latter category of weak-coupled systems. A master algorithm is the algorithm that determines the exchange of information, the ordering of information and contains further information about the simulation run itself. Consequently, separate dynamic systems are named as slaves. Co-simulation can be also referred to as modular simulation or simulation of weakly-coupled systems. Extensive work has been conducted in the field of co-simulation stability and error estimation. [25]

Difficulties in judging the validity of a co-simulation is regarded as one of the major current challenges related to co-simulation. The highest need for further research is seen in hybrid co-simulation. Further research need beside other is seen in simulator black boxing and IP protection, as well as usability and performance. [26]

Current opportunities comprise a growing community, better communication between the numerical part, implementation and industry as well as user-friendly tools. The threats include improper use due to a lack of information, a lack of cooperation between numerical part, implementation and industry and the incompatibility of different standards and co-simulation approaches. [15]

A finding of the taxonomy is the focus on the coupling between two simulation units from two different domains. Arose challenges from the taxonomy comprise semantic adaptation, modular coupling, stability and accuracy as well as standardization for hybrid co-simulation. A research gap is identified for modular, stable and accurate coupling of simulators in scenarios with dynamic structure. As standard interfaces have been developed in the past, the current focus on development in the field of co-simulation lies in the industrialization by tackling the issues of IP protection, XiL, and general scaling. [11]

3.1.3. Usage of Co-Simulation Systems

Co-simulation is used in the context of smart grid also for the validation of components, such as distributed controls in the form of SiL or HiL applications [27]. The work in [28] addresses the challenges of complete vehicle simulation by co-simulation and proposes numerical advances and a model library.

Cyber-Physical Systems (CPS) often comprise DE as well as CT components which result in a hybrid co-simulation. Hybrid co-simulation has only limited support by FMI. The proposed solution adds a global time resolution for the simulation system and can handle disparities between the time resolutions of co-simulated FMUs. The solution is implemented in a wrapper that can be added to existing master algorithms. [29]

The work in [30] contributes to flexible co-simulation frameworks by proposing a software architecture based on the entity-component-system. An entity is defined by its traits which can be changed during simulation. Thereby, flexibility within the simulation system is reached and state and behaviour can be separated. The System Structure and Parameterization (SSP) standard is used to define the characteristics of the example for application. [30]

The work in [31] addresses co-simulation research needs in the field of CPS, holistic prognosis and system planning. Thereby, co-simulation shall be enhanced in terms of framework usability, collaboration with stakeholders and support for decision makers. [31] Co-simulation is also used as a technique to set up a digital twin [32]. The digital twin based on co-simulation can be used for decision-making support, system optimisation as well as predictive maintenance applied to the context of manufacturing. An approach is introduced which wraps each participating simulation model into an agent. Subsequently, the co-simulation is set up by an agent-based communication of the so-wrapped models. [33] In this context, the co-simulation serves as a utility function of an optimisation process. Thereby, a cycle is created: Scenarios are used to initialize the co-simulation, its results serve as inputs for an optimiser. Based on the optimisation, new scenarios are created. [12]

3.2. Systems Engineering and Standards

Product development becomes faster and more complex in parallel, while handling requirements in ecology, safety and legislation. Therefore, interdisciplinary (virtual) development is required to reach well-integrated solutions in contrast to add-on developments. Therefore, an iterative process with early-integration is proposed. [5] The shortened time-to-market also applies for complex CPS as a combination of hardware and software. In parallel, the demand for effective strategic decision making increases. With regard to sustainability and circular economy, those CPS need a circular management throughout their life cycle. [34]

Virtual engineering requires automatized workflows for simulation model derivation and parametrisation. Addressed problems comprise the information reuse, communication within the development team, data provision in (semi-)automated processes and support within the development process. [35]

The ISO 15288 provides guidance for systems and software engineering over life time in form of a process framework adopting a systems engineering approach. Systems engineering is defined as the transdisciplinary and integrative approach over the lifetime of engineered systems for all stakeholders and their needs. The scope covers the range from idea conception to the system's retirement. A system is defined as an arrangement of parts or elements that result in a stated behaviour. A system of systems is a set of systems that interact and thereby provide a unique capability compared to stand-alone single systems. The system life cycle comprises the stages of concept, development, production, utilisation, support and retirement. The co-simulation at hand supports the decision management process in the context of charging infrastructure. This process according to the norm aims to objectively identify, characterize and evaluate a set of alternatives for a decision. The configuration management process comprises the establishing and maintaining of consistency, integrity, traceability, and control. [6]

Parametrisation of a system of software components is an issue that is also discussed in the context of cyber-physical production systems. A consistent parametrisation of the software components and their adoption to new circumstances and cases of application is required. [36] In [37] the integration of field data into simulation-centred decision-making is regarded as crucial. A hierarchy for knowledge, information and data is proposed to structure the multiple data sources. [37] The study in [8] discusses the use case of digital twins in smart cities. Prerequisite is the availability of measurable attributes. Patterns can be understood and predictions can be conducted. Thereby, new applications are enabled. [8]

In [38] a structural analysis and its decomposition is done as a starting point for the smart grid system analysis. Thus, interfaces and interoperability are understood. [38] The Smart Grid Architecture Model (SGAM) has three dimensions: Interoperability layers, domains and zones.

The layers comprise business, function, information, communication and the component layer with each representing a view on smart grids [39], [40]. An architectural modelling framework with three steps is derived: Business analysis with the output high level use cases, functional analysis with the output functional model, architecture development with the output architectural model. [39]

GAIA-X works as a project towards data sovereignty and secure data exchange. It contributes to an ecosystem approach and aims to facilitate the collaboration of stakeholders in digital space. [41] The project Catena-X is closely interlinked with GAIA-X and pursues the idea of an open data specifically for the automotive industry and also facilitates the collaboration across companies [42]. In the following the related standards to co-simulation in the context of systems engineering are introduced.

FMI

The FMI standard provides a standardized interface for simulation models and a standard to export them as a container in the form of a Functional Mock-up Unit (FMU) [43]. The Extensible Markup Language (XML)-file of a FMU provides model-related metadata which comprises the size of the dynamic system, the variables, parameters, constants and inputs. [44] FMI was originally developed for the coupling of continuous systems, but also allows to simulate hybrid systems. [11]

FMI was developed in the project MODELISAR with a focus on improving the design of systems and of embedded software in vehicles. Consistent initialization is addressed from a mathematical point of view as the need to solve a system of algebraic terms. [44] The slave-specific XML-file "modelDescription.xml" provides also all information that is required for communication in the co-simulation environment. The definition of the capability flags, such as "canHandleVariableCommunicationStepSize" is an important part of the FMI implementation. [45] The flexible adoption of models and their reuse in different simulation scenarios is addressed in [46] for co-simulation with usage of FMI.

The interaction between FMUs can be either realised as so-called "model exchange" with the master algorithm in charge for numerical integration methods and on the other hand, "co-simulation". In the latter, the FMU incorporates the solver. [23] An extension to the FMI standard is presented in [47] to ensure a deterministic co-simulation. The results presented in [26] show that FMI is regarded as the most accepted standard for CT and hybrid co-simulation and is used for those applications by more than 90% of the respondents.

System Structure and Parameterization-Standard

The SSP standard extends the FMI standard. It provides a tool-independent format for the description, packaging and exchange of a network of component models. Its content comprise the included models with their signal flow, parametrisation and the ZIP-based packaging format for the entire simulation system. For each model the parametrisation is included and dependencies of parameters between different components can be considered. The SSP standard accounts for tool independence, simplicity and reusability and is designed for the following five use cases: First, the design of a simulation structure, second the provision of a template for interfaces and parametrisation, third as a central parametrisation description, fourth for the provision of particular instances of ready-to-simulate simulation systems and finally for the reuse of elements during the development process. The SSP standard includes automatic unit-transformations and name-mapping. [48], [49]

High-Level Architecture

The High-Level Architecture (HLA) provides a structure for the reuse of capabilities from multiple simulations to finally reduce costs and time in the process. HLA separates the functionalities that are required for individual simulations from those that are related to infrastructure. [50]

The basic definition of the HLA comprises the HLA rules, the HLA interface specification and the HLA Object Model Template. HLA was developed for U. S. Department of Defense. For time management, the following three approaches are provided for the federates according to [50]:

- Paced, independent time advance
- Paced, coordinated time advances
- Unpaced, coordinated time advances

HLA is a standard that provides an architecture that accounts for reuse and interoperation of simulations and is designed application-independent. Federation is a combinable set of interacting simulations. A federate is a single simulation that can be a computer simulation or e. g. a manned simulator. Object representations are part of the federates which contain particular capabilities for interaction between objects. The data exchange is enabled by services within the Runtime Infrastructure (RTI). The RTI also comprises federation management support functions. As the third functional artefact, the runtime interface provides the specification for the interaction of the RTI with the federates. Furthermore, it provides structural basis for simulation interoperability between federates and RTI. [51]

Thereby, the following architecture definition ”major functional elements, interfaces, and design rules, pertaining as feasible to all simulation applications, and providing a common framework within which specific system architectures can be defined” is derived. The RTI comprises the functions for federation, object, time, declaration, ownership and data distribution management. HLA offers the essential minimum for interoperability, the simulation themselves have to account for additional consistency. [51]

A system’s model can be later used for maintenance of the system. A dynamic system is defined as a model of a real system which is characterized by a state and a notion of evolution rules. Hybrid co-simulation cannot be formally defined. The FMI standard is developed for CT co-simulation whereas the HLA standard was developed for DE co-simulation. Therefore, both standards have limitations for hybrid co-simulation. [16], [11]

	FMI	HLA
Scenario	Federation	Co-Simulation
Simulation Unit	Federate	FMU
Orchestrator	Run Time Infrastructure	Master Algorithm

Table 1: Comparison of FMI and HLA by [10]

The work in [52] investigates hybrid co-simulation using HLA and FMI. The main challenges include time and data synchronisation between continuous and discrete models. Therefore, the time control for the continuous model is moved to the simulation wrapper, so that the simulation progress in time can be executed centrally. [52]

3.3. Ontology Matching

In this section the fundamentals for ontology matching are introduced starting with the introduction of the concept and relevant classes of ontologies. In the following the methodology of ontology matching and belonging fundamentals of machine learning are elaborated.

3.3.1. Ontologies

There are four types of ontologies: First, information ontologies are used by human, e. g. to cluster ideas in the development process of a project. Therefore, visual language e. g. in form of diagrams or other structured associations is used. Second, linguistic or terminological ontologies concentrate on terms and their relations to each other. Dictionaries are an exemplary category for this kind of ontology; additionally the Resource Description Framework (RDF) is a further representative for this branch which is a language to illustrate concepts, terminologies and information in web.

Third, software ontologies are used in software development projects and comprise, beyond others, schemata for data bases and data transformation to ensure data consistency. The modelling language Unified Modeling Language (UML) is often used here. Finally, the type of formal ontology is introduced. It uses formal logics to describe rules for concepts and relations, the most popular language is Web Ontology Language (OWL), which is also further used in this work.

An ontology is defined as an explicit specification of a conceptualization. The set of objects and their relationships are condensed in representational vocabulary which again represents knowledge. Ontologies comprise classes, relations, functions and other objects as human-readable text. [53] An ontology in the context of computing science can be summarized as the representation of the reality for a context or a domain. Therefore, the existing knowledge for a domain must be structured, relevant terms identified and set into relation with each other. Additional information can be integrated as attributes.

Semantic interoperability between heterogeneous systems is a challenge to be overcome. For co-simulation, the use of ontologies is proposed as part of a framework in which the connection between subsystems is realised by a multi-agent-approach. The term scenario is defined as a simulation scenario because a user finally aims to compare the results of several scenarios. [54] Ontologies support the different stakeholders in the context of co-simulation for smart grid scenarios, as they integrate domain knowledge and structures the process of co-simulation. The use of existing ontologies allows the reuse of term definitions and vocabulary. [55]

As the term ontology is wide, the term domain ontology is used within this work to describe an ontology which aims to comprehensively describe the terminology and its relations to each other for a specific field of interest.

This representation consists of different types of artefacts that represent the type of entities for a domain (concept) as well as the dependencies and connections between the concepts (relation). On the other hand, an ontology in general can also mean the knowledge representation of a model. An ontology is regarded as more formal regarding its abstract syntax than an UML representation [56]. The here-used ontology is formulated in OWL [57]. A comprehensive smart mobility ontology is still pending [58].

3.3.2. Ontology Matching

The task of matching between the models and the developed domain ontology is comparable to the matching of two decent ontologies, also called ontology alignment. That task is tackled by NLP in the work of [59] using Bidirectional Encoder Representations from Transformers (BERT). A similar approach is pursued in this work.

Ontology matching identifies correspondences between semantically related entities of ontologies. A harmonic mean of the precision and recall (F1-score) between 40 and 80% is regarded as good enough for particular application of ontology matching. The assessment of ontology matching results by the user at the end of the process can be seen as state of the art. [60] To combine or connect two ontologies with each other, the technique of ontology matching applies. Ontology matching is here defined as the process in which the interdependencies between the entities of two ontologies are identified. Thereby, the following four goals are pursued:

- Interoperability between different ontologies
- Detailed and more comprehensive information by knowledge sharing
- Flexible access to information
- Building a comprehensive global ontology for multiple purposes

For the process of ontology matching four types of heterogeneity have to be overcome. Syntactic heterogeneity describes differences due to different languages and diverging formal logics. A feasible solution is the translation of the ontologies into a common language and the identification of equivalents. Second, terminological heterogeneity appears if different terms are used while using the same semantic. Third, pragmatic heterogeneity deals with the different interpretation of the same term by different persons. Finally, conceptual heterogeneity describes several forms of ontology on the identical topic, either for its span, degree of abstraction or perspective.

There are several techniques and methods to connect or match heterogeneous ontologies. The majority of them bases on conservative methods of lexical or structure-based techniques, but do not account for semantic and context-sensitive differences [61].

The neglect of contextual differentiation arises the problem of hynonyms and different languages or different expressions within a language. For the ontology matching three types of information is available: lexical, structural and semantic information. This categorization is equivalent to the general techniques described above in Subsection 3.3.1. The semantic information processing is state of the art and shows the highest potential for ontology matching [62]. Within the semantic information processing the gaps between entities can be either closed by use of external resources or by NLP from which the latter is pursued in this work.

For ontology matching, two approaches are differentiated. First, techniques on the structure level consider the entities and their relations to each other whereas the element-wise techniques only base on the former. The structure-base techniques comprise four subcategories. First, the graph-based and taxonomy-based approach both base on the representation of the ontology as a graph. With the graph-based approach, the similarity of the ontologies is determined as the overlapping pair of nodes and their related position. For the taxonomy-based approach only the particular relation between classes are considered with the super and the sub classes of one's class.

Third, the model-based technique assumes entities to be similar based on their same interpretation. Thereby, the semantic interpretation behind the ontologies' elements is analysed. Finally, the instance-based technique considers the instances of each class. Similarity is concluded from similar instances of different classes.

The second major category of ontology matching comprises the element-wise techniques. First, the string-based technique takes the entity's name and description as a sequence of characters. The similarity is then determined by comparing the similarities of sequences of different entities. Second, the language-based approach takes the entities' name and description and analyses in particular their meaning. This matching technique bases on NLP. Third, the constraint-based technique considers the boundary conditions of the entities, e. g. data type, value range and attributes. Finally, the informal and formal resource-based technique is introduced. Both categories take external resources to which the entities are compared in terms of similarity. Thereby, the informative gap between entities is overcome. The techniques differ in terms of the external resource's structure with the former being unstructured and the latter using formal external resources such as data bases.

The inconvenience of a small vocabulary of external resources such as WordNET in the application for domain-specific ontologies can be overcome by NLP. In [63] the high precision of word embeddings for ontology matching is outlined. By extension of the model for domain-specific word vectors an improvement of the matching quality is intended.

3.3.3. Machine Learning

Machine learning can be clustered into supervised and unsupervised learning. Both categories share the principle that feature variables (x-variables) are used for training. The training data for the supervised learning does contain target-variables (y-variables) in addition to x-variables. During the training process, the relation between several x- and a y-variable is learnt. After the training process, the algorithm shall predict a target value (y-variable) for an incoming x-variable. Unsupervised methods aim to identify similar expressions of a x-variable and thereby obtain clusters. This method is often applied in the context of text processing for the thematic cluster of documents and texts. [64]

Having introduced the two principles of machine learning, the learning of neural networks is elaborated. Central components here comprise the optimisation of weights, a belonging loss function and an optimisation algorithm. The weights' optimisation is conducted iteratively throughout the training. The loss function's formulation is highly adaptable and represents the dependency between the actual and the estimated target value. The optimisation of weights is realised by help of the backpropagation method, followed by the gradient descent method. During that procedure, the aim is to reach the tale of the defined loss function.

Conclusively, the optimisation algorithm has the goal to drive the weights of the neural networks steadily towards the minimum of the loss function. The weights are optimised iteratively after each batch (set of training data per iteration). NLP can be applied to a variety of problems related to handling and analysis of human language. The range of problems comprises text processing, text completion and evaluation of text similarities beside others. NLP is at the intersection of machine learning and linguistic analysis which is further elaborated in the following.

Word embeddings are defined as numerical representation of words in a vector space. The method aims to project the meaning of words and their relation with each other into a vector space. E. g. each word is represented as 30 continuous variables with each variable describing a grammatical or semantic characteristic. Thereby, for each word a specific position in the vector space is derived. By analysing the distance between words in this vector space the similarity to each other is determined. [64] A text corpus is taken to train a word embedding model. The model learns the relation between words and their surrounding words. The initial training to obtain a word embedding model requires enormous data and computing power, therefore an existing model is usually applied. A major shortcoming of word embeddings is the static representation of words in context-independent vectors. Therefore, the word embedding model cannot differentiate between the contexts a word is used in. This limits the interpretation of sequences of words and sentences which can be overcome by transformers.

The transformer model was developed in 2017 by Vaswani et al. [65]. The core characteristic of a transformer is the so-called attention which incorporates the relation between words of the same sentence.

For the application of transformers, pre-trained models are applied usually due to the same reasons as above for word embeddings. For the application, the model selection and application as well as the specific further training of the models dominate nowadays. The architecture of a transformer consists of an encoder and a decoder and bases on the self-attention principle. The self-attention principle allows to determine the words' meanings but without any information about their sequence of appearing.

The encoder receives an input sequence consisting of sentence fragments, so-called token which can be either words or sub words. By the help of embedding layers these tokens are vectorized. Subsequently, the positional encoding is added to the individual token. In addition to the self-attention mechanism, an add-and-norm layer accounts for the training and optimisation ability of parallel self-attention mechanisms. The output of one encoder is normalized and serves as an input for the following encoder. The result of the entire encoder operation is the representation of single tokens and the entire input sequence. In contrast to word embeddings, the encoder returns context-sensitive representations of tokens.

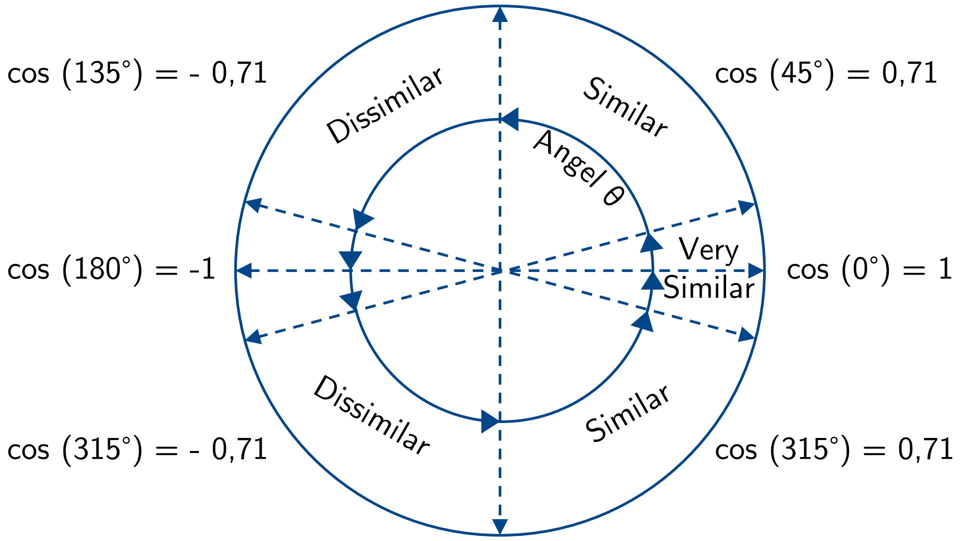


Figure 6: Interpretation of cosine-similarity in semantic vector space

The focus of the decoder is on the return of the sequence. Similar to the encoder, the token is embedded and the position is encoded. After the add and norm layer, it follows the subsequent decoder block which includes the output of the last decoder block and the output from the encoder as the representations of the input sequence. By the encoder's output and the predicted output sequence, the decoder predicts the following word.

The BERT model enables the context-sensitive and dynamic embedding of words, but does not account for the representation of individual sentences. Therefore, the model was further developed to add the functionality of semantic similarity evaluation of entire sentences which resulted in the model Sentence Bidirectional Encoder Representations from Transformers (SBERT). By use of the cosine-similarity, the similarity of sentence embeddings can be determined. With a and b representing the vectors of the considered text, i describing the index of a sentence and n expressing the amount of sentences to be analysed the formula (1) results for the similarity angle θ. The interpretation of the cosine(cos)-similarity is summarized in Figure 6.

$$\cos(\theta) = \frac{a \cdot b}{\parallel a \parallel \parallel b \parallel} = \frac{\sum_{i=1}^{n} a_i \cdot b_i}{\sqrt{\sum_{i=1}^{n}(a_i)^2} \cdot \sqrt{\sum_{i=1}^{n}(b_i)^2}} \tag{1}$$

In [66] the principal characteristics of context-sensitive and insensitive methods are summarized. Context-sensitive methods consider the syntactic characteristics of a sentence which allow their effective application on sentence-level. On the other side, context-independent embeddings are most effective on word-level because of the consideration of the morphosyntactic characteristics.

3.4. Charging Infrastructure for Electric Mobility

For an efficient charging infrastructure development, the ramp-up of a comprehensive fast charging network is crucial. The acceptance of the offered charging infrastructure depends on its number, location, pricing and further rules of utilisation. Complexity in usage shall be reduced whenever possible. The investments shall be supported by public grant instead of adjusting the revenues of the charging procedures. The distribution of charging points is conducted with regard to spacial coverage, travel axes and demand nucleus in urban areas. [67] Further approaches to charge replenishment comprise mobile plug-in charger and mobile battery-swapping station [68]. Such systems are studied, but are not practically applied or planned in Germany currently. Globally analysed, the sales of EVs have doubled in 2021 compared to 2020 and the positive trend continues. The expansion of charging infrastructure, supported by public grant, remains important. [69]

Electric Mobility and the Mobility Ecosystem

Electric mobility shall be an integrated part of a new mobility ecosystem that accounts for decarbonization, liveability and practicability in parallel. Electric mobility comprise electric private and commercial cars, communal vehicles as well as micro mobility offers such as E-bikes. The coupling with multiple interests from different stakeholder groups is stressed, e. g. energy providers, transportation companies and the municipalities themselves. [70] Electric mobility is a system good as its offer requires the offer of multiple complementary goods [71] and that affects the Original Equipment Manufacturer (OEMs), the energy sector, the EVs themselves, traffic system, municipalities and the charging infrastructure itself [72].

In [73] a study investigates the interdependency of fuel availability and the demand for alternative-fuel vehicles in general. Since the publication of the findings in 2012, electric mobility has evolved, even if critical points such as availability of charging infrastructure, range and price are still discussed nowadays. Smart charging has been studied for over ten years now [74]. The authors of the work in [75] argue that public charging infrastructure is mainly needed in densely populated areas.

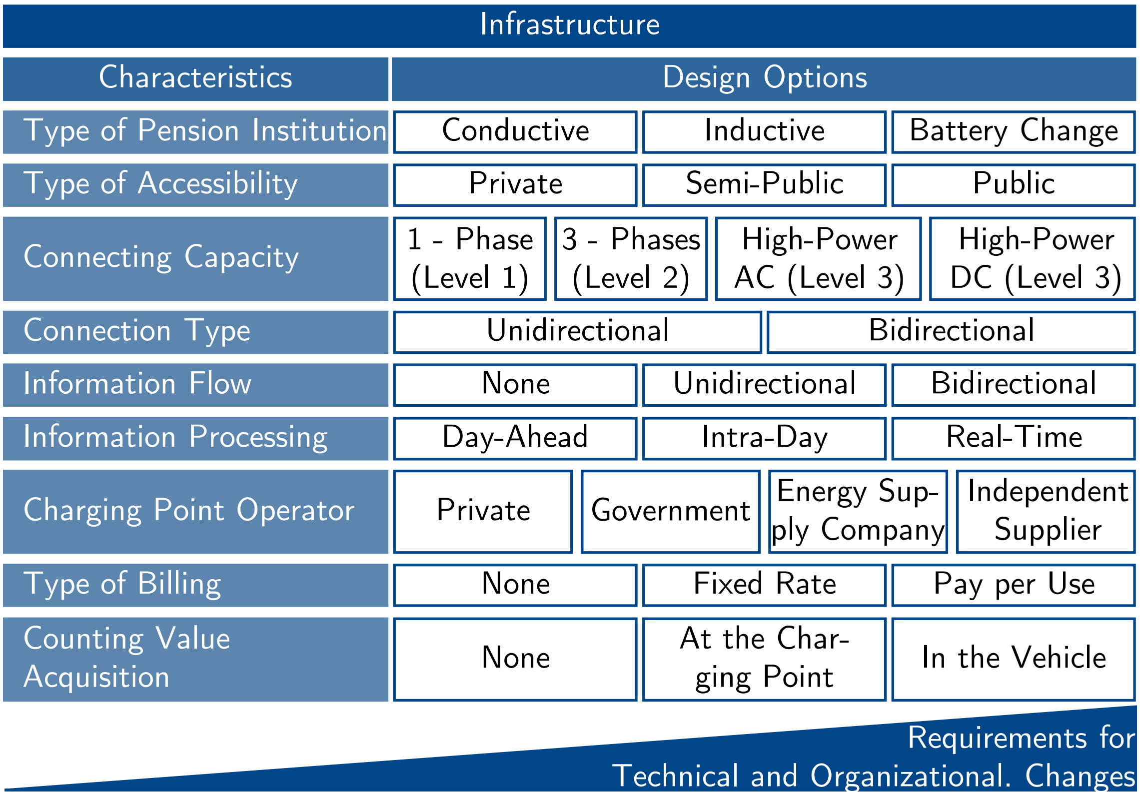
The study in [76] analysed the influence of public charging infrastructure on the EV market penetration for the US and concluded that Direct Current (DC) charging points have a particular impact, even one replaces 10 Alternating Current (AC) points. Moreover, the price for public charging is also important, resulting in a strong limit for allocation of required investments to charging infrastructure. The analysed dimensions of impact comprise the BEV sales, increase national electrified mileage and lower Greenhouse Gas (GHG) emissions. [76]

The location and dimensioning of car sharing stations is a comparable multi-criteria optimisation problem to public charging infrastructure planning. The profitability of car sharing highly depends on the stations' demand level [77].

In [78] the transition to electric mobility is analysed from a innovation and social transition perspective and it is concluded that the momentum was relatively low to the point of the study. Moreover, the development of new functionalities in the context of electric mobility is regarded as crucial. [78]

3.4.1. Classification of Charging Infrastructure

Charging locations are classified into public (accessible and public ground), semi-public (public accessible and private ground) and private (limited access and private ground) [71]. An overview about charging infrastructure is given by the morphological box in 7.



Infrastructure

Characteristics	Design Options			
Type of Pension Institution	Conductive	Inductive	Battery Change	
Type of Accessibility	Private	Semi-Public	Public	
Connecting Capacity	1 - Phase (Level 1)	3 - Phases (Level 2)	High-Power AC (Level 3)	High-Power DC (Level 3)
Connection Type	Unidirectional	Bidirectional		
Information Flow	None	Unidirectional	Bidirectional	
Information Processing	Day-Ahead	Intra-Day	Real-Time	
Charging Point Operator	Private	Government	Energy Supply Company	Independent Supplier
Type of Billing	None	Fixed Rate	Pay per Use	
Counting Value Acquisition	None	At the Charging Point	In the Vehicle	

Figure 7: Morphological overview based on [79]

In [80], the Charging Use Cases (LUC) are classified into seven categories: First, the private LUCs: LUC 1 describes charging at a family house, 2 at a multi-party house and 3 at the employer. The public LUCs are clustered into fast charging inner-city (LUC 4) and at traffic axes (LUC 5) and on the other side, occasional charging at customer parking lots (LUC 6) and roadside charging (LUC 7). [81] In the following it is referred to these LUCs.

Charging Infrastructure (CI) can be also clustered into basic, fuel station, and add-on charging infrastructure. The interdependencies related to sector coupling are stressed. Municipalities have a high impact on the charging infrastructure, even when they do not act as operator, by provision of public space. Public grant might help to reach the political goals related to charging infrastructure availability. [82] Its mapping to private and public is illustrated in Figure 8.

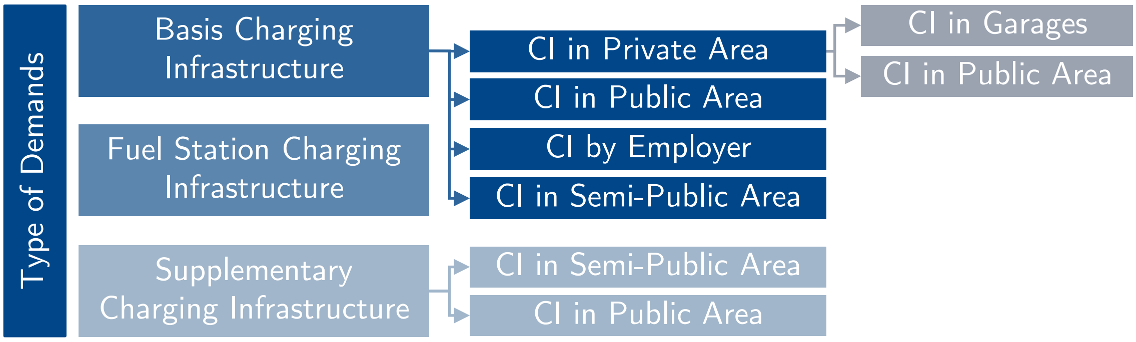


Figure 8: Classification of charging infrastructure according to [83]

In [84] energy supply for BEVs is classified into four categories: DC charging, AC charging, inductive charging and battery swapping. Charging procedures are classified into private, semi-private (parking lots of companies), semi-public (e. g. access for customers) and public (e. g. roadside). [84] Charging technology can be clustered into conductive (regularly tethered), inductive (contact-less), and battery swapping [85], [86]. Inductive charging is under investigation, but currently not part of concrete planning or practical implementation due to the lack of economic feasibility [87].

A lack of charging infrastructure is a major obstacle for the market penetration of electric mobility. The demand for charging infrastructure is classified into daily and long distance traffic. The realistic range of BEVs compared to their nominal range is approximately 10% lower. Also they conducted a stakeholder analysis. The international expectations regarding the share of private charging infrastructure highly differs: Whereas California expects a high share, Japan expects a relatively low share. Fast charging infrastructure was seen as a facilitator for long-distance driving by EV and therefore, took a corridor approach. With a higher market penetration inner-city fast chargers gained more importance. [88]

Fast charging at travel axes is evaluated in separated research projects such as in [89]. Charging at home or nearby is highly important independent on the living situation. Further highly-desired locations for charging comprise employers, fast charging hubs and public parking lots. Roadside charging is rated lower but has to be overall analysed together with charging at home for users without a private parking lot. [90]

3.4.2. Planning of Charging Infrastructure

Research related to planning and location of charging infrastructure is intensively conducted since 2012 according to [91]. The research is classified in the categories of content orientation, structure focus and content result. For content orientation, the classes of user, route and destination are proposed. For the structure focus, modelling theory in the direction of synthetic data and empirical application with data from case study region are separated from each other. Finally, the content result is clustered into demand density, partitioning and network optimisation. [91]

In [86] charging infrastructure planning is conducted twofold: First by decision support by assessing scenarios and second by prioritization in a given set of candidate locations. [86] In this work, the former way is pursued. Concerns regarding the ramp-up of charging infrastructure comprise under-capacity and over-capacity in parallel. Reliable predictions shall incorporate the differences between several user types with top-down modelling lacking the required precision. [92] A multi-period infrastructure-planning framework is required according to [93].

In [94] (from April 2020) is stated that the ramp-up of charging infrastructure has to incorporate the interdependencies between different charging options, in a sense that "each Kilowatt-Hour (kWh) is only charged once". Considered perspectives have to be demand orientation, economic feasibility and interdependencies between different charging and power variants. The prognosis is to possibly reach rentability from 2025 on. Taking the assumption of 10.5M EVs, a German-wide prognosis of 40K DC and 130K AC charging point is given as a bottom line. In the highest prognosis, the demand for charging points is 950k in Germany with 40% public charging and 90% AC charging points. [94]

The German government prognoses up to 14.8M BEVs and Plug-in Hybrid Electric Vehicles (PHEVs) for 2030 in Germany. The share of private charging is estimated between 76 and 88% with 61% of private parking lots being equipped for charging. The number of charging points at roadside and public parking lots is estimated to 420K. The total number of public accessible charging infrastructure is estimated between 440K and 843K. [81]

The study in [95] investigates the required charging infrastructure in Germany for 2050 with a 100% share of EVs in private traffic. The study reveals a need for approximately 40 million charging points and related investments of 80B to 110B €. Based on 2018's numbers, private charging points are approximated with around 2K €, public AC chargers with approximately 8K € and DC chargers with 38K €. [95]

The study in [96] prognoses between 10M and 38M private charging points by 2050, 0.5M to 2M public AC charging points and 0.05M to 0.2M DC (fast) charging points. The exact number within the range depends on the share between BEVs and Fuel Cell Electric Vehicles (FCEVs) according to the study.

The costs are approximated with 1.65K€ for a private charging point, 7.5K € for AC charging point, 52.5K € for public 50 Kilowatt (kW) DC charger and 160K€ for a DC charger with 150 kW and more. [96]

Whereas traditional methods to determine the charging point need are based on the number of EVs, the study in [97] introduces more detailed metrics. The incorporated factors comprise the housing type, the spatial coverage, policy adoption, and private infrastructure support. [97] The planning of public charging infrastructure needs to consider strongly the available private infrastructure. Regarding the grid, the additional charging load may be handled by charging time management. [98]

The choice of frequented locations for charging points serves the user experience as well as the economical feasibility of charging infrastructure. Restrictions for location may appear due to scarcity of places and technical feasibility, in particular the access to the low or medium voltage network depending on the type of charging point. The work points out the broad range of assessment factors and their interdependencies related to charging infrastructure. Moreover, the importance of a user-centric planning is stressed. [99]

The work in [100] presents an approach for allocating charging points by prescriptive analytics with a focus on public-sector organizations. The study in [101] deals with the planning of a fast charging network and proposes a two-stage solution. The work closely analyses the interdependency with the grid to ensure voltage stability. [101]

In [102] the question of charging infrastructure planning is addressed by combining the perspectives of the residential distribution grid, the EV's travelling costs for recharging and the investment and variable costs of fast charging infrastructure. [102]

In [103], the stakeholders related to electric mobility are identified and a suitable framework for a service-oriented infrastructure including new application systems is proposed to account for the required secure information exchange. It is based on state-of-the-art open standards and includes aspects of the smart grid. [103]

Political Framework

Climate neutrality is the goal of the European Union (EU) for 2050 [104] with the road traffic being responsible for 26% of all Carbon Dioxide (CO_2) emissions in the EU in 2019 compared to 15% in 1990 [105]. The share of the mobility sector of final energy consumption in Germany is above the European average with around 30%. Although the specific energy consumption has decreased by 10% since 2005, the final energy consumption has increased due to the increased amount of traffic. Therefore, the electrification of the car fleet has priority. [106] The update of the federal law for climate protection from 2021 sharpens the GHG emission reduction by 2030 to 65% instead of 55% and by 2040 by 88%, all compared to 1990. For 2045 a net zero is approached and for 2050 even negative GHG emissions. [107]

The EU set a regulation framework in 2014 to develop infrastructure for alternative fuels in Europe, including charging infrastructure for EVs, which shall be then specifically implemented by the individual nations [108].

The main political statement for public charging infrastructure in Germany is the "Masterplan Ladeinfrastruktur" which has been released in its second issue in 2022. It sets the user perspective, meaning the drivers of EVs (person and utility), in focus. Moreover, the sector-coupling between electric mobility and electrical grid is stressed. In the original "Masterplan" of the German government from 2019, the goal of 1M public-accessible charging points by 2030 is defined with public grant until 2025. Furthermore, the foundation of a national coordination centre is set. Additionally, regulatory is developed for equipping new buildings' parking lots with charging infrastructure. For private charging points, wallboxes are subsided. [109] The federal net agency provides an overview about the public accessible chargers in Germany [110].

The goal of 1M electrified vehicles in Germany in 2020 has been reached in mid 2021. The "Deutschlandnetz" shall be a fast charging net with 1K locations and the aim of a nearby fast charging point by the end of 2023. [111] The aim of public charging infrastructure is to enable the full replacement of internal combustion cars by electric cars. Therefore, a spatial resolution approach is pursued. [112]

Policy changed from a EV-share-based charging point planning to more sophisticated methods incorporating further criteria for a charge point and thereby, assigning specific values to charge point types. For this approach it is evaluated how much energy a charge point can provide to the EV fleet and if the charge point is publicly available. According to the study 1.3M public charge points are needed EU-wide in 2025 and approximately 3M in 2030 respectively. The invest is approximated with 1.8B € in 2025 which is 3% of the EU's annual budget in road transport infrastructure. [113]

To support the demand-oriented ramp-up of charging infrastructure, German public authority has developed the tool "StandortTool" which supports investors' decisions for concrete locations. Public grant is provided for public as well as private charging infrastructure. [114]. The "StandortTool" incorporates data from OpenStreetMap (OSM), Regional Statistical Area Typology (RegioStar), Mobility in Germany (MiD) and further public as well as private data sources [115]. Moreover, the market penetration of electric mobility is supported by law providing privileges e. g. related to public parking, until 2026 [116].

Technical Aspects

Harmonization on a technical as well as terminological level is required in the field of charging infrastructure according to [117]. The International Organization for Standardization (ISO) 15118-20 defines the standards for bidirectional charging and has been released in 2022 [118]. The Open Charge Point Protocol (OCPP) specifies a common back-end protocol with the aim of reducing and securing overall investment costs related to charging infrastructure.

International Electrotechnical Commission (IEC) 61850 addresses the integration of electronic devices into the energy distribution process. Where as OCPP focuses on the business domain of CPOs, the IEC 61850 deals with grid automation and a technical focus. [119]

Regarding payment options, the contact-less on-site payment by credit or debit card has been defined as mandatory for new charging points from 2023 on. This measure aims to facilitate the use of public chargers without smartphones and across countries in Europe. [120]

3.4.3. Stakeholder Groups

In [121] six potential conflicts between stakeholder interests have been revealed: the split of responsibilities within public charging infrastructure, the placement of charging points, the paths to influence the charging behaviour, the importance of fast-charging (AC vs. DC), required standardization effort for charging equipment and supportive policies for EVs. In terms of stakeholders, the following seven groups are identified: National as well as local government, car manufacturers, electricity producers as well as electricity grid operators, oil companies and dedicated infrastructure providers. [121]

Stakeholder groups beside others include the EV drivers, distribution system operators, municipalities and electricity providers. For location planning the macro (regional scope) and the micro (e. g. grid accessibility) perspective are distinct. [86] The interaction between stakeholders is classified into advise, enable/regulate and facilitate. The considered stakeholders include CPOs, policy makers and grid operators. [122]

Stakeholders related to charging infrastructure are clustered into power, legitimacy and urgency. Concrete stakeholders, beside others, comprise the energy suppliers, CPOs, users and politics. [123] In [124] the KPIs for charging infrastructure are derived from a stakeholder analysis. The analysed stakeholders comprise municipalities, EV users, residents without EV, CPOs and grid operators. The goals are sustainability in a cost-effective way, stimulation of electric mobility, optimised utilisation of CI, facilitation of a positive business case and safeguard grid quality. [124] Also the economic feasibility is discussed in [83].

User behaviour

According to [125] cars are taken as major mobility option for 57% of the ways and 75% of the persons kilometres in Germany. The share of availability of a private parking lot is significantly higher for EVs compared to German average. The driven mileage with electric cars is slightly lower (approximately 10%) compared to the average. The ramp-up of electric mobility has been at the beginning at the point of this study. [125]

The study in [126] concludes that psychological factors of EV drivers and their impact on economics of public charging infrastructure are not well studied yet. Moreover, government policies are important but its tailoring to maximize the effectiveness must be further studied. In particular, the technology development of public charging infrastructure and batteries must be closely considered for the economics and ramp-up of public charging infrastructure. [126]

The study in [127] investigates the importance of public charging infrastructure in Germany for the market penetration of EVs. Due to range anxiety its importance is existent, although only approximately 10% of the overall charged energy is charged at public charging points. [127] These findings highlight the importance of a feasible and economical ramp-up of the public charging infrastructure. The study in [128] concludes that price parity between BEVs and comparable conventional vehicles will be soon reached for different market segments. For luxury BEVs the price parity is estimated in 2023, for mid class in 2026 and for small cars before 2030. [128]

The usage of charging infrastructure highly depends on the locations of the charging points which influences the economic feasibility again. The study incorporates data from transport networks and traffic volumes, settlement structures, vehicle characteristics, power supply and user requirements and covers methodological-wise whole Germany. [129] EV drivers prefer charging at home. A network of fast chargers is crucial for the success of EVs as they prevent long charging durations. [130]

Range anxiety has a strong impact on BEVs' utility which is significantly reduced by public charging infrastructure. Additionally, the increase of charging power at home does not add utility, whereas charging opportunities at workplace offer important benefits for a selection of users. [131] The motivation of lowering range anxiety in mentioned in [132], [101] and [133].

The choice of taking the data from MiD is also conducted in [134] to approximate the user behaviour of electric mobility. A new version of the MiD is currently on its way. The survey is planned for 2023 to account for the new normal in mobility. The methodology is comparable to the version of 2017 with only minor changes. [135]

Charging infrastructure and the electrical grid

In [136] the positive and negative impacts of EV grid integration are summarized. The negative impacts comprise the load demand increase, potential component overloading, phase and voltage unbalance, power loss and stability issues beside others. On the other side, the power management and power quality can be improved. Furthermore, regulation tasks can be simplified and the renewable energy support can be enhanced. [136] An overview about the structure of the electrical grid in Germany in provided in Figure 9.

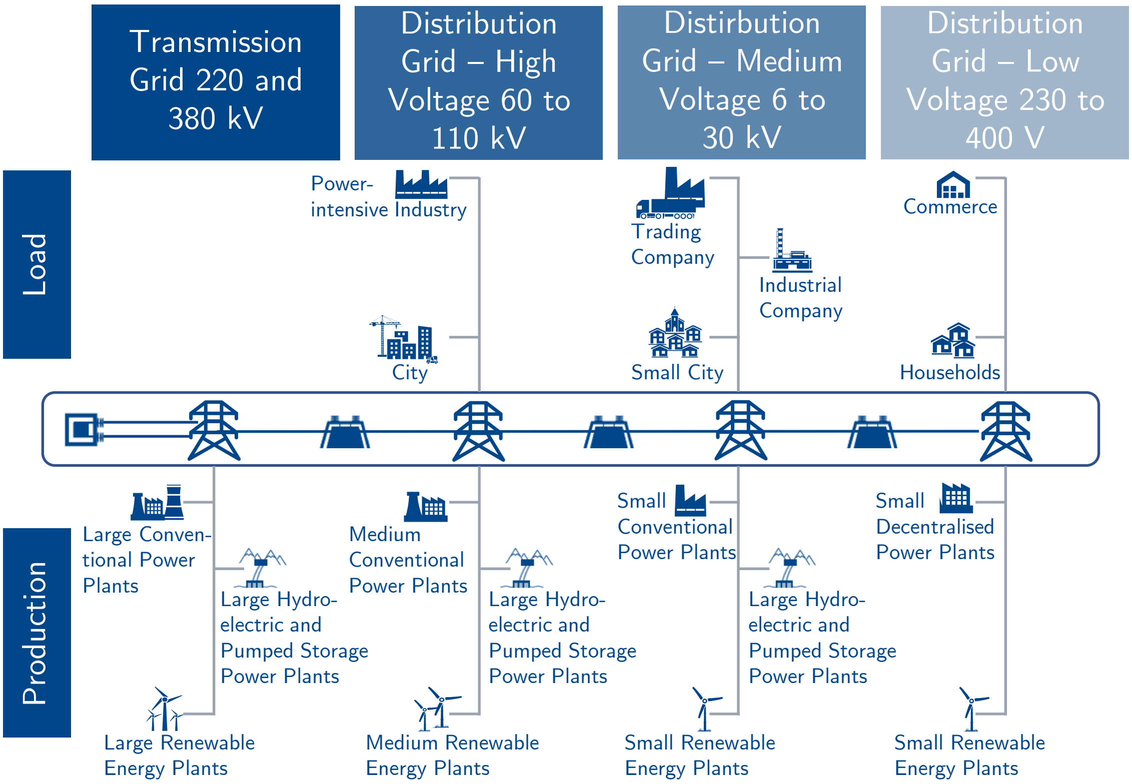


Figure 9: Classification of grid voltage levels according [137]

The impact of charging infrastructure operation on the distribution grid is studied in [138] for the early stage of EVs' market penetration. In [139] the peak loads from uncoordinated charging of EVs have been addressed by proposing a scheduling method based on a charging urgency indicator with the aim to minimize the peak-valley load difference.

The study in [140] investigates the sector coupling between EV charging and its impact on the grid. It is assumed that the energy consumption of a BEV depends linearly on the travelled distance. A parameter variation is conducted with the result that an increasing number of charging stations and energy storages with an increased capacity have a positive impact on the grid-related objectives. [140] The possibility to steer charging stations is regarded as crucial to remain the grid stability. Charging infrastructure shall account for grid stability, e. g. by providing reactive power and by control of the power consumption. [141]

A joint simulation of transportation systems, power systems, and vehicle technology is proposed in [142]. The analysis reveals the high expected impact of electric mobility on the power sector as the load curves and utilisation rates of network assets are significantly changed. To overcome these challenges, a communication infrastructure and the use of algorithms is proposed. [142]

The balance of power demand and supply must be constantly ensured as it guarantees a constant power frequency and thereby a stable quality of supply. The increased share of decentral energy supply by renewable energy is a major driver for the undergoing change in the energy sector. The European energy system was formerly a hierarchical and central structure. [143] In low voltage grids, the voltage level is regarded as a particular challenge to be solved. Battery storage is an costly option compared to on-load tap-changer or, with restrictions, demand side management. [144] A combination of different types of charging stations in terms of charge power leads to an overall more economical charging infrastructure [145].

The choice of the connection power shall incorporate the number and type of vehicles at the specific location, their charging power, average time of parking, the charging behaviour of the owners and the load management. A reduction of the required connection power can be reached by adding a stationary battery storage on-site. Grid operators offer a discount (§14a German Energy Sector Law (EnWG)) for controllable sinks. [146] The work in [147] investigates how stationary batteries can improve the profitability of fast charging stations. As a crucial success factor the battery price is identified and the use case is more profitable at inner-city locations compared to highway locations. A battery is assumed to save grid connection costs of 75K €. [147]

The principles of Vehicle-to-Grid (V2G) applications are presented in [148]. The underlying fundament is the provision of power by the EV to the grid while the EV is parked. The three prerequisites to be fulfilled are a grid connection, a communication and control with the grid operator and vehicle-on-board control. Providing baseload power by V2G is economically not feasible, but peak power is under certain circumstances. The most meaningful usage of V2G is to provide spinning reserves. Spinning reserves are defined as an additional source of power that is already synchronised with the grid. This state can be automatically achieved if an EV is connected to the grid (plugged in) assuming the required communication and controls. [148]

A V2G approach is pursued to fulfil multiple objectives: minimization of peak demand, variance of load profile, battery degradation costs and charging/discharging costs [149]. Nonetheless, bidirectional charging is only grid-serving if a sufficient amount of EVs participate [71]. Network charge has a high impact on the costs for installation as well as operation of charging infrastructure. The power price varies by factor 12 within Germany according to [150] and its impact in particular for DC charging is high. [151]

3.5. Design Space Exploration and Decision Support

In this subsection the fundamentals of DSE and decision support are summarized. Starting with the description of scenarios as a fundamental to describe the scope under analysis comprehensively, the field of DSE and decision support is summarized with its interlinkage and application in the field of charging infrastructure planning. The basic distinction is visualized in Figure 10.

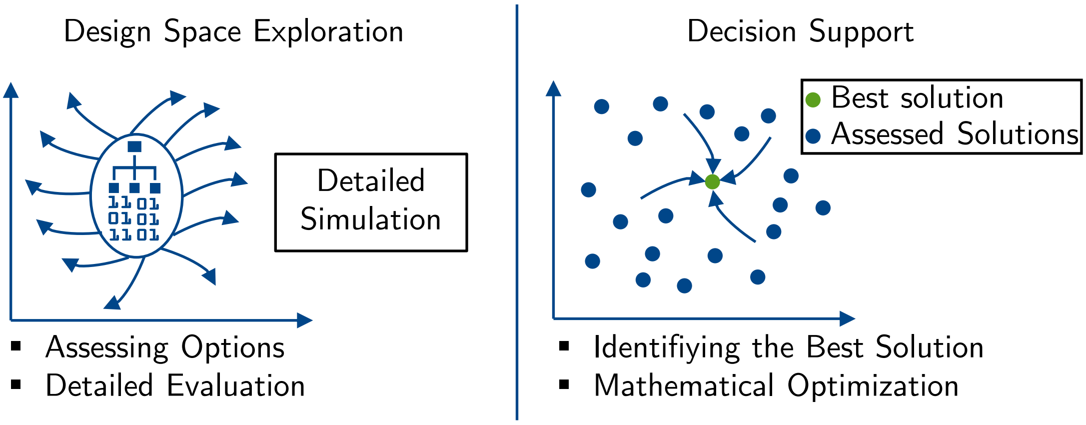


Figure 10: Comparison between design space exploration and decision support

3.5.1. Scenario Description

Scenarios are defined as sets of parameters which are varied between different simulation runs [12]. A scenario shall be plausible, coherent and consistent. Scenario-based decision support is recommended to challenge decision makers' perception of future developments. It lacks the combination of systematic scenario construction and evaluation of alternatives. [152] The approach in [153] analyses scenarios in four dimensions: The content of a scenario, its purpose for which it is used, the form of expression and the life cycle how a scenario is manipulated. The classification regarding abstraction is part of the scenario's content. The content can either be concrete, abstract or a mix of both. [153]

In [154] a scenario is defined as a collection of assumptions for different impact factors and a set of basic parameters. It comprises a complete description of all relevant artefacts which are required to start the subsequent processes of, in that case, optimising water infrastructure. [154]

The representation of scenarios can be conducted manifold: First, a scenario can be represented by raw information such as video recordings or second as free format data, e. g. free form text. Moreover, scenario can be represented structurally e. g. by the help of structural text or semi-formal syntax with some semantics, e. g. pseudo code.

Finally, scenarios can be represented by formal languages with well-defined semantics, e. g. state charts. [155] Exogenous variables are defined as external variables to the process under consideration. These variables come from outside of the system under consideration. Decisions are rather a series of decisions than a single decision with current decisions constrain future decisions. Beside the correct order, the right moment in real time is also of high importance to obtain correct decisions. [156]

In the context of automated driving, scenario-based testing is performed to assess the system's or function's validity. This leads to the need to derive concrete parameter combinations for test cases based on abstract linguistic descriptions. The proposed five-level scenario description treats layers as different aspects of a scenario, e. g. environmental conditions, rather than defining multiple levels of abstraction. Regarding the level of abstraction, a process is roughly described without defining the details of the conducted transitions. [157] In [158] the term scenario description for the context of smart grids is defined as the definition of the system's scope and the level of detail of the participating entities. In [159] scenario technique is connected to usage in co-simulation in the context of renewable energy resources. The scenarios are developed and evaluated within a co-simulation. A domain ontology provides the terminology standardization whose attributes are instantiated for the evaluation scenarios. [159]

The knowledge-based life-cycle approach to scenario management in [160] includes top-down and bottom-up processes. A basic scenario is defined as a complex situation analogous to a data-driven instantiated model. A scenario can be broken down into a combination of data, model and solver. A scenario structure is defined as a template object integrating models, solvers, visualizations, contained scenarios and related data. An aggregate scenario includes multiple scenarios with a top-level scenario broken down to low level scenarios. With the term scenario planning the decomposition of the top-level scenario into suitable scenarios for development, simulation, analysis and evaluation is meant. In decision making, each scenario spans a range of circumstances which have a significant impact on the issue under study. A breakdown of classes and components including their programmatic interaction is provided, but content-wise traceability is not addressed. [160]

For the trend impact analysis the user identifies the impacting factors and assesses their probability of occurrence and their strength of impact. By the help of trend extrapolation future events are incorporated. It is designed for one key decision or forecast variable which is quantitative and for which historic information is available. Scenarios can be validated in direction of the following criteria: plausibility, consistency/coherence, creativity/novelty, relevance/pertinence, importance, transparency and completeness/correctness. [161]

The MOSAIK framework enables the reuse of simulation models in the context of smart grids. The framework consists of six layers in descending order: control, composition, scenario, semantic, syntactic and a technical layer. For parameter sets, a distinction is made between a simulator parameter set and a model parameter set. [162]

Whereas the former includes a number of non redundant simulator parameter values and multiple subordinate model parameter sets, the model parameter sets include the model parameters and their specific values for the model. [162]

OpenScenario is designed as a low-level and concrete specification format for scenarios in the context of simulation-based testing of autonomous driving systems. The implementation is conducted in XML and three levels of abstraction are developed which are of particular interest here including the transition between these layers. A functional scenario is a possible representation of an abstract scenario. An abstract scenario is characterized by the traffic participants under investigation and the sequence of the scenario. It follows the level of logical scenario with introducing the range of parameters. For a concrete scenario, the parameters are specified to concrete values each from the value range which was defined by the abstract scenario. Each step of concretisation of scenarios must be within the span that is defined by the level above. The standard provides a semantic framework with standardized names and corresponding units in form of an ontology. Additionally, a description in prose is provided. A meta-model by UML is provided, in which the artefacts are related to each other mainly by composition and inheritance. [163]

3.5.2. Design Space Exploration

DSE comprises the issues of evaluating a single design point and covering the design space during exploration processes. The DSE has to be conducted under consideration of trade-offs between evaluation accuracy, required time to evaluate a design point, the precision of the design space coverage and the possibility for automating the exploration process. [164]

The terms of problem space and solution space have to be differentiated: The former is described by the natural characteristics and properties of the design space. The solution space is given by the objectives of DSE. Simulation is defined as a model's execution of the system under evaluation making usage of a defined set of stimuli. On a higher level of abstraction, system-level simulation takes place. [164]

Optimisation methods can be classified according to the timely sequence of search and decision making: First, decision making before search. The objectives are determined and aggregated e. g. in a cost function or a set of constraints. Second, search before decision making: This procedure starts with the search for optimal solutions in multiple dimensions. The objectives are not aggregated and the procedure results in a set of Pareto-optimal solutions. As the found solutions are not problem-specific, they can serve multiple decisions. Finally, decision making during search as a mix form of two above-presented approaches. It also starts with search steps which are followed by defining further constraints. Iterative repetition may follow.

Regarding objectives it can be distinct between primary and secondary objectives. Primary objectives are usually directly optimised while secondary objectives either focus on specific properties or provide supportive information. Combined metrics synthesize multiple objectives to account for conflicting criteria or to reduce the problem's dimension. [164]

Strategies for covering the design space: First, analysing every possible design point is an option which leads to an extensive but unbiased search process. Second, randomly sampling of the design space leads also to an unbiased search, but without full coverage of the design space. Third, the incorporation of knowledge of the design space into the search process, usually done by heuristics. Path-oriented search shows a dependency on previously evaluated designs whereas unguided search randomly assesses the defined design space. Further distinction is made concerning the timely process of the design space evaluation. Either a single design is evaluated at time or a set of possible designs. Assuming a (certain) independence of the design parameters, a sensitivity analysis of the design space can be conducted by the help of a reference benchmark. [164]

Multi-Criteria Decision Making (MCDM) aims to enable a systematic process to solve concurrent qualitative and quantitative multi-criteria problems from real world and to identify the best compromise alternatives under uncertainty. A sensitivity analysis of the outcoming candidates allows their assessment regarding robustness. Criteria sensitivity and resulting uncertainty highly correlate with each other. [165]

Multi-Criteria Decision Analysis (MCDA) is defined as a technique for comparison of a set of alternatives with regard to multiple objectives. In a sensitivity analysis in the context of MCDA the input parameters are varied to an initial result ex post. Thereby, the robustness of the analysis' outcome is tested, but no further scenarios are assessed. [152] In [166] the weights of different factors in multi-criteria decision models are evaluated. The variation of criteria weights within a sensitivity analysis reveals the robustness of the rankings and supports the selection of an alternative. [166] Diverse preferences lead on the one side to uncertainty regarding weighting of criteria, but criteria are also not necessarily quantifiable [167].

Charging infrastructure planning is currently more focused on the quantity than the quality of the available charging stations. The work concentrates on preference evaluation criteria to assess the operational efficiency and service quality of charging points. The performance assessment is considered as a MCDM problem. The assessed criteria comprise planning rationality, operational efficiency, service capability, charging safety and sustainable development. It is concluded that an increase of the share of fast-charging stations, a reduction of average waiting time and increasing the payment convenience are crucial points for the quality of charging experience. [168]

In [169] hierarchical clustering is performed to plan charging locations in urban areas. First, road information is quantified into data points and in the following, demand clusters are created by hierarchical clustering analysis. [169]

In [133] an user-centric allocation model is developed that incorporates quantitative as well as qualitative characteristics. It aims to provide decision support for governments and providers. [133] In [170] a charging network for urban taxis is studied and a decision support system for the charging stations' placement is set up. In [171] a sequential approach is pursued: First, EVs' consumption is evaluated by a model incorporating realistic driving data. Afterwards, the resulting energy needs are optimised by an integer linear optimisation program to allocate charging stations. [171] Therefore, this approach can be considered as a combination of the introduced DSE and the optimisation methodology as presented below.

3.5.3. Optimisation

MCDM can be solved either by outranking, selecting, weighting, fuzzy, or multi-objective [165]. The definition of the weight value or utility function for each criterion is challenging [172].

Evolutionary Algorithms (EAs) can be classified into three categories: First, evolutionary strategies are characterized by an adoptive optimisation strategy and the utilisation of continuous solution parameters. Genetic algorithms encode the solutions binary which makes them useful for combinatorial problems. Finally, the genetic programming aims to develop optimal strategies and programs rather than parameter optimisation. [173]

The Non-Dominated Sorting Genetic Algorithm II (NSGA-II) is a multi-objective EA and therefore belongs to the group of genetic algorithms. Pareto-optimal solutions are those in which an increase of one objective is not possible without the decrease of another. Therefore, Pareto-optimal solutions are the "best" solutions in multi-objective problems that could be identified. The crowding distance is measure of each solution's distance in each objective dimension to its nearest other solution and thereby expresses the diversity of a solution compared to other solutions.

The process of the NSGA-II is as follows: At first, a random parent population is instantiated. This population is sorted based on non-domination and each solution is classified according to its non-domination level. In the following, binary tournament selection, recombination and mutation operators are applied to generate further candidate solutions. Both generations together are analysed and the classification according to the non-domination level is again applied. For the final new population the selection is made as follows: The candidate solutions within the highest (multiple) non-domination levels in descending order are taken. If not all candidates from a non-domination level can be taken as the aimed population size is reached, the candidates are taken in the descending order of their crowding distance. The NSGA-II shows increased performance against comparable multi-objective EAs. [174] The application of the NSGA-II can be classified into three categories: conventional without any changes in the operators, modified application with changes in the operator and finally, hybrid variants in which the NSGA-II is combined with different techniques. [175]

In [176] a genetic algorithm is applied to the questions how many charging points are needed in a defined area and later, where to place them. The problem is formulated as a minimization of the deployment costs related to new charging stations while serving the customers demand. The work considers the influence of area traffic density, costs regarding the set up as well as related to operation, the charging station's capacity and the electric grid capability. The applied algorithm encodes the optimisation problem into a chromosome structure and subsequently, applies the population genetic operators of two-point crossover, Gaussian mutation, and permutation to avoid repeated affectations and recombination. [176] In [177] a mixed integer program is formulated and solved by a genetic algorithm. Each candidate solution is represented by a chromosome and fitness of each is measured by a cost objective value. Based on this measurement a natural selection is conducted followed by building of a new generation of candidate solutions. [177]

In [178] a multi-objective planning approach is proposed. With a given candidate construction plan of EV charging stations, the EV traffic flow, power losses and voltage deviations in the distribution system are considered. It is aimed to maximize the charging service ability, and minimize the total power loss as well as the voltage deviation in parallel. [178] In [179] an activity-based approach using a genetic algorithm is applied to identify optimal locations for public charging stations. The study in [180] also makes usage of a genetic algorithm with a model based on conventional driving data.

In [181] a multi-criteria approach towards electric mobility is presented. It is stressed that the stakeholders' interests and their weights relatively to each other have to be investigated systematically. As relevant factors for E-mobility-related decisions, the following have been identified: Ecological, economic, social, political, comfort, performance and other factors have been identified. These categories of factors are given actor-specific weightings.

Finally, the work stresses the importance of analysing the heterogeneous EV users in depth. [181] A Pareto optimal solution is searched in [182] for the two objectives in the following: The maximum number of reachable households and the minimum overall transportation energy consumption for charging actions. The study in [183] deals with the charging scheduling by multi-objective optimisation. The objectives comprise large-scale EV deployment, transport and grid systems. [183] A weighted multi-criteria approach is pursued which incorporates beside others, demographic, economic and available services (points of interests). [132]

In [184] the planning of charging stations in a distribution system is separated into two major steps. First, environmental factors and the EV drivers' convenience is considered. Second, a mathematical model is applied to minimize the total costs of the planned EV charging stations under consideration of grid aspects. [184] The study in [185] analyses the demand for charging infrastructure based on the EVs' market penetration.

Charging demands are clustered into slow, regular and urgent demand and an optimisation model is applied with the aim to minimize the annual integrated costs of investment and operation. [185]

The work in [186] uses an optimisation model for the placement of charging stations based on historical routes of EVs. The analysed key factors are investment and ease of use. As optimisation model an Mixed Integer Linear Programming (MILP) is applied. [186] The model presented in [187] aims to minimize the overall placement costs of charging stations under consideration of installation, maintenance and operation. A power system reliability check is conducted and user-related restrictions are incorporated. [187]

In [188] charging pads for inductive charging are incorporated beside charging stations. The optimisation problem maximizes the amount of refuelled energy. [188] In [189] a study optimises the use of fast charging points. It incorporates the EVs' battery size, the derivation of charging time distribution and the consumer waiting time beside others. The work in [190] proposes an mixed-integer mathematical model to optimise both, the location and number of EV charging stations, under consideration of customer's choices in competition. The study in [74] formulates a linear optimisation program to minimize the vehicle operator's total cost while meeting further constraints and applies a heuristic to solve it.

3.5.4. Modelling and Simulation for Decision Support

The work in [191] deals with planning of a fast charging network not from a central planner's perspective but in a competitive market. Modelling-wise a multi-agent optimisation framework is developed with the agents not necessarily cooperating with each other. [191] An agent-based study of EV driver behaviour has been e. g. conducted in [192] which also investigates home charging options.

In [193] the agent-based model is coupled with a planning model for charging infrastructure as the results of the planning model being investigated by the multi-agent simulation in terms of their feasibility. [193] An agent-based modelling framework with an evaluation scheme incorporating multiple stakeholders is proposed in [123]. For the operator, the period of amortization is minimized in the objective function. [123] An agent-based decision support towards public charging infrastructure is proposed in [194].

The work in [195] presents a co-simulation approach for charging infrastructure planning with a particular focus on the impact on the distribution network. The co-simulation is set up by multiple model and databases for which the individually required data transfer is realised via non-standardized Application Programming Interfaces (APIs). [195] The study in [196] sets up a co-simulation to investigate the smart grid on the low voltage level. A co-simulation approach towards flexible-demand EV charging management is presented in [197].

A co-simulation of an agent-based EV user model and a grid model (implemented in PowerFactory) is presented in [198]. It aims to evaluate the impact of EVs on the low voltage grid level in detail. The co-simulation is realised by a bridge interface between the two models. [198] The study in [199] makes usage of distributed simulation to investigate the impact of fast charging on the distribution grid. Whereas the latter is modelled in DIgSILENT, the fast charging stations with their usage are modelled in MATLAB. Data regarding the voltage and load profiles are exchanged. Although, it is not explicitly stated in the paper, it seems that a sequential simulation approach is pursued. [199]

The work in [200] applies a two-step process. First, the traffic flow is analysed to determine the capacity of charging stations based on queuing models. Afterwards, a cost-based model evaluates the economics of possible charging infrastructure plans. [200] For short-term availability of charging points, a space-time series model is developed [201]. The study in [202] investigates charging infrastructure planning for a smart city. It comprises a vehicle mobility model, an attraction model for the usage of charging stations and a subsequent deployment optimisation. [202] The study in [203] investigates the interaction of fast charging stations and the grid for random arrivals of EVs to support decisions regarding the charging stations' placement.

Within the study in [204] a planning model is developed at first which incorporates the region layout, mobility patterns, infrastructure layout and vehicle specification. It follows the simulation with different configurations and multiple runs which is then taken as input for scenario analysis for infrastructure assessment. The feedback loop is closed by optimising the planning model based on the scenario analysis. [204] The simulation assumes that the CPO has a customer interface which is independent of the customer's electricity provider when analysing public charging infrastructure. This is described as a separate customer interface in [71]. The work in [205] follows a user-centric approach to place charging infrastructure. Statistical analysis of real travel data is performed and optimisation is applied.

3.6. Related Work

Having introduced the state of the art within the associated research fields, the work conducted in this thesis is set in context of comparable research work. Therefore, selected literature is assessed regarding seven criteria which are introduced in the following. First, it is evaluated whether the work includes a Decision Support System (DSS). This can be either an explicit optimisation or another contribution to the field of decision-making, e. g. DSE. Second, it is evaluated whether the work deals with CI for EVs for which no distinction is made here between public and private CI. Moreover, the research is assessed regarding the incorporation of Mobility Behaviour (MB), e. g. as a simulation model or an impact factor. In analogy, the modelling of energy-related aspects or incorporation of an Energy Grid Model (EGM) is analysed.

Whereas the former introduced criteria are mainly related to the use case of planning public charging infrastructure, the following three belong to the research contribution in the field of simulation and system architecture. Therefore, the usage of Co-Simulation (CS) and of the here-utilised standard FMI are regarded. Finally, the research work is assessed for its contribution to the field of Flexible System Architecture (FSA), e. g. the exchangeability of simulation models or the applicability of the presented work in different domains. The assessment results for the considered research work are summarized in Figure 11 and further analysed thereafter.

	DSS	**CI**	**MB**	**EGM**	**CS**	**FMI**	**FSA**
Albagli et al. 2016 [206]				X	X		X
Bücs 2019 [211]					X	X	X
Hoerstebrock 2014 [193]	X	X	X	X			
Hölker 2018 [210]	X	X	X	X	X		
Li et al. 2022 [207]	X				X	X	X
Puch 2019 [212]	X		X		X		X
Schütte 2013 [215]		X	X	X	X		
Schwarz et al. 2019 [208]				X	X		X
Stanley et al. 2021 [2013]	X				X	X	X
Wang et al. 2013 [214]				X	X	X	
Wang 2022 [209]	X			X		X	X

Figure 11: Summary of related work

Addressing the field of developing smart grids, an ontology provides the semantics to ensure interoperability between the simulated models. The ontology itself is aimed to become standardized and share knowledge for a field of application. Regarding the ontology, concrete artefacts are introduced that represent solely electrical aspects and node models with the simulation models being implemented based on HLA. [206] With a strong focus on formalization, the work in [207] contributes to the interplay between digital entities based on unified ontology modelling. Thereby the integration of artefacts into a co-simulation environment shall be accelerated. The scope comprises the establishing of an executable co-simulation, its automatic executing as well as the analysis of results. The ontology forms the knowledge for the co-simulation which is first used for simulation execution and in the following as input to the knowledge base for the results' interpretation.

For the implementation, the FMI standard is used for the interfaces and the co-simulation is structured following the master-slave concept. Shortcomings are identified regarding suitable and widely accepted domain ontologies. [207]

The work presented in [208] also addresses the smart grid domain and deals with the challenges of large co-simulation systems and scenarios. The co-simulation components are structured in a catalogue clustered for the categories general, technical, mathematical and domain information with the latter being implemented as an ontology in OWL. Based on this structure, the simulation execution is planned. Thereby the work contributes to the structure derivation of required simulation runs. [208]

In his dissertation Wang presents a flexible co-simulation approach for planning urban energy systems and aiming for decision support to reduce energy demand. An architecture consisting of four layers is presented with a simulator, interconnection, interoperability and a control layer. On the simulator layer, the concrete simulation tools are integrated with the interconnection layer providing the communication functionalities. On the interoperability layer, the simulators orchestration is conducted by the master algorithm following the master-slave approach. Finally, on the control level, the simulation intentions and scenarios are defined based on expert-knowledge. Implementation-wise, the FMI standard with its functionalities is used as standardized interface, alongside with the MOSAIK co-simulation middleware as an orchestrator. With this approach the execution and interplay of simulation artefacts is structured, but a lack of structure is identified when it comes to the application of expert knowledge: On the control layer the expert knowledge is used to define scenarios and the scope of the simulation but no further structure is given. Regarding decision support, a sequence of five steps is presented: First, the overall system design with the architecture and simulator being defined. Second, the models' development in the individual modelling environments. It follows the co-simulation setup, in which the above-described four layers are applied. Finally the two steps of simulation and results analysis provide the actual decision support. [209]

Related to this field of application, the work of Hölker evaluates algorithms for distributed energy management as those gain importance in the context of decentralised power supply and demand. For the algorithms' analysis, a closed simulation environment is developed which enables co-simulation of supply and demand as well as the necessary communication. The system architecture is distributed for the energy management algorithms as well as individual components for supply and demand. Whereas those components seem not be foreseen for exchange and adoptions, the incorporated communication technologies and the grid model can be exchanged. [210]

The work in [193] aims to support the ramp-up of charging infrastructure for electric mobility. As the framework for event-based multi-agent-simulation JASIN is used in which the classes and functionalities for the different models, e. g. for mobility behaviour and traffic simulation, are implemented. Thereby a simulation composed by multiple models is set up in a closed environment. In analogy to the thesis at hand, Hörstebrock also uses the MiD data for modelling the mobility behaviour.

The exemplary application is conducted for Bremen and Oldenburg and aims to analyse user- as well as technology-related effects. [193]

The usage of co-simulation in the context of assisted and automated driving calls for similar approaches regarding system architecture and flexibility. In his dissertation, Bücs presents a consistent path through the development phases of Advanced Driver Assistance Systems (ADAS) from first software prototypes to the functions' validation. This contribution to model-based design tools incorporates co-simulation for evaluation and testing of algorithms as well as HiL artefacts. With the implementation based on simulation models as FMUs, the work deals with the reuse and refinement of artefacts during the development phase. [211] Second, Puch develops a method for the co-simulation usage in the context of driver assistance development incorporating MB in his dissertation. The co-simulation framework is embedded into techniques for statistical model checking to enable the simulation of rare events with a reduced number of simulation runs while maintaining the original probabilities. The methodology is inherently domain-independent and therefore accounts for FSA. Regarding Co-Simulation the work bases on the HLA standard as the FMI standard was not available yet, but the FMI-based co-simulation is marked as future work. [212]

Mobility and energy systems can be further abstracted as CPS or regarded as a subcategory respectively. The research presented in [213] deals with the embedding of a co-simulation system into a multi-objective optimisation framework. Therefore, the co-simulation based on FMUs builds the core to which a search algorithm for DSE is added. The application is conducted for a CPS of an unmanned platform with two different search algorithms from which is the NSGA-II is one. [213] A similar embedding of co-simulation in an optimisation is also pursued in this work.

The work presented in [214] deals with a modelling and co-simulation toolchain to support and design CPS. The approach bases on System Modeling Language (SysML) as a generic modelling language in the context of systems engineering.

The individual models are integrated as FMUs. The developed workflow starts with the model transformation step in which the different domain models are imported in SysML. It follows the system configuration step with the selection of the corresponding SysML blocks to set up the simulation environment. Finally, the configuration files and simulation scripts are generated automatically in the last step. Conclusively, this work focuses on the structured deviation from different domain models to an executable co-simulation by transforming model into a common environment. A major prerequisite is the availability of SysML representations for the domain-specific artefacts which limits the integrable tools beyond their compatibility with the FMI standard. This approach requires access and knowledge to the modelling and is therefore not applicable for black-box models to be integrated in an existing environment. [214]

A similar aim is pursued in [215] with further distinction on technical artefacts rather than the workflow. The corresponding framework is structured in six layers top-down as follows: control, composition, scenario, semantic, syntactic and finally the technical layer which deals with simulator processes. On the syntactic layer the interface for the simulator's integration is provided. The semantic layer focuses on exchanged simulation data and interoperability, therefore formal simulator descriptions are created based on simulator descriptions. On the scenario layer, the users' simulation intentions are formally captured. The composition layer deals with the concepts and methods for handling and executing the overall simulation. On the control level, the control mechanism for manipulating the state of the simulated entities are defined. Consequently, the approach structures the tasks and challenges into layers and provides belonging solutions, but shortcomings can be observed regarding the sequence of abstractions. The composition layer as well as the syntactic layer deal with implemented artefacts, the scenario model instance and the interface implementation respectively. In between, the scenario and the semantic layer handle meta models of the scenario and the semantic itself respectively. Moreover, aspects of decision support are neglected and marked as future work. [215]

The analysis of the related work reveals the research gap regarding comprehensive simulation system configuration that combines enhanced simulation methodologies with decision support systems in the context of mobility. Regarding co-simulation approaches, the FMI standard is used in a high share of related work or, as in [212] is named as an important standard in the field. Furthermore, the topic of flexibility within simulation approaches is discussed even beyond the field of co-simulation. In addition, special attention shall be paid to the levels of abstraction within the configuration steps related to system architecture and the derivation of simulation systems.

4. Use Case: Decision Support for Public Charging Infrastructure

The probably most demanding change in individual mobility is currently underway with the increasing market penetration of EVs. In contrast to prior mostly incremental developments of cars, the change of energy source requires not only adoptions within the vehicle, but also related to infrastructure. Due to the close interlinkage with the energy infrastructure as well as specifics for life style, e. g. driven distances or regional structures, charging infrastructure has to be analysed and planned relatively individually for nations and regions.

Also public grants, the local energy market and national regulations have a high impact on how charging infrastructure is feasible. Therefore, this work focuses on Germany and the specifics of the German market. Furthermore, the German government has set the goal of one million public charging points in 2030 and renewed this goal recently [109], [216]. As recent studies for Germany demonstrate [94], a suitable charging infrastructure is required from the demand side - the drivers of EVs. Additionally, other participating parties and stakeholders support this point [121].

4.1. Motivation and Aim

The general aim of the tool under development is a decision support tool for the development of future public charging infrastructure. A nucleus here is the technical consideration of sector-coupling, the economic feasibility as well as the users' demand and behaviour. In contrast to available solutions, the aim is to build a simulation system which is flexible and accounts for the integration of externally-developed models. Charging infrastructure is only one component of a city's ecosystem. Due to the closed integration and interaction with energy supply, the regional structure as well as further mobility-related projects in a municipality and the consideration of interdependencies are crucial points. Consequently, for a holistic view on the individual municipality, all those influences shall be considered even when deciding on a mobility aspect like charging infrastructure. To account for that flexibility, the decision support, in this case by a simulation tool, must allow the adoption of models as well as the integration of models from other sources or an additionally modelled aspect with a reasonable effort.

A further aspect is the integration of models that were developed in multiple environments and manners. Related to the aspect of sector-coupling, the use e. g. of specialized energy modelling environments shall be feasible. Available models e. g. from prior studies with a similar focus, e. g. analysing the mobility behaviour with focus on public transport, might also be integrated in the decision support for charging infrastructure.

Available solutions tend to focus on closed stand-alone solutions for decision-support in the given context, either by providing results from an internally-hosted tool or by providing a closed application to the user, e. g. as in [114].

The here-developed simulation framework accounts for the assessment of possible solutions at a certain point in time. To derive recommendations for actions, the solutions have to be compared in post-processing and a further optimisation algorithm is required. An example for a comparison is the consideration of bidirectional charging capability ceteris paribus. As the usage of bidirectional charging requires the connection of EVs to a charge point not only for charging but also for grid services and subsequent recharging, the degree of charging points' utilisation tends to increase. With the simulation system at hand, both options can be evaluated in different simulation runs, also with further varied parameters, e. g. the amount of planned charging stations. Thereby, the optimal solution can be not only derived for a specific scenario (e. g. without bidirectional charging), but also the (nearly-)optimal solutions for different scenarios (bidirectional charging vs. no bidirectional charging) can be compared and overlapping can be identified. The here-developed and used optimisation algorithm is described in Subsection 4.5.

4.2. Considered Models

The selection of models is done to demonstrate the feasibility of the methodology for multiple types of models and to gain a holistic perspective on charging infrastructure in parallel. Therefore, three models have been developed which are presented in detail in the following subsections. They cover together economical, behavioural and physical aspects related to charging infrastructure. Thereby, the interdependencies between these diverse aspects can be taken into account for the aimed decision support.

The idea behind the models is twofold: First, to build a demonstrator which enables the analysis of the scope under interest, in particular the interdependencies. Second, the model development including their integration allowed the practical analysis of required functionalities as well as the exploration of the feasible degree of automatization in the given context. Finally, the set of scenarios is introduced which aims to cover the foreseeable range of parameter values for electric mobility. Therefore, the term scenario is used here as a set of parameter describing a foreseeable future situation.

4.2.1. Electric Vehicle Drivers

The model bases on the work which is described in the master thesis of Robin Schmidtke. [217] The EV-driver-model aims to cover the perspective of the current as well as the potential users of charging infrastructure. As the scope for the tool is Germany, the mobility data from MiD study is used [218].

The data contains a sum of one million ways conducted by 316K persons in Germany and can be regarded as representative for the daily mobility in Germany. The data subset "B1" has been used for modelling, as it contains the highest resolution of socio-demographic and economic data of the households.

From that data, only the mobility ways conducted by passenger cars are taken into account for the modelling. Further clearance for artificial data left a data base of 380K ways for the model's development. To account for regional specifics, this data has been divided following the classification of RegioStaR7, a definition by the German Federal Ministry for Digital and Transport for region types. The corresponding region types are summarized in Figure 12.

As the latest available data at the time of the model development has been collected in 2017, there is no distinction made between fuel types for the vehicles. Consequently, in the current model version it is assumed that the mobility behaviour is independent from the fuel type and does not change over time. This decision is made due to the high uncertainty and lack of predictability from the status quo. Therefore, the use of possibly non-representative data is avoided.

Room Type According to RegioStaR 7	
City Region	**Rural Region**
Metropole	Central City
Regiopole and Big City	Regiopole and Big City
Middle Town, Urban Space	Small Town, Village Area
Small Town, Village Area	

Figure 12: Region types used for data classification based on [219]

Two further classifications of the data are made: First, between weekday mobility (Monday to Friday) and weekend mobility (Saturday and Sunday), and second, regarding the vehicle segment: Ways with small cars are separated from those driven with medium and upper class cars. Thereby, different mobility behaviour dependent on days and the type of cars in use are considered. To sum up, the overall data set is clustered for regional types, vehicle segments and weekdays to have a suitable data base for the model. For each way the following characteristics are taken into account for the modelling as summarized in Figure 13. Details for the assignment of destination to charging use cases can be found in [217].

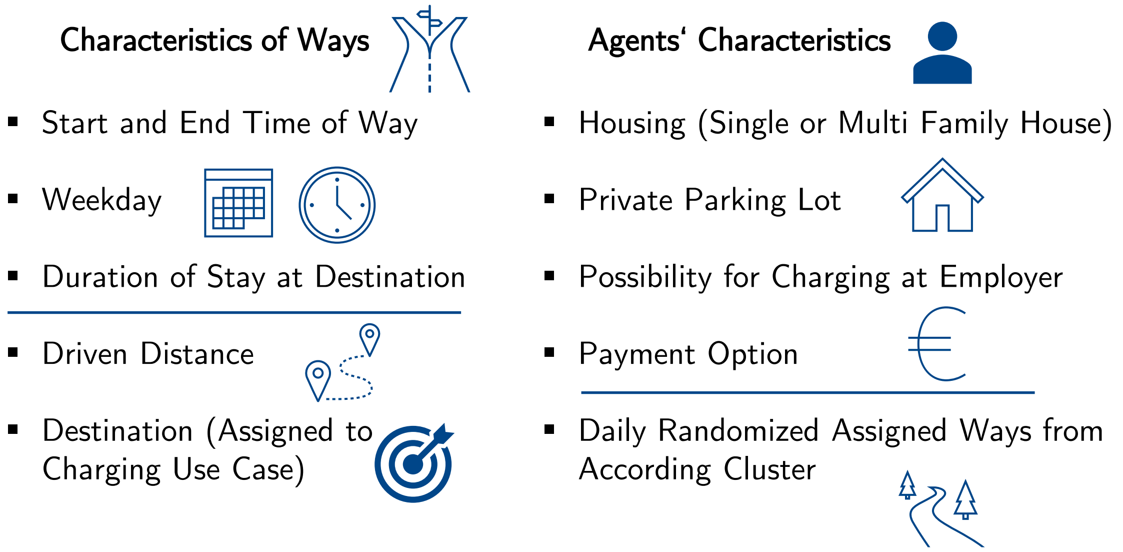


Figure 13: Details on ways and agents in EV driver model

The model itself is agent-based which means that individual persons are simulated with their mobility behaviour and charging demands. The aggregation of the individual behaviour builds the actual model characteristics. The agent's characteristics are summarized in Figure 13. The assignment of cars and the chosen payment option is done based on a combination of rules and randomized assignment. Charging options AC and DC charging is made available for the agents depending on the charging use case according to the classification by National Organization Hydrogen and Fuel Cell Technology (NOW) [80]. From those, the LUCs 1-3, 4 and 7 are modelled with the 4 (charging hubs inner-city) as the only LUC with DC charging. The rest of the modelled charging use cases is associated with AC charging.

The model's procedure starts with the daily simulation of the agents' mobility behaviour based on the MiD data. Each agent represents a specific EV of a household. Therefore, the ways of the households are incorporated and the destinations of the ways are mapped to the charging use cases. The State of Charge (SOC) decrease is modelled based on the EV's average consumption. Based on the SOC after a way or the predicted SOC after the following way, a charge desire is set. Depending on the charging use case and the vehicle's characteristics, a desire for the charge power is set. Depending on the agent's availability of charging at home and at work, a price model is chosen. The agents require external feedback whether their charging desire can be fulfilled (charge permission) and which charging power is available for the upcoming 15 minutes (released charging power). Furthermore the model is prepared to receive the daily costs because of charging at public charging points and adopt the chosen price model at run time. Furthermore, the loaded energy of each agent is calculated in 15 minutes steps and the blocked time at public charging stations is accumulated.

Blocked time means the time, an agent spends at a public charging point between reaching a SOC of 100% and departing for its next way. Finally, the share between the desired energy to be loaded and the actual loaded energy is calculated as an analysis variable to assess the fulfilment of the agent's charge desires. As further analysis variables, the daily total number of charging procedures for each charging use case is collected. A summary of the models parameters, inputs and outputs is given in Figure 14.

The applied charging power for an individual charging procedure is the minimum from the three constraints power of charging station, available power in grid and the possible charging power of the vehicle type. This model is developed to be adopted by parametrisation to any municipality in Germany. Because of the clustering in region-type-dependent mobility behaviour, changes of the model structure are not required on a first glance. On the other side, the consideration of municipality-specifics, e. g. a well-developed public transport, would require structural changes or the use of another, possibly priorly developed model.

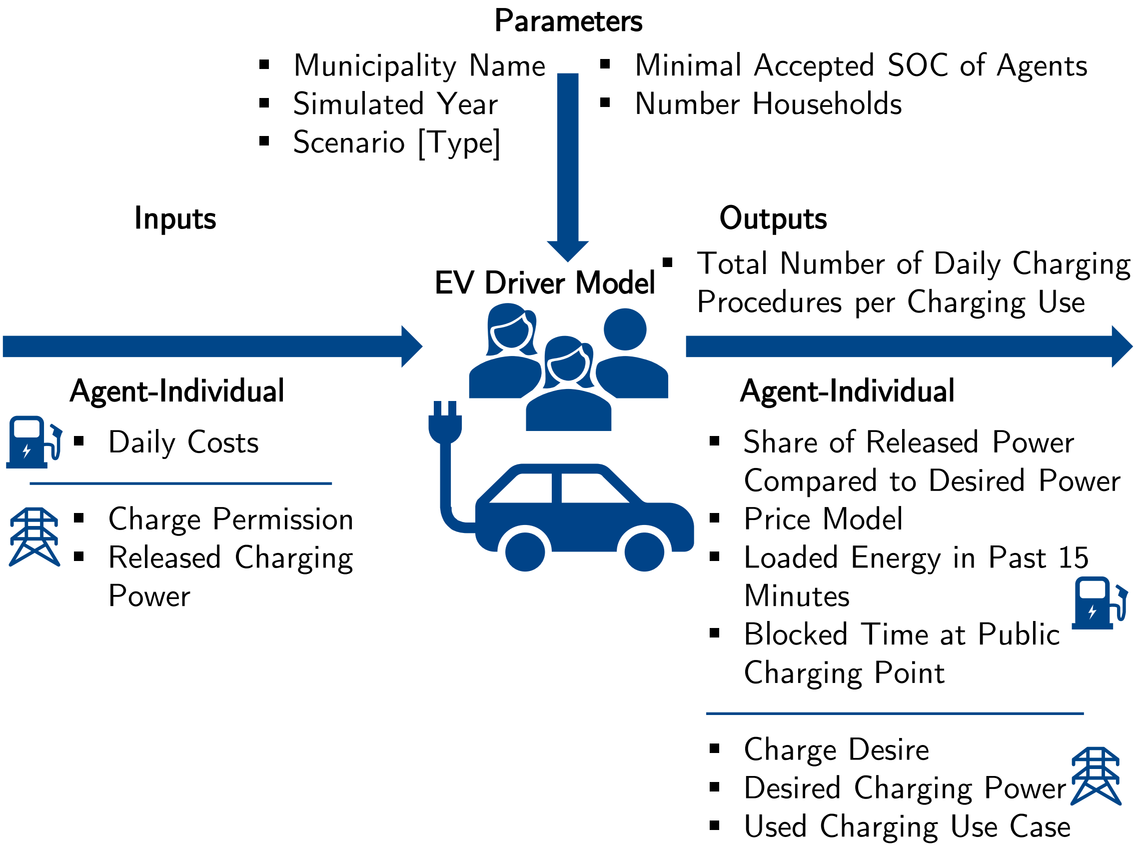


Figure 14: Parameters, inputs and outputs of EV driver model

4.2.2. Charge Point Operator Model

The CPO model covers the financial and more general, the economic aspects related to the operation of public charging infrastructure. As the German Government aims a private-owned public charging infrastructure [124], [83], the economic feasibility is a crucial point to reach the targeted charging points. The model aggregates the tasks that are related with the installation, operation, and maintenance of charging infrastructure over life time.

The tasks of a CPO can be summarized with planning, permission, installation and operation. Further subtasks are maintenance, service and back end operation. The location choice has been identified as one of the major driver for the charge point's financial success [112].

First, the considered costs can be classified in Capital Expenditure (CAPEX) and Operational Expenditure (OPEX). Figure 15 summarizes the types of costs that are considered in the model. For the payment three options have been considered: a direct payment and a standard (monthly) option, both comprising a quantity-based and a block fee. With block fee, an additional payment is meant which is charged when blocking a charging station after having fully charged the EV. Complementarily, a frequent-user option is offered with a lower quantity-based fee, but an additional monthly fee.

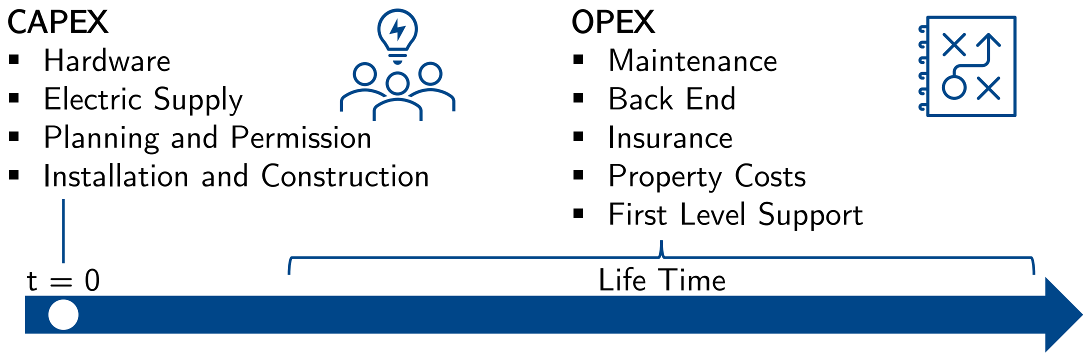


Figure 15: Considered types of costs for the model

The model itself is parametrised with the number of AC and DC charging points to be considered. Moreover, the scenario type to be analysed is required as a given parameter. The model procedure is as follows: The agents' charging behaviour serves as an input on a quarter-hour-base. Filtered for the charging use cases in public, here mainly inner-city hubs and roadside, the loaded energy of each agent is processed twice. First, for the agents-individual costs and one time for the operator's perspective. The agents-individual costs are only calculated for public charging, expenses for private charging are not considered.

The agents-costs comprise, the consumption-based fee, a fee for blocking public charging stations after reaching a SOC of 100% and an optional monthly fee in exchange for a reduced quantity-based price. The agents-individual costs are calculated after each day according to their chosen price model and set to an according output. In parallel, the accumulated loaded energy for all agents is collected charge-case-individually. Furthermore, the chosen payment option for each agent is considered to account for payment-option-related costs and recurring payments from the monthly fee.

Furthermore, the model processes the current line and power utilisation of the electrical grid. Based on the grid-related data and the usage of the public charging points, the maximal accumulated power for all public charging points together is determined. This variable is of interest as a major part of the operator's electricity costs result from the power price to be paid. For details on the applied numbers and their sources, it is referred to [217].

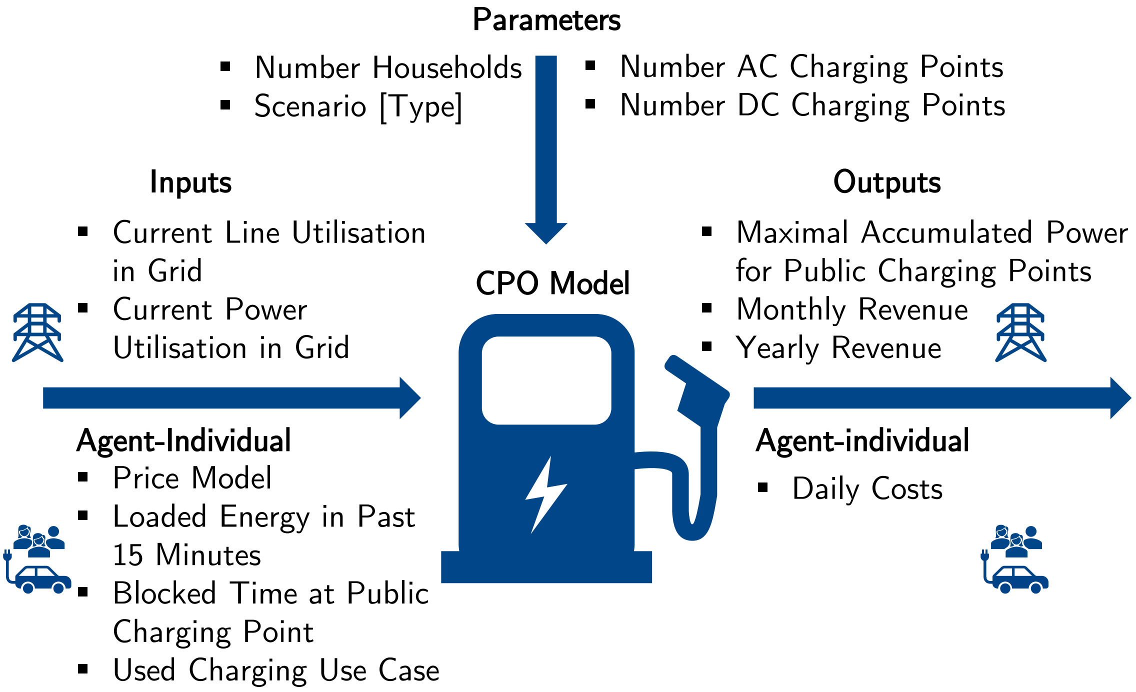


Figure 16: Parameters, inputs and outputs of CPO model

Public funding has not been considered as this is fluctuating and not generally quantifiable. For charging points, a life time of ten years is assumed. Sensitivity analysis in [217] showed that the usage of the charging points, beside the electricity tariff for the operator, has the highest impact on the rentability. Neither thinkable repayments e. g. for bidirectional charging nor price changes for hardware or further costs have been varied.

This model does not require further adoptions when applying it to different municipalities within Germany. Although there might occur local tariffs, its parameter base is configured for any German region. This can be content-wise supported by the national-wide operation of participating companies for charging infrastructure installation as well as operation.

4.2.3. Grid Operation

The development of the grid model aims to have a model library with scalable exemplary topologies that span the types of existing electrical nets in Germany in the low and medium-voltage layer. On the other side, the use of electrical grid simulation is established with grid operators and will be even more used in the future [196], [197] [198]. This subsection was supported by the master thesis of Tobias Marzahl [220].

Therefore, the here-developed model has a dual role: First, it enables the detailed analysis of charging infrastructure's impact on the grid for exemplary topologies and applications. Second, the model serves as a proof-of-concept for the integration and requirements for a detailed grid model in co-simulation. Thereby, the later integration of models from real grids, e. g. provided by the grid operator of the municipality which is planning its charging infrastructure. Regarding the integration of real grids a twofold approach shall be feasible: Either the required data base is provided to build a grid model in the form at hand with an exchanged data base or the grid model is provided as a complete model providing the necessary interfaces.

The grid model shall account for the requirements flexible parametrisation, scenario-adoption and scalability for low-voltage as well as medium-voltage level. Whereas single charging points and private wallboxes are most likely to be connected to the low voltage grid, large installations in particular of DC charging points are regularly connected to the medium voltage grid. Therefore, the model shall enable both by switch with the low voltage grid as default. The scope which shall be represented by the model covers a neighbourhood as the smallest entity and a city's grid as the largest one.

Grid topologies are defined as the composition of electrical grid components to a basic structure. Important topologies to be considered consists of radial, meshed and ring layouts. Ring topologies are operated as radial networks unless in failure cases. [221] The modelling approach at hand considers the component types transformers, cables, consumers, generators, electric storages and switches.

The main factors for grid stability are voltage and frequency stability with the latter being a task for the transmission system operator. Current trends for electrical grid include decentral energy production, smart grids and the here-focused electric mobility. The electric mobility does not only bring in new consumers with a relatively high power demand in comparison to households.

The electric mobility might also contribute to grid stability by steering the charge process or in the future by serving as a buffer storage in the context of bidirectional charging. The use-cases for the grid model can be clustered into stand-alone use cases on the one side and those within a co-simulation system on the other. A summary is given in Figure 17, from which the focused use cases are highlighted in bold.

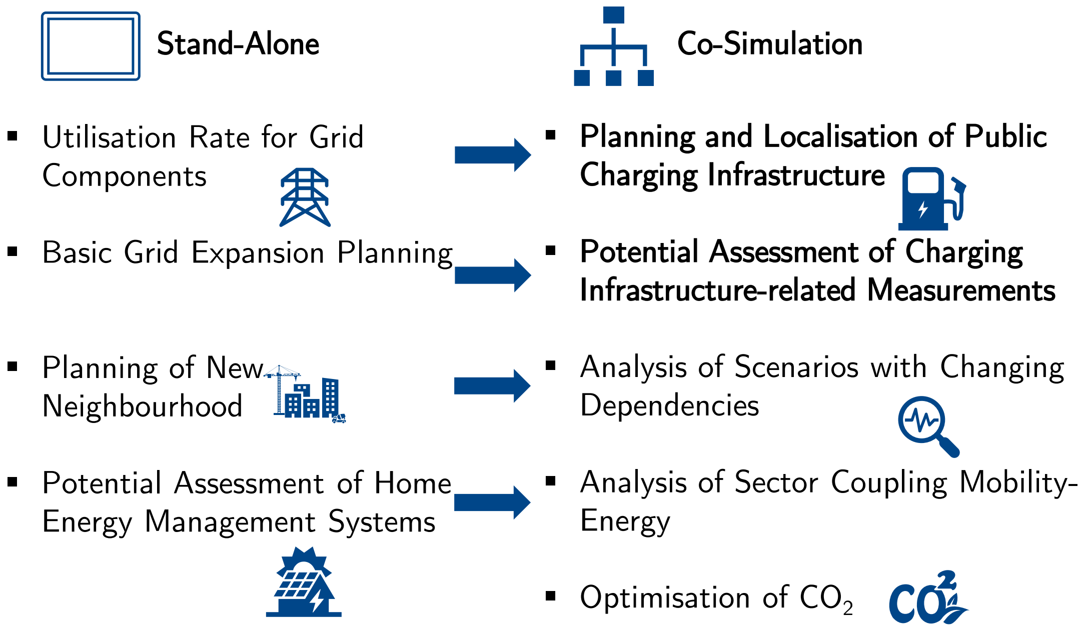


Figure 17: Use cases for grid model

The model is implemented in Python [222] and uses the package pypsa [223] as base for the component library. This decision has been taken after comparing available options for grid modelling with the requirements described above, as e. g. load flow calculation is regarded as sufficient. In [223] a comparison of different tools is conducted which is displayed in Figure 18.

Data on exemplary and representative grid topologies and load profiles are used from the research project SimBench [224]. Regarding voltage-level, low-voltage as well as medium-voltage is modelled. A switch has been implemented to choose whether low- or medium-voltage is considered in a simulation run. The topology is defined and initialized at the beginning of a simulation run. Input parameters are the number of households to be considered, the municipality name to account for regional and spatial particularities, the simulated year and the scenario type. Thereby, a suitable generic net with its topology and representative loads (not including electric mobility yet) is generated. Based on the parameters for AC and DC charging points, charging points are added to the electrical grid. For the placement, the different charging use cases including private and public use cases are incorporated as well as the meaningful distribution over the grid.

Software	Power Flow	Linear OPF	SCLOPF	Nonlinear OPF	Multi-Period Optimisation	Investment Optimisation	Energy Sector Coupling
PyPSA	✓	✓	✓			✓	✓
PYPOWER	✓	✓		✓			
pandapower	✓	✓		✓	✓		

Figure 18: Comparison of grid modelling options based on [223]

During run time, the EV drivers' charging desires are processed. First, all agents with their charging desire and if yes, their desired charging power and charge use case are processed. The representative load from the SimBench profile is given priority. Thereby, the available charge power for all agents accumulated is constraint by the grid's capacity and in addition, for the public charging points by the power that is released by the CPO. The agents' is granted individually a charge permission according to their charging use case and moreover, the charge power they can use. Regularly, the released charge power is equal to the desired charge power. In case of limitations because of the paid power or grid restrictions, the agents are granted an equal share of their desired charge power. A summary of the grid model's parameters, inputs and outputs is provided in Figure 19.

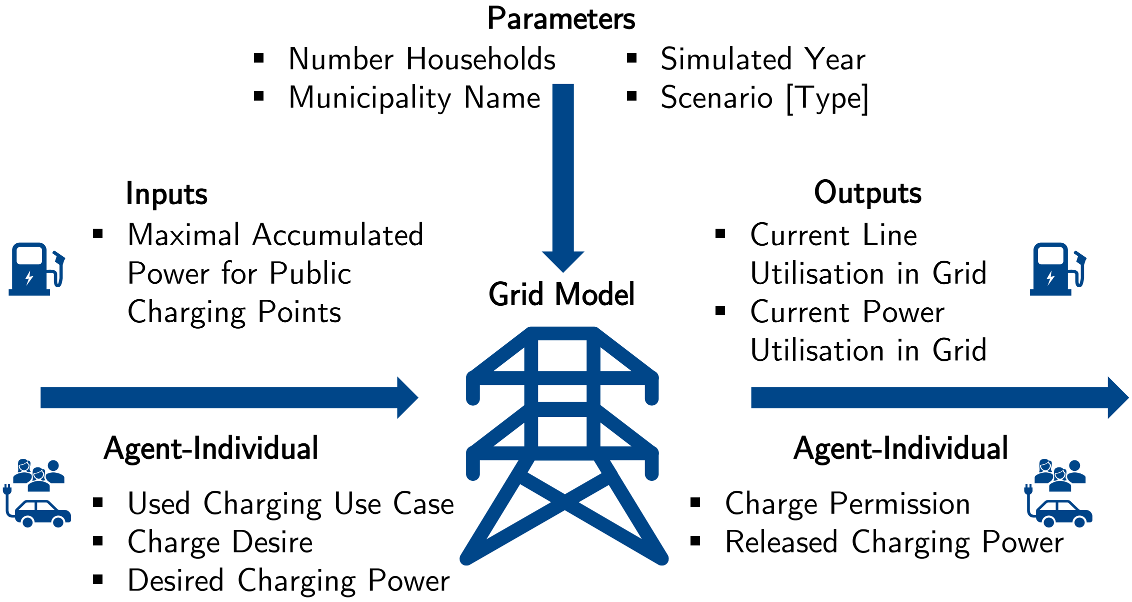


Figure 19: Parameters, inputs and outputs of grid model

4.3. Domain Ontology

This section deals with the domain ontology which is an essential artefact within the simulation system. It shall include and represent all concepts that are part of the models, in particular that can be found within the models' parameters, input and output variables. Therefore, the domain ontology here must comprise the topics of electric mobility with its user behaviour, electrical grid and economic aspects of the charging infrastructure operations. To ensure the extension possibility of the model as well as of the simulation system with further models, the ontology shall not be limited to a specific model or simulation system version.

As the ontology's scope partly defines the feasible content scope of the simulation system, a most likely comprehensive domain ontology which is widely accepted within the domain is aimed. The domain ontology sets the frame for the considered domain, concepts and terminology which can be processed within the simulation system.

Due to the lack of a comprehensive ontology available for the purpose of charging infrastructure planning, an ontology is developed by combining existing ontologies for subdomains of the simulation system at hand. Concretely, parts of the ontologies iCity (vehicle and parking) [225], [226], Urban IoT (electric mobility) [227] and SEAS (electric power systems) [228] dealing with parking, grid and vehicles have been combined. Manual adjustments were necessary to delete duplicates and to set the connections between the concepts of the different sub-ontologies accordingly. This merge was conducted with the lowest possible amount of changes in the original ontology to ensure synchronisation with other research in this domain. The composition of the ontology is summarized in Figure 20.

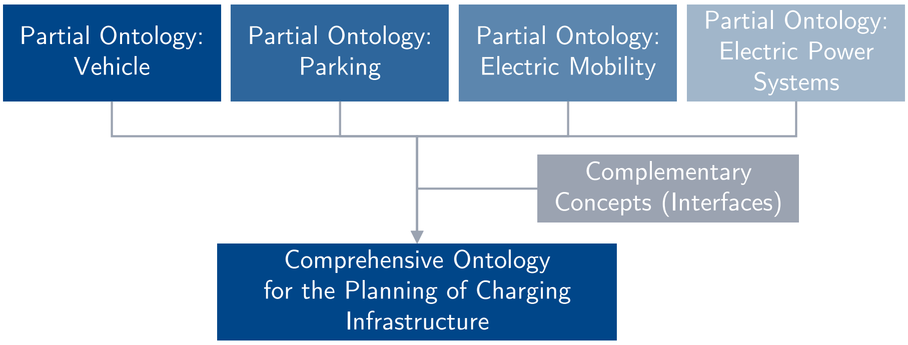


Figure 20: Overview about the composition of the domain ontology

In the following the comprised concepts and classes of the merged ontologies are introduced. The SEAS ontology is organized in three main modules with a feature set of interests and their properties, the evaluation of these properties and a module providing connections with further systems [228].

The urban IoT ontology was defined by the Milan municipality with the aim to support the integration and publication of data from multiple service provider in the urban context. The electric mobility ontology as it is used here includes the aspects of a service provider, the service usage by the users and related IoT devices. [227]

The iCity parking ontology provides the concepts related to parking, use of space in cities and associated rights and costs. The allocation of charging infrastructure within the ontology builds the connection point to electric mobility. [226] Finally, the iCity vehicle ontology includes the concepts that are related to an individual vehicle and its characteristics including the persona and cargo capacity. Most relevant for the simulation of EVs are those concepts that describe the drive unit of the vehicle. [225]

The consequences of the absence of a widely accepted domain ontology are discussed later in this work. To broaden the applicability of the developed simulation system and further extension, the used ontology is not limited to the concepts that are currently used in the included models. As the development of the models is not assumed to be based on the ontology regarding terminology, the naming conventions from the ontology is only partly fulfilled. On the other side, the scenarios, as introduced in the following Subsection 4.4 are considered as a part of the simulation framework comparable to the domain ontology. Therefore, the terminology of the scenarios is harmonized with the introduced domain ontology.

The domain ontology for the given context of public charging infrastructure shall cover aspects related to mobility, user behaviour, electrical grid and electric mobility in general. Due to the wide range and the newness of parallel consideration of those fields, there was no suitable ontology identified that covers all of the here-required aspects.

4.4. Analysed Scenarios

The analysed scenarios mainly base on the master thesis of Robin Menke [229]. A scenario is here understood as the synthesis of influencing factors into a set of parameter values that are used in simulation to describe a foreseeable future situation. The underlying technique is called scenario analysis based on [230], [231]. To extract the scenarios, trends with their prognosis values with foreseeable ranges, the interdependencies between trends and the expert-knowledge-based allocation to bundles are taken into account. Also, the path that leads to a certain scenario is investigated. Considered trends comprise mobility, technological and socio-economical factors, from which the CASE trends are investigated most deeply.

The methodology starts with an analysis of the status quo and relevant trends for the topic under interest, followed by the individual analysis of the trends' development. Thereafter, the analysis of interdependencies between the trends with regard to charging infrastructure is conducted.

	Impact Factor	**Details**
Mobility and Society	Electric Mobility	Number of BEVs and PHEVs in Germany [M]
	Connected Vehicles	Number of CVs in Germany [M]
	Autonomous Vehicles	Number of AVs in Germany [M]
	Shared Mobility	Share of SM ways in Germany [%]
	Urbanization	Share of German Population Living in Cities and Metropolitan Areas [%]
Charging Behavior	Demand Charging Points	Aggregated Number of Public Charging Points in Germany [K]
	Private Charging	Average Share of Charging Procedures at Private Charging Points in Charging Procedures in Germany [%]
	Public Charging	Average Share of Charging Procedures at Public Charging Points in Charging Procedures in Germany [%]
Battery Technology	Battery Price	Average Battery Price [$/kWh]
	Energy Density	Average Energy Density [Wh/kg]
Electric Energy	Charging Power Batteries	Average Maximal Charging Power of BEVs [kW]
	Renewable Energy	Share of Renewable Energy in Gross Energy Demand in Germany [%]
	Price for Electricity	Average Electricity Tariff in Germany [€/MWh]

Figure 21: Summary of considered impact factors for scenarios and their explanation

Therefore, a relative scale for impacts with negative, neutral and positive meaning is applied which results in a consistency matrix. From this matrix, the final values and combinations for the scenarios are derived by combining all individually applicable factors with the base values for each trend. In the last step, the extracted scenarios with their values are embedded into visions.

The factors with the highest influences on public charging infrastructure and their use are related to battery technology: Battery density, battery prices and charging power. From customer perspective, the synthesized main driver on the German market towards electric mobility are vehicles' range, availability and power of charging stations and the costs for EVs [2].

The scenarios consist of 13 descriptors each representing an impact factor. A summary including their units is provided in Figure 21. A time span between 2025 and 2050 with five-year-intervals is covered. The year 2022 is chosen as the base year for analysis in which the status quo is investigated. The sum of derived scenarios cover the foreseeable range of developments with none of them having a higher probability of occurrence. Nonetheless, a trend scenario is synthesized as the average of the other scenarios' values for each descriptor. Its values are summarized in Figure 22.

Descriptor	**2022**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Electric Mobility [M]	0.616; 0.567	2.7; 2.4	10.2; 7.4	20.3; 11.8	30.5; 11.0	38.9; 6.8	47.4; 2.5
Connected Veh. [M]	11.6	18.6	37.6	44.4	47.8	49.0	49.8
Autonomous Veh. [M]	0.01	0.2	2.0	6.1	12.4	23.0	36.0
Shared Mobility [%]	8.0	12.0	18.3	23.2	28.2	34.9	41.5
Urbanization [%]	77.6	78.3	79.3	80.4	81.5	82.6	83.7
Demand Charging Points [K]	62	274	700	1,27	1,57	1,72	1,83
Private Charging [%]	85.0	76.0	65.9	61.7	57.4	47.6	37.6
Public Charging [%]	15.0	24.0	34.1	38.3	42.6	52.4	62.4
Battery Price [$/kWh]	137.0	108.4	84.3	71.7	63.3	59.9	57.4
Energy Density [Wh/kg]	300	408	532	598	664	731	797
Charging Power Batteries [kW]	50; 125; 175	123; 216; 308	183; 367; 440	220; 440; 550	256; 513; 660	293; 587; 770	330; 660; 881
Renewable Energy [%]	41	51.1	62.1	65,5	69,6	72,3	75,2
Price for Electricity [€/MWh]	96.8	88.7	67.2	71.7	76.2	80.7	85.1

Figure 22: Analysed trend scenario with its concrete values

4.5. Applied Optimisation Algorithm

This section deals with the optimisation algorithm used in the simulation system. Its development has been supported by the bachelor thesis of Sophia Bailer [232]. The overall approach of the optimisation is summarized in Figure 23 and explained in the following. The co-simulation system composed by the three models grid, EV driver and CPO as introduced before, builds the core to evaluate possible solutions to the optimisation problem and therefore serves as the DSE part.

As an input the co-simulation systems gets a pair of AC and DC points, complemented by a city or a similar scope, the scenario and the year. Whereas the latter three are defined by the user, the optimisation algorithm defines the pair of AC and DC points to be simulated. The output of a co-simulation is analysed regarding the chosen optimisation criteria and the corresponding objective functions are calculated. The results of the objective functions for multiple AC and DC pairs are then compared to each other from which the following pairs are derived by the optimisation algorithm. Thereby, an iterative process is reached which forms the optimisation.

The pair of AC and DC charging points is considered to be an individual. Whereas a-priori optimisation methods require the definition of the individual weights for each criterion in multi-objective functions, the here-applied a-posteriori optimisation algorithm does not require such a weighting, but provides a set of non dominated individuals. As the relations in this project cannot be directly expressed as formula or similar mathematical relations, the application of heuristic algorithm is feasible to account for the complexity and interdependencies of the co-simulation system.

A distinction is made between a simulation run and an optimisation run. Whereas the former describes the one time execution of the co-simulation system for defined input parameter including a fixed pair of AC and DC charging points, an optimisation run describes the execution of the optimisation algorithm to identify the "best" pair of AC and DC charging points for a defined year, scenario and city or scope which includes multiple simulation runs. Due to the field of application only integer solutions for AC and DC pairs are allowed.

The chosen algorithm for this work is NSGA-II which is a population-based, evolutionary and heuristic optimisation algorithm. Objective functions can be also described as fitness functions. For each individual the fitness functions are calculated from which their individual rank is derived: From the population with the individuals' fitness functions, the non dominated solutions build the first rank. In the following, the non dominated solutions are separated from the population and for the remaining population the non dominated solutions build the second rank and so forth. This procedure is called non dominated sorting.

As a second criterion the crowding-distance is calculated for each individual as the normalized difference between maximal to minimal criterion value between one individual and its neighbours for each criterion. The individuals' total crowding distance is the sum of the crowding distances for each criterion. The consideration of this criterion ensures a certain coverage of the solution space within the population and during the optimisation process.

The reproduction between the generations is separated in recombination and mutation. In recombination the input parameters of multiple individuals are selected and combined to a new individual. Thereby, the well-evaluated solutions can be exchanged and further enhanced. The second factor for reproduction is the mutation. Therefore, the individual input parameters, here number of AC and DC charging points, are varied along a normal distribution with a relatively low standard deviation to strengthen the local character of the reproduction.

For the transition between two generations, individuals from multiple fronts are selected with a focus on those individuals with a higher rank. If a selection has to be made between different individuals of the same rank, the individuals with the higher crowding distance are preferred. Concretely, for the creation of the following generation, the defined number of individuals (the population size) is selected from the current generation. First, the individuals of the first rank are selected if there are less individuals of the first rank and the aimed population size. Otherwise, the individuals with the highest crowding-distance are selected in decreasing order until the population size is selected. In case of a higher population size than the number of individuals of the first rank, individuals from the second rank are selected in decreasing order of their crowding distance according to the prior described procedure. The thereby selected individuals are then evolved by the prior described recombination and mutation and subsequently, the following generation is created.

As concrete criteria for evaluation three outputs, one of each model, are chosen to account for the diverse stakeholder perspectives on the one side and the feasibility of the results' interpretability on the other. Furthermore, the addition of criteria leads to larger Pareto fronts result with a tendency to lower solution quality. Concretely, the following three outputs are incorporated in the optimisation: First, the maximal occurring voltage deviation in the modelled grid as an indicator for the grid feasibility of the charging infrastructure layout. Second, the average load fulfilment for the users as an indicator for the user satisfaction by the layout under analysis and third, the monthly profitability of the public charging infrastructure from the CPO's perspective to assess its economic feasibility.

The whole optimisation problem is handled as a minimization problem. As the different criteria are partially criteria to be maximized, these criteria are multiplied with -1, here concretely applied to the monthly profitability and the load fulfilment.

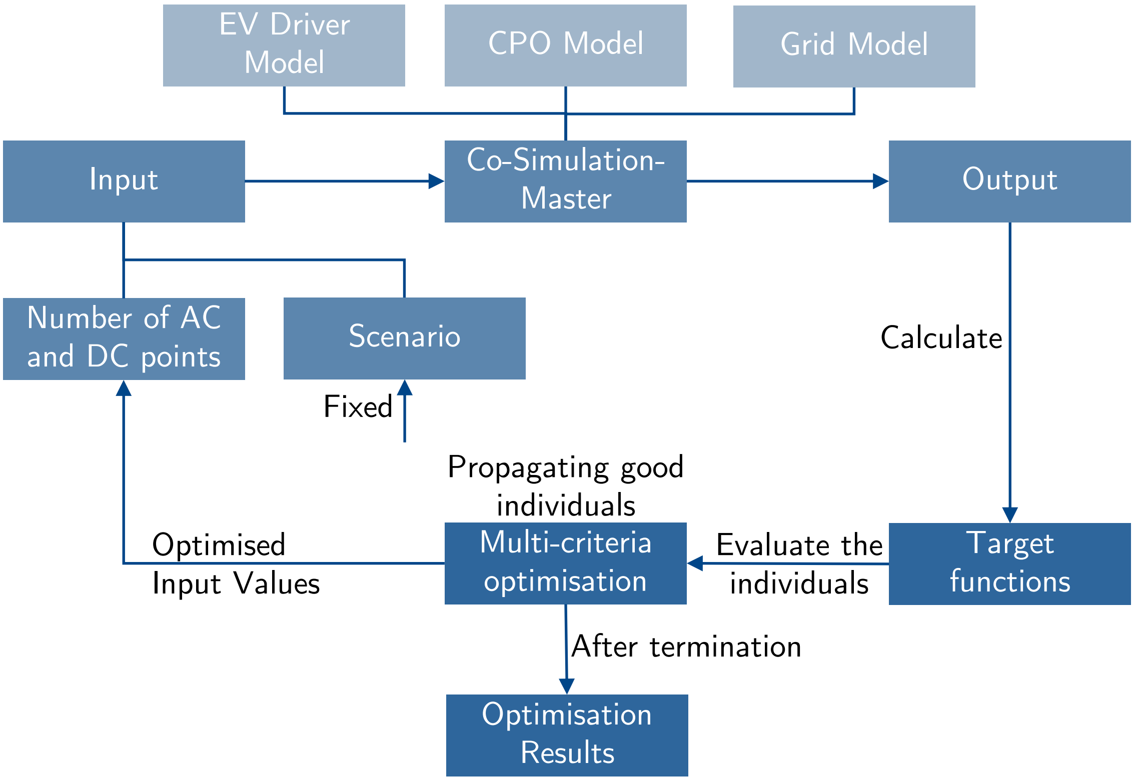


Figure 23: Usage of optimisation in simulation

The choice of optimisation criteria is made with regard to cover relevant aspects from literature while ensuring their availability in the simulation models at hand. The optimisation framework is developed to find an optimal pair of AC and DC charging points for a defined year, scenario and scope (e. g. neighbourhood or city). A latter enhancement to reflect prior optimal paths of development is foreseen by restricting the solution space accordingly, e. g. by adopted lower boundary conditions. Due to the different dimensions of these outputs, a normalization of the fitness functions is conducted based on a set of test configurations. The scaling factor for each fitness function is the average value of these from test configurations' resulting fitness functions.

The choice of the lower and upper boundaries for the solution space is conducted based on expert-knowledge and with regard to political decisions as presented in Subsection 3.4. For a scope of 10 generations, 30 individuals are generated and analysed each. This amount is determined as a compromise between covering the solution space appropriately and the required computing time.

Regarding the implementation, the recombination is implemented by the help of the pymoo package [233]. The parallelization is realised by the parallel() function of joblib [234]. The parallelization was only applied to the individuals of one generation to avoid conflicts in the merging and calculation of fitness functions across several generations.

4.6. Composed Simulation System

Having introduced the individual models for the aimed decision support, the models' interplays, the parameter under variation as well as further variables for analysis are introduced. At first, the parametrisation is explained. All three models get the four parameter "number of households", "municipality", "year" and "scenario type" which are explained in the following. The number of households defines the scope to be analysed, e. g. an entire city or a district. The exact quantification of the considered households allows to set up a suitable grid and provides a base for the determination of the EVs under analysis. The municipality is given to consider regional specifics. The year together with the scenario type, e. g. "optimistic" (from the scenario data base) determines the overall scenario under analysis, e. g. the market penetration for EVs and the share of renewable energy. Thereby, the characteristics of the simulation run are defined.

Further, partially model-specific, parameters are introduced in the following. The EV driver model requires "minimal acceptable SOC", a parameter that defines the agent's behaviour in terms of charging. With an occurring lower SOC accepted, the frequency of charging tends to decrease while the loaded energy per charging procedure tends to increase. The CPO model gets the "share between DC and AC charging points" as a parameter to overwrite the default of an equal share. Although the charging power is most probably increasing in the upcoming years, a combination of AC and DC charging is most likely [94].

Having explained the parameters, the exchanged variables at run time are presented. The EV driver model simulates the mobility behaviour and the charge desires. The charge desire for each agent is given to the grid model complemented by the current charging use case desired charging power. The grid model gives back if the charging desire can be fulfilled (free charging point) and if yes, the applicable charging power.

Furthermore, the EV driver model communicates the payment model of the agents to the CPO model together with the used charging use cases, the loaded energy and the blocked time at public charging points. With blocked time, the time span is meant between the EV being fully charged and the departure from the public charging point, so the time without charging in which a charge point is blocked. The CPO model returns the daily costs, including monthly fees, to the user model. Third, the exchange variables between grid model and the CPO model. The grid model gives the current grid utilisation in form of power and line utilisation to the CPO model. The CPO model returns the maximal power of public charging points which is associated to the capacity charge.

Finally, the additional outputs for analysis purposes of the models are introduced. All output values of the models as described above can be used for analysis purposes. Nonetheless, several variables specified for analysis that are not part of the variable exchange at run time are introduced. For the grid model, the values for "peak power", "overall consumed energy" and "peak voltage deviation" are taken.

The variable "peak power" returns the highest measured power demand in the grid over the simulated year. The variable "overall consumed energy" gives back the amount of energy that is used for EV charging over the year. The "peak voltage deviation" returns the maximal voltage deviation in the grid that occurred over the year.

The EV driver model has two additional outputs. First, the total number of charging procedures clustered for the charging use cases. Second, the relation between the desired energy for EV charging and the actual charged energy. This variable is given as percentage. The CPO model does not have additional outputs. The grid model gives out the resulting peak power and the peak voltage deviation within the analysed grid as well as the overall consumed energy and timely-resolved current network usage.

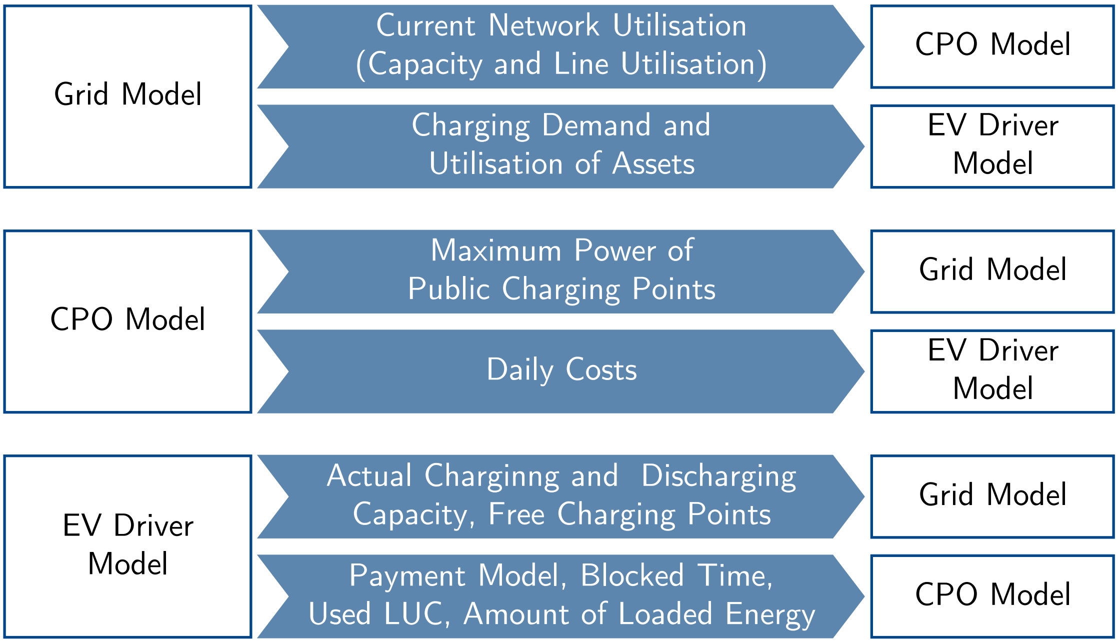


Figure 24: Variables that are exchanged during runtime in the simulation system

The scenarios have been stored as XML files with four hierarchy levels. In the following those are summarized in descending order:

- scenario n, e. g. 1
- descriptor, e. g. Battery price
- year,e. g. 2030
- value, e. g. 65.3

The models' implementation is conducted with regard to their aimed use for co-simulation. A focus has been set to use open source solutions to facilitate the demonstrator development.

Moreover, the choice to use the FMI standard requires a tool chain for the model development which allows the model's export as a FMU. Therefore, all models have been implemented in Python and are then exported as FMUs by the help of pythonfmu [235]. As FMUs shall be standardized, the validity and value of the demonstration is not limited by this decision, but it has facilitated the development process.

4.7. Simulation Results and Decision Support

According to the simulation system as explained above, the achievable evaluation by the simulation system is summarized as follows: For a specific regio type within Germany, a flexible number of EVs with their charging behaviour is simulated in interplay with an exemplary and representative topology of the electric grid and a further model representing the financial perspective of a CPO. All three models are parametrised based on the scenario file, e. g. the considered number of EVs for a specific scenario and the analysed number of households. Depending on the number of households, the size as well as the voltage level to be analysed is determined. With the input of considered number of AC and DC charging points as optimisation variables, it can be assessed by the system what amount of public charging infrastructure is feasible for the thereby defined area within Germany, but without further spatial resolution within this area.

For the exemplary results within this work, a pessimistic scenario according to the scenario file at hand for the year 2030 is taken. To achieve a sufficient number of EVs and accounting for the random component within the mobility behaviour, a number of around 1000 agents is approached with leads to approximately 11,000 households to be considered for the grid. As the analysis of the medium voltage level for the grid is most feasible for this amount of households, a cross-check has been conducted how many households are part of a representative mid-voltage area such as Braunschweig. With a mid-voltage topology having 10,225 households in total, a number of 890 electric vehicles is derived from the scenario's break-down of the German average.

In addition to the already introduced decisions, the optimisation run needs to be configured, in which multiple options of pairs of numbers of AC and DC charging points are assessed, each by a simulation run with the prior defined scope. For the configuration of the optimisation run the number search space as well as the number of assessed solutions must be determined. Moreover, the optimisation criteria must be determined. For the search space, a span of 10 to 800 AC charging points and 2 to 105 DC charging points respectively, is defined. In addition, to the ranges for AC and DC charging points, the sum of both is also restricted to the range of 10 to 800 charging points in total. The restriction of the search space was made as a compromise between expert-knowledge and the political goals on the one side, and the achievable coverage on the other side within a suitable run time.

For the number of assessed solutions, a compromise between run time and coverage of the search space is required. Within the number of assessed solutions, the number of generations as well as the number of assessed solutions per generations needs to be determined. The higher the number of assessed solutions per generation, the more precise the analysis of the evolutionary algorithm is. On the other side, a higher number of generations leads to a more frequent application of evolution. To solve this conflict, a number of 30 assessed solutions per generation is chosen with a total of 10 generations assessed.

Moreover, the optimisation criteria are defined. With regard to three models at hand, each model shall be represented by one criteria. The limit to one criteria each is taken to account for the increase of non-dominated solutions caused by further considered criteria. For the grid model, the maximal occurring power is assessed as representative for the grid utilisation and named as "peak power" in the following and the corresponding figures. Second, for the CPO model, the CPO's monthly revenue is analysed which incorporates the income as well as the expenses including the depreciation associated with the assessed amount of public charging infrastructure. Finally, the EV driver's load fulfilment as the share of available charging power relative to the individually desired charging power. These three optimisation criteria are assessed to determine the so-called fitness of the assessed solutions.

In Figure 25 the assessed individuals for the first generation as well as the final 10th generation are summarized besides the selection of the non dominated individuals. Both generations reveal a high degree of coverage of the solution space with the latter revealing a convergence of the solutions towards a lower amount of public charging infrastructure in general and a lower number of AC charging points in particular.

In Figure 26 the relative fulfilment of the chosen criteria for selected solutions is displayed. The relative fulfilment is set to 100% for the most fulfilled criteria out of the three analysed criteria. The further criteria' fulfilment is given relative to the other assessed solutions within a generation. Conclusively, these net diagrams express, in which criterion a solution performs best and second, how balanced an assessed solution is to fulfil all criteria. Conclusively, a large covered space within the net diagram represents a balanced solution. Within the figure, the assessed solutions with a high amount of public charging infrastructure show a high degree of load fulfilment while performing relatively low for monthly revenue and peak power. On the other side, few public charging infrastructure leads to a low degree of load fulfilment while peak power and monthly revenue are evaluated well. A balanced amount of charging infrastructure, here represented by the pair of 94 AC and 83 DC charging points, shows a good compromise between load fulfilment for the users and the monthly revenue of the CPO, but a low relative value for the peak power.

At this point, the interpretation of the detailed results from the individual simulation run starts to reach the actual decision support. The analysis of the absolute values reveal that the peak power shows the least variance of the three optimisation criteria.

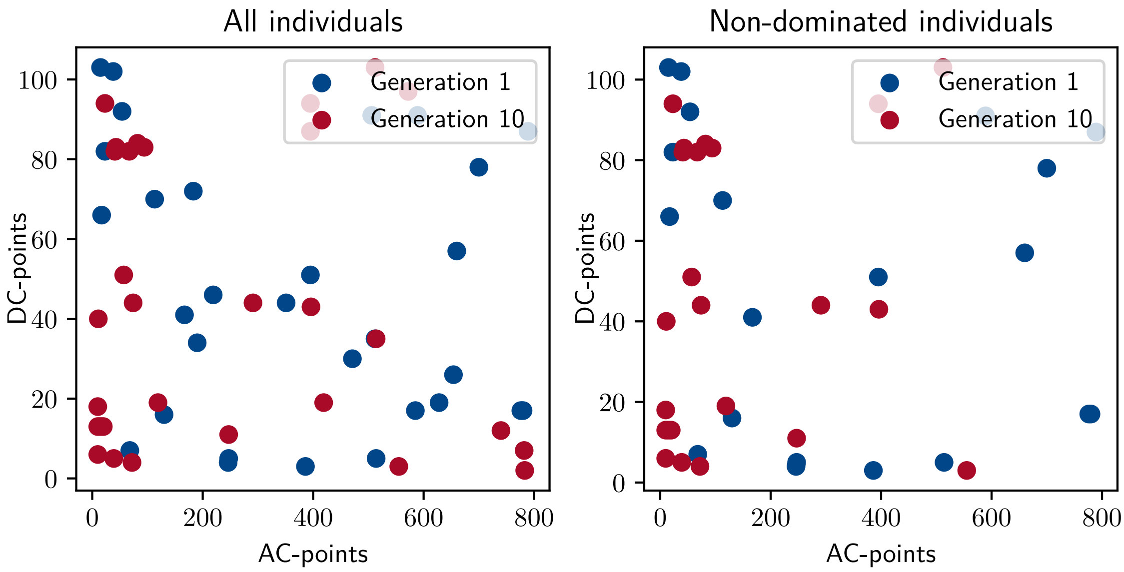


Figure 25: Individuals of selected generations and non-dominated individuals of those generations

Furthermore, the CPO's monthly revenue is highly negative for the assessed solutions with several hundred public charging points in the scenario at hand. Therefore, it is recommended to remove non dominated solutions for the practical applicability by adding further restrictions, e. g. a maximal expected CPO's loss before public grants or a minimal load fulfilment of the charging demands.

Conclusively, the application of the developed simulation system including the optimisation requires a further framework which realises the decision support by guidance and aggregation. The comparability between several assessed scenarios is an important point and the analysis of the results regarding their feasibility in general as well as under consideration of the applicable local circumstances. Moreover, the most feasible solutions for a certain point in time must be compared to further points in time to finally reach a path for the ramp-up of public charging infrastructure. This leads to further applicable restrictions within the search space for the optimisation's application.

In this section the use case for this work on co-simulation has been introduced: the decision support for future public charging infrastructure. The analysis of the state of the art revealed the need of advances in the field of co-simulation for infrastructure planning tasks. More specific, the development of charging infrastructure is a field in which multiple stakeholder perspectives have to be considered with technical, behavioural and economic aspects.

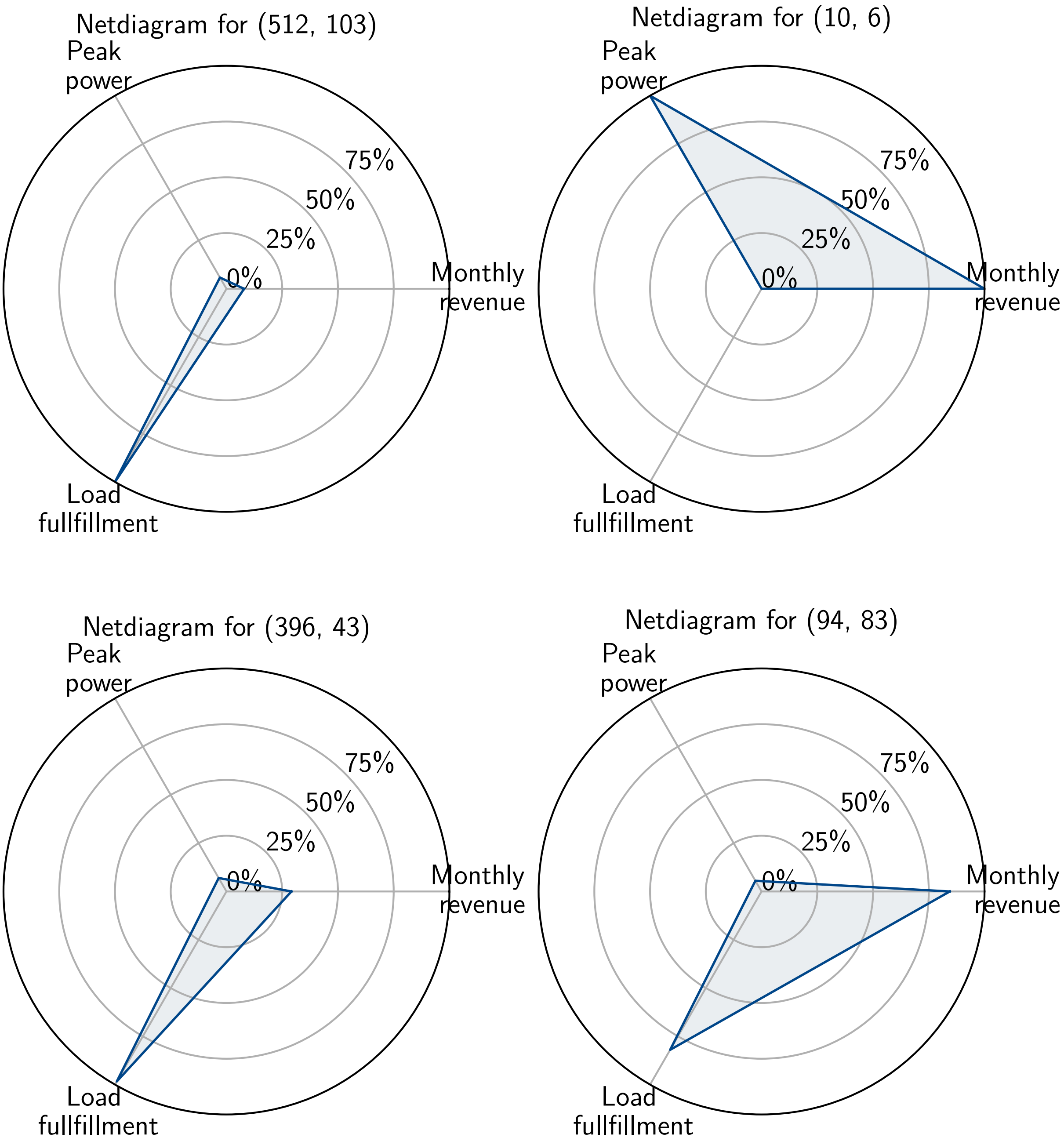


Figure 26: Net diagrams for selected pairs of AC and DC charging stations

As their individual modelling require different modelling approaches and tooling support, the application of co-simulation accounts for specific tooling support, model exchangeability and model reuse in parallel. The individual models have been introduced covering the perspectives of EV drivers, charge point and grid operators. Finally, the composed simulation system and the analysed scenarios have been summarized.

5. Challenges and Framework for Simulation System Configuration

This section deals with the conceptual framework and its functionalities that have been developed to enable and facilitate the handling of large-scale heterogeneous co-simulation systems. First, the purposes of the overall framework and its basic structure are introduced. In the following, the diverse challenges that have been tackled are explained and their solutions are described. A focus was set on the simulation system configuration. Examples for explanation purposes are taken from the use case introduced in Section 4.

5.1. Addressed Challenges in Model Handling

The methodology of co-simulation is well-established for workflows with a priori definition of models and their interfaces that shall interplay with each other. Consequently, the models can be developed or adopted in a way that not only fits the simulation purpose, but also let to models directly fit to each other. This can be summarized as a top-down approach: First, the interface and model's content definition is done, then the actual model development follows.

In contrast, this work pursues a bottom-up approach: Starting with existing models, possibly from different sources and then dealing with the task to build a consistent simulation system for a specific purpose. In the following, the four main purposes for this approach are introduced: the reuse of models for different contexts, the replacement of a model by another, the synchronisation of models within a simulation system and finally, ensuring traceability; all four are summarized in Figure 27.

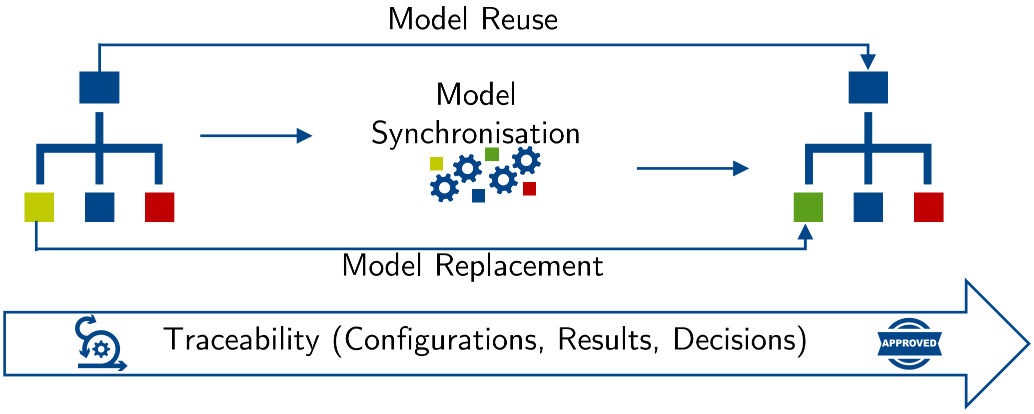


Figure 27: Relations between addressed challenges

Model Reuse

The reuse of models aims to utilise a simulation model in several contexts. E. g. if a model of the municipality's low-voltage grid has been developed to integrate a development area, this model can be also used in the context of charging infrastructure planning. A prerequisite is the availability of a suitable interface of the model itself and a corresponding documentation to make it usable for non-domain experts. With regard to IP protection, the embedding into a black-box container is a feasible way.

Nonetheless, at least information about inputs, outputs and important parameters are required. This includes information about value ranges, but also about meanings and context. Thereby, the correct use of the model can be ensured, even in a different environment and possibly unserved inputs can be replaced by reasonable assumptions.

Model Replacement

The second purpose for the aimed bottom-up functionality is the replacement of a single model within a simulation system that is composed by multiple models. E. g. the initial calculations have been conducted with a generic grid model which is replaced later by a precise local model. For the replacement, there are two options. Either the local model was developed in advance, then the above-explained challenges and requirements for model reuse apply additionally.

Or the new model is still under development, which leads to the following challenges: First, an analysis of the previous model which is now replaced is required. Thereby, the model's accuracy, scope and interfaces are understood and this knowledge supports the development of the model-to-be-integrated. Having gained the understanding of the model to be replaced, its successor does not necessarily be a one-to-one replacement. An example in the grid context could be the additional consideration of the medium-voltage level in the succeeding model. Thereby, the model's original scope is extended. In parallel to the model reuse, the adoption to the remaining simulation system needs to pay attention to unserved inputs of the model itself, but also to possibly unserved inputs in the remaining models.

Model Synchronisation

The model synchronisation comprises the aspects of harmonization of multiple models in a simulation system as well as the systematic parameter variation for parameter studies. With parameter studies the different scenarios are meant here.

Regarding the harmonization in the simulation system, the case can either be the initial setup of the simulation system, the replacement of a model, or the adding of a further model. Independent on the case, a common understanding of each model's scope, its input, outputs and parameters is required. Inputs and their belonging outputs from other models have to be connected to each other and similar and identical parameters have to be identified.

By this analysis, also overlapping between models can be identified, e. g. identical required inputs. In the next step, the set values in the models have to be synchronised. Therefore, the start values of inputs and outputs as well as the parameters have to be set consistently.

This consistency is not only required for the initial built-up, but also for systematic parameter studies or simulation experiments: In the example at hand, the scenarios that are introduced in Section 4.4 serve as sets of parameters that are varied. By this consistent and structured parameter variation, the aimed decision support of a bottom-up designed simulation system is reached.

5.2. Introduction to Framework and Belonging Procedures

The co-simulation is designed in a master-slave concept. Thereby, the models are each connected to the coordinating master algorithm without having direct connection to each other. This solution allows that the compatibility for data exchange and transfer of each model only needs to be ensured between master algorithm and the model itself. Therefore, this decision minimizes the interfaces to be dealt with.

As described in the state of the art, the master algorithm is limited to the algorithm which coordinates the data exchange during runtime. Although the later described functionalities are technically part of this algorithm, they are described as additional software artefacts to comply with common terminology.

The framework is structured in a 3x3-matrix with the timely progress horizontally and is summarized in Figure 28. This is divided into the three phases of preprocessing, run time and post-processing. Vertically, the three considered layers comprise the process steps, the concrete functionalities and the domain layer. By the distinct separation between general and domain-specific aspects the developed framework is made adoptable to different domains compared to its initial use case. Finally, a user interface with a dashboard for the decision support complements the framework and needs also application-specific adoptions.

The preprocessing spans the process steps of scenario definition, model parametrisation and simulation configuration. Domain-wise, the preprocessing requires the models to be integrated, the scenario set or simulation experiment and the domain ontology. The domain ontology shall cover the breath of content-wise information in the participating models and its relevant terminology. The scenario database itself usually takes its terminology from the domain ontology.

The preprocessing loop starts with the models to be integrated on which the functionalities are applied one after each other. First, the model's information is read and summarized regarding its inputs, outputs and parameters.

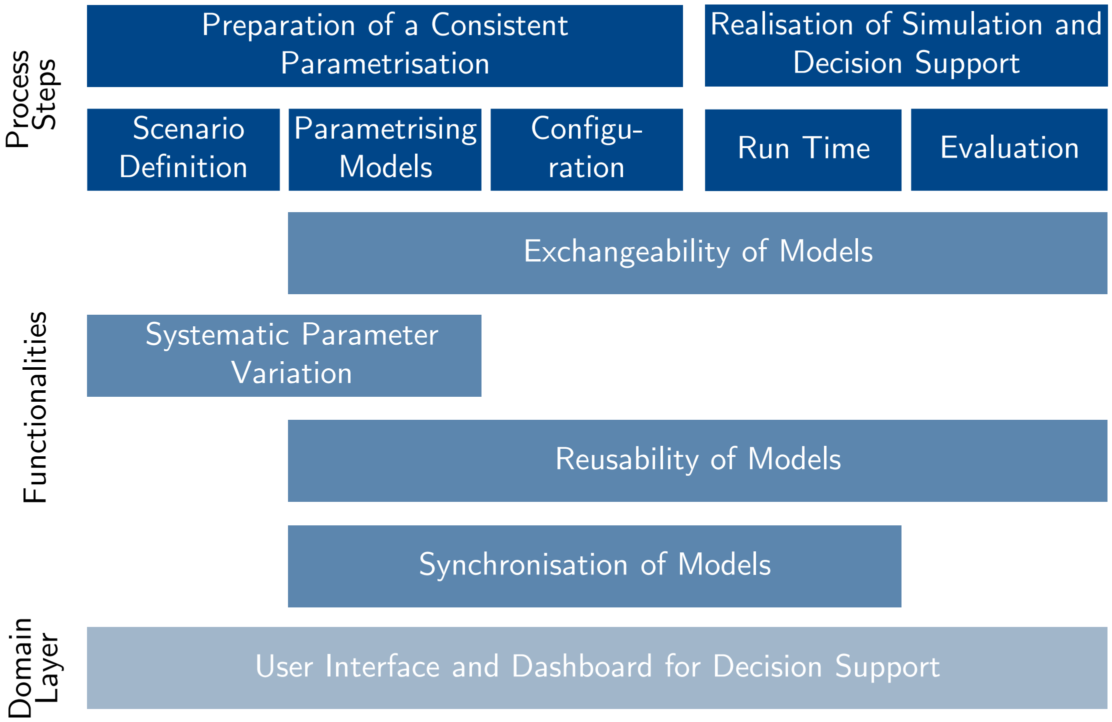


Figure 28: Mapping of challenges to framework structure

In the following, the models' descriptions are compared to each other by the help of the domain ontology. On the one side, this step reveals information on the models themselves by reducing their content to the standardized terminology of the ontology. This is provided as an overview to the user.

Second, this step allows to set the parameter values and the start values of inputs and outputs consistently according to the scenario under analysis. The specific values for this step are provided by the scenario database. Having finished those steps, the models have been parametrised consistently. Inputs and outputs have to be connected accordingly. For the repeated usage of a defined simulation system towards decision support, only the steps of parameter variation and setting the models' values accordingly have to be repeated. The further described functions are only necessary for the initial setup.

The following is the step of simulation execution. Specification for the simulation run are made initially and are then kept to ensure comparability between different simulation runs of a fixed simulation system. The actual execution is coordinated by the master algorithm. The challenges during run time comprise the transformation of variables when exchanged between models complemented by boundary violations of such values.

The case of the appearance of unexpected values out of a foreseen range, e. g. as an output, might lead to the violation of other model's behaviour when such an output value is processed as an input, the limit of automation during run time is reached.

The same applies for an unforeseeable change of parameter scale which nullifies the transformation defined in preprocessing. Further runtime challenges, e. g. numerical issues, are not part of this work. The run time segment requires concrete functionalities, but no domain-specific artefacts.

Simulation Post-Processing

The third and final phase of the framework is the post-processing which is divided into the storage of the simulation run's results and the actual decision support. The result storage can be a domain-independent data base and shall account for reliability, flexibility, and accessibility. Depending on the aim of the simulation, the decision support and analysis varies. All variants have in common that an analysis and comparison of the simulation results in combination with the underlying configuration is conducted.

Therefore, a comparison shall not only consider the results, but also the corresponding configuration. Depending on the scope and key performance indicators, the comparison and decision support is set up. An actual decision support can be conducted by either showing the simulation results in a domain-specific dashboard and moreover, by comparing multiple simulation runs with each other. Therefore, a functionality is required that allows the user to choose the simulation results that shall be compared with each other including an, optionally multi-criterial, optimisation. With the latter being domain-specific, a separation between general comparison and specific optimisation functionalities has to be made.

When comparing multiple simulation runs or multi-dimensional decisions, data management and a suitable reduction of details gain importance. Therefore, e. g. only a representative extract of the results is recommended for displaying in accordance with their mapping to the relevant KPIs. To ensure comparability at this point, it must be ensured that a harmonization of the extract is automatically pursued. Mapping the above-explained challenges (model reuse, replacement, synchronisation, traceability) reveals that model reuse and synchronisation are challenges that have to be dealt with in preprocessing. On the other hand, the model replacement is challenging for pre- and post-processing, as the comparability of results between different simulation composition (traceability) must be ensured. The challenges at run time are here not considered, but are also not affected by the considered challenges.

The framework aims to reach a high degree of automation and user guidance. Nonetheless, manual steps and corrections cannot be excluded, in particular with the limited information availability and at points which require user choice. Such touchpoints shall be realised via a suitable user interface, which provides guidance for these manual steps. When (re)using a model within the simulation system its content is only accessible to a certain degree which calls for further meta information about its validity and boundaries.

That could be delivered with the model itself or already known by the user because of its expertise in the given context. Furthermore, the user has to compose the simulation system and define the scope of one's interest during preprocessing and derives the relevant implications in post-processing for further usage.

5.3. Variable Types and Their Transformation

For the type of simulation system at hand, the terms inputs, outputs, and parameters are distinct. With the former one building together the exchanged variables at run time and the latter defining the model's reality in the pre processing phase. In addition, the start values for the exchanged variables are also set in the pre-processing step. For the post-processing, the outputs are the most relevant category, as they provide the results. In this step, the parameters play a supporting role that their values help to compare the results from different simulation runs. This leads to overlapping between types of variables and simulation phases: Outputs are part of all three phases, inputs of the first two phases and parameters are most prominent in the preprocessing phase and latter supporting.

All three types of variables can appear on the different scales of nominal, ordinal and cardinal values with not necessarily being consistent over the simulation system. Consequently, the transfer between scales is an issue that might appear for exchanged variables the same as for parameters. In addition to the transfer between scales, also the transfer within a scale might be a challenge to be dealt with. In the following, the foreseeable issues are explained scale-wise. Algorithm 1 summarizes the examples for each scale transformation by taking the example of Charge Power of a Vehicle (CPV). All algorithms presented in the following are written according to the notation provided in [236].

Starting with the nominal scale, its contained information limits the transfer to other scales, as the ordinal and cardinal scale requires more information about a value. E. g. the CPV cannot be put in an order to other cars without different information and can also not be mathematically further processed. Within the nominal scale, parameters can be compared to each other regarding equality. Furthermore, NLP can support to overcome inconsistencies between values that are caused by spelling mistakes or naming conventions ("CPV 1" and "CPV_1"). Due to the limited information, a user interaction might be necessary in case of an appearing inconsistency.

Second, the ordinal scale with taking multiple values for CPV of different cars as an example. A descending or ascending list of multiple CPVs can be reached and multiple lists containing an identical entry can be merged. Third and finally, the cardinal scale. In addition to an equality check and ordering, also quantifiable distances of values can be determined.

Algorithm 1 Parameter Transformation

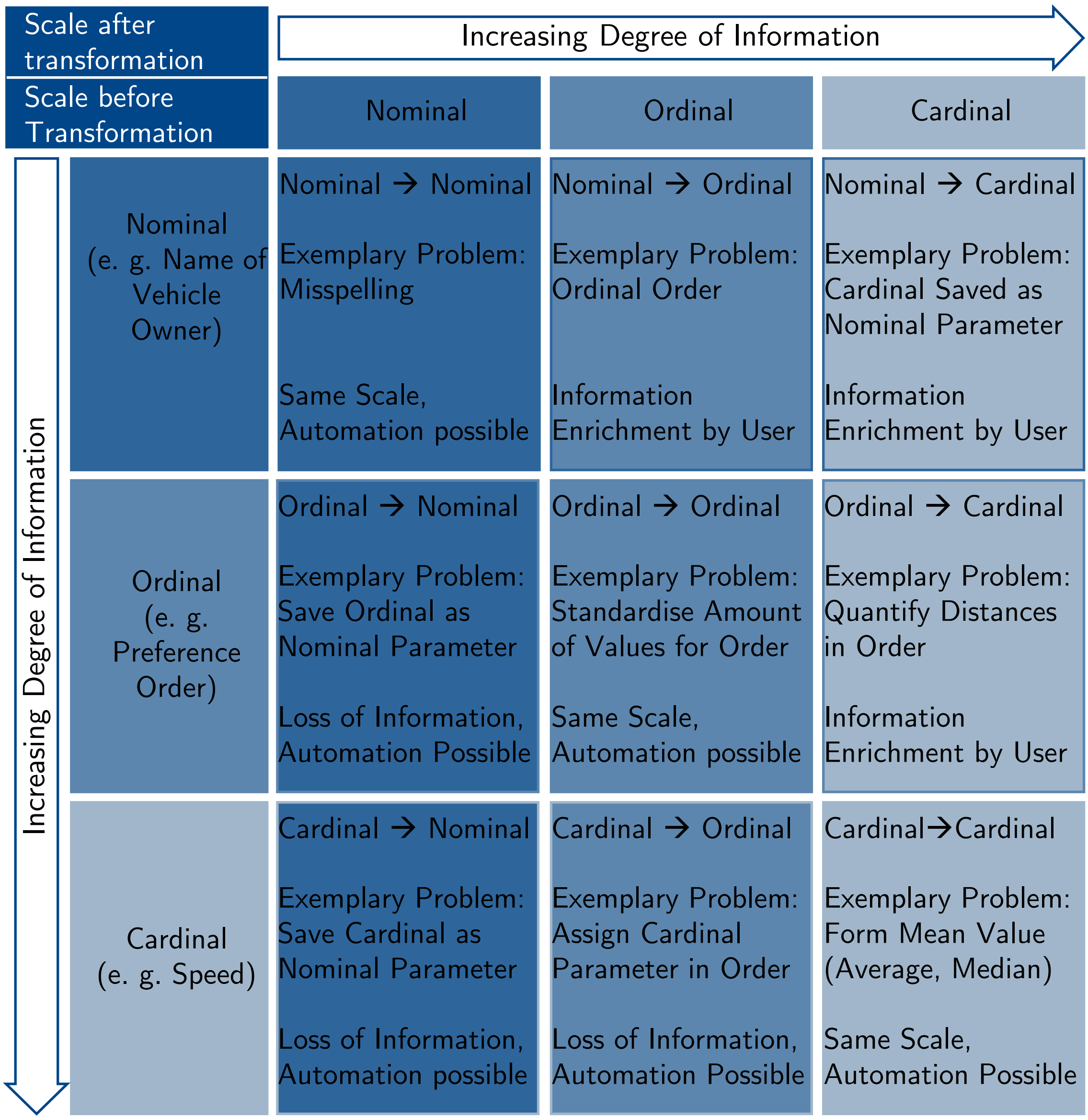
```
Charge Power of Vehicle := CPV                                  ▷ For examples below

$Information_{\text{Nominal}} := I_{\text{N}}$
$Information_{\text{Ordinal}} := I_{\text{O}}$
$Information_{\text{Cardinal}} := I_{\text{C}}$

$I_{\text{N}} \subset I_{\text{O}} \subset I_{\text{C}}$                 ▷ Increasing amount of information available

                                                  ▷ Transformation within a scale
$CPV[kW] \equiv CPV[W] \cdot 1000$                              ▷ Cardinal to cardinal
                                                                ▷ Ordinal to ordinal
$CPV_1 < CPV_2 \cup CPV_2 < CPV_3 \rightarrow CPV_1 < CPV_2 < CPV_3$
$CPV_1 \neq CPV_2 \neq CPV_3 \rightarrow CPV_1 \neq CPV_3$      ▷ Nominal to nominal

                          ▷ Transformation with decreasing degree of information
$CPV_1 \equiv 1.5 \cdot CPV_2 \rightarrow CPV_1 > CPV_2$        ▷ Cardinal to ordinal
$CPV_1 \equiv 1.5 \cdot CPV_2 \rightarrow CPV_1 \neq CPV_2$     ▷ Cardinal to nominal
$CPV_1 > CPV_2 \rightarrow CPV_1 \neq CPV_2$                    ▷ Ordinal to nominal

                  ▷ Transformation with increasing information; enrichment by user
$CPV_1 \neq CPV_2 \cup Input() \rightarrow CPV_1 > CPV_2$       ▷ Nominal to ordinal
$CPV_1 \neq CPV_2 \cup Input() \rightarrow CPV_1 \equiv 1.5 \cdot CPV_2$   ▷ Nominal to cardinal
$CPV_1 > CPV_2 \cup Input() \rightarrow CPV_1 \equiv 1.5 \cdot CPV_2$      ▷ Ordinal to cardinal
```

If values for a variable show inconsistency, e. g. for the start values, the distance between the values can be determined and evaluated whether the difference is relevant. Possible reasons for small inconsistencies could also be numerically or due to rounding. Further inconsistencies could be caused by different units which can be solved by conversion. The conversion formula can be either part of a data base or might require user interaction in case of specific and unforeseeable conversions.

To sum up, the scales offer an increasing share of information beginning with nominal, via ordinal to cardinal. Consequently, a cardinal variable, such as the CPV can be transferred into an ordinal variable without any further information required. E. g. the two values of 100 kW and 150 kW differ by exactly 50 kW, but its also possible to simply rank the two values with the latter being higher than the former. So if model 1 gives the two exact values as outputs, a model 2, requiring a ranking of CPV 1 and 2, can be served without additional information. Figure 29 summarizes the parameter transformation on and between scales. Analysing the other way around, a parameter transformation does require additional information. From a list of ranked CPVs, it can not be derived how much the CPVs differ.

Therefore, the model's documentation must either provide additional information how the list can be further interpreted or the other model requiring a cardinal input must be somehow enhanced to deal with the incoming ordinal parameter.

As parameters are static at run time, conversions of scales is only once required in the preprocessing step, whereas the conversion for exchanged variables might be required during run time. This leads also to the issue that scale conversion appears at a certain point during run time. If such an issue cannot be solved automatically or already foreseen in preprocessing and thereby solved, a user interaction during run time is necessary.



Scale after transformation Scale before Transformation	Nominal	Ordinal	Cardinal
Nominal (e. g. Name of Vehicle Owner)	Nominal → Nominal Exemplary Problem: Misspelling Same Scale, Automation possible	Nominal → Ordinal Exemplary Problem: Ordinal Order Information Enrichment by User	Nominal → Cardinal Exemplary Problem: Cardinal Saved as Nominal Parameter Information Enrichment by User
Ordinal (e. g. Preference Order)	Ordinal → Nominal Exemplary Problem: Save Ordinal as Nominal Parameter Loss of Information, Automation Possible	Ordinal → Ordinal Exemplary Problem: Standardise Amount of Values for Order Same Scale, Automation possible	Ordinal → Cardinal Exemplary Problem: Quantify Distances in Order Information Enrichment by User
Cardinal (e. g. Speed)	Cardinal → Nominal Exemplary Problem: Save Cardinal as Nominal Parameter Loss of Information, Automation possible	Cardinal → Ordinal Exemplary Problem: Assign Cardinal Parameter in Order Loss of Information, Automation Possible	Cardinal→Cardinal Exemplary Problem: Form Mean Value (Average, Median) Same Scale, Automation Possible

Figure 29: Variable transformation by scale

5.4. Tool Chain and Implementation of Framework

This section deals with the implementation of the prior described concepts, functions, and models to provide fundamentals for the subsequent described system configuration. The main artefacts for implementation that have been used are the programming language Python, the model exchange standard FMI, the markup language XML, the data standard Comma Separated Values (CSV) and for frontend design QT. The models' implementation is explained in the corresponding section, in which each model is introduced (Subsections within 4.2).

Overall Tool Chain and Used Standards

For the realisation of the framework at hand, the focus lies on the exploration of solutions and their demonstration for a latter industrial application. Therefore, the external artefacts which are used and developed are aimed to reflect state-of-the-art tooling and formats from industry. On the other side, such artefacts as front end and back end functionalities shall be implemented with regard to the usage of open-source solutions and flexibility for modifications.

The standards of FMI, XML and CSV are widely established within the context of simulation as demonstrated in Sections 3.1 and 3.2. The tool chain to derive a FMU model in general, is used as follows. First, the model is implemented in Python using the specialized packages as required. Second, the whole model functionality is integrated into a class which inherits from the class FMI2Slave which is provided by the package pythonfmu [235]. The incorporation of further scripts, functions and data sources for the latter FMU is also possible - the main advantage of the package "pythonfmu" for which is it chosen here.

Simulation System and Back End

The model's step during run time is defined by the function "do_step" inside the model class. This function is mandatory to be defined and must end by returning the keyword True. Meta-information about the model can be defined in accordance to the fields provided by the FMI standard, e. g. the authors name, the current version and a description. The interface is defined in the model classes' initialization providing the FMI types inputs, outputs and parameters with their corresponding types, e. g. "Real" or "Boolean".

The packages to its version available in mid-2023 only supports the FMI standard 2.0 which does exclude the support of arrays as realised in the standard's version 3.0. A further inconvenience for the latter use of thereby developed models is the requirement of an python instance on the execution instance with all packages that are used inside the models. Although this limits the exchangeability of the developed models, the flexibility and open-source characteristic of the pythonfmu package makes it suitable for the given context.

The used master algorithm bases on the FMPy [237] package as it allows the addition of self-developed automation functions and modification as required because of its full accessibility. The package provides the necessary functions for FMU handling including support for the FMI 3.0 version. In the context at hand, self-developed functions bundle the provided functionality and add functions that are required for building the simulation system, such as defining the connections between inputs and outputs. Further back end functionalities are implemented in python as required, e. g. for data and configuration management.

Front End

For the development of the front end, the decision for QT has two main reasons: First, it is established within the company which makes design components reusable and second, a python back end is realisable via bridge functionalities. The development was conducted in the QT creator using the qml markup language and various packages provided by "QT Quick". From python side, the PySide6 interface for handling "QObjects" is used, complemented by "tkinter" for accessing files on the computing instance. The actual bridge is realised by instantiating a "Bridge" which inherits from "QObject". The data handling and transformation between python and qml is realised via separate functions within the bridge.

Requirements Towards Models

Models shall be available as FMU in its version 2.0 due to the available FMPy master algorithm during the implementation of this work. The benefits regarding array handling in the FMI version 3.0 are advantageous for the handling of models with high amounts of variables and parameters for a detailed specification, e. g. the characteristics diagram for a loading curve of an EV model.

Models shall have meaningful variable names and descriptions as those two pieces of information are analysed via NLP for each variable which is described in the models interface. Furthermore, models must not stand in hierarchy to each other. Consequently, there is no mechanism foreseen that handles subsystems or prioritize the connections between certain models above similar suitable connections.

The model's content shall be reflected in the scenario file as well as in the domain ontology. This is not a mandatory requirement but keeps the manual effort relatively low. In reality the slightly modification of the scenario file is foreseen if models are incorporated from a relatively unknown source. In contrast, the ontology is regarded as holistic regarding the terminology of its scope. Conclusively, models that utilise concepts which are not part of the ontology tend to be regarded as not suitable.

6. System Configuration: Deriving the Simulated Scope

In this section the first part of the simulation system configuration is introduced which builds the core of this work. At first, an introduction to the concept is given explaining its aim and scope. In the following, the first three of five configuration layers are introduced with their individual procedure, dependencies and front end implementation. In Figure 30 an overview about the five configuration steps and the there-after answered questions is provided.

	Configuration Step	Questions Answered Here-After
🎯	KPI	Which are the overall relevant goals?
🔄	Qualitative Interdependencies	Which influencing factors interact with each other accounting for which KPI?
🔍	Simulation Scope	Which models represent the defined influencing factors?
🖧	Model Decomposition	What is the models‘ content and how do the model interact with each other?
🛢	Model Parametrisation	Which scenario is applied to the scenarios and how is the optimisation configured?

Figure 30: Summary of configuration steps

The concept for system configuration sets the framework for the configuration of the simulation system itself and accounts for the traceability and comparability of different configurations and their results. Thereby, its application is by choice not limited to the use case at hand, but considers the needs that arise within the domain of infrastructure development and smart mobility. The concept for system configuration shall not only account for the needs of a specific aim or a given model configuration, but shall allow a consistent and defined path from high level goals to be investigated down to the concrete and consistent parametrisation of a simulation system. Even the considered system shall be not limited to simulation, but shall comprise also further artefacts of virtual engineering.

Consequently, the concept for system configuration supports virtual engineering in the preprocessing as well as in the post-processing phase. On a bigger scale it shall serve as the fundament from which the virtual engineering process is started and accompanies the entire process of virtual engineering.

Therefore, the concept shall not only be feasible to start on a blank page, but also account for adaptability throughout the process and integration of existing models (model reuse). In Section 2, the following four points have been discussed as a motivation for this work: Thinking in systems, rapid development cycles, virtual engineering, and finally, support throughout life cycle. With the concept for system configuration, in particular the points of virtual engineering and thinking in systems are addressed.

Therefore, the concept shall support along the relevant tasks within the system configuration in the development process and accounts for the traceability and comparability of multiple configurations and runs. The basic idea starts with the definition of the high-level goals which are broken down in the following until an executable and parametrised simulation system is derived. This configuration is used to obtain results and optionally uses an optimisation algorithm in which the results of the simulation runs serve as an input. In the post-processing step the traceability of the system configuration allows the derivation of the high level goal fulfilment by using the traceable path reverse. The concept does not aim for a single and exclusive one path to be derived, but to ensure that each concretisation step is compliant to the further step with the need to consider only one prior step within the process.

Starting with the definition of key performance indicators, the system is broken down until a simulation system or more generally, a system for virtual engineering is parametrised. Further aspects of system configuration, such as parallelization of execution and the definition of simulated time, are excluded from the system configuration here. The concept aims to provide a traceable and structured approach to derive a parametrised simulation system from high-level goals, but does not comprise detailed aspects of the simulation and software engineering further down the process.

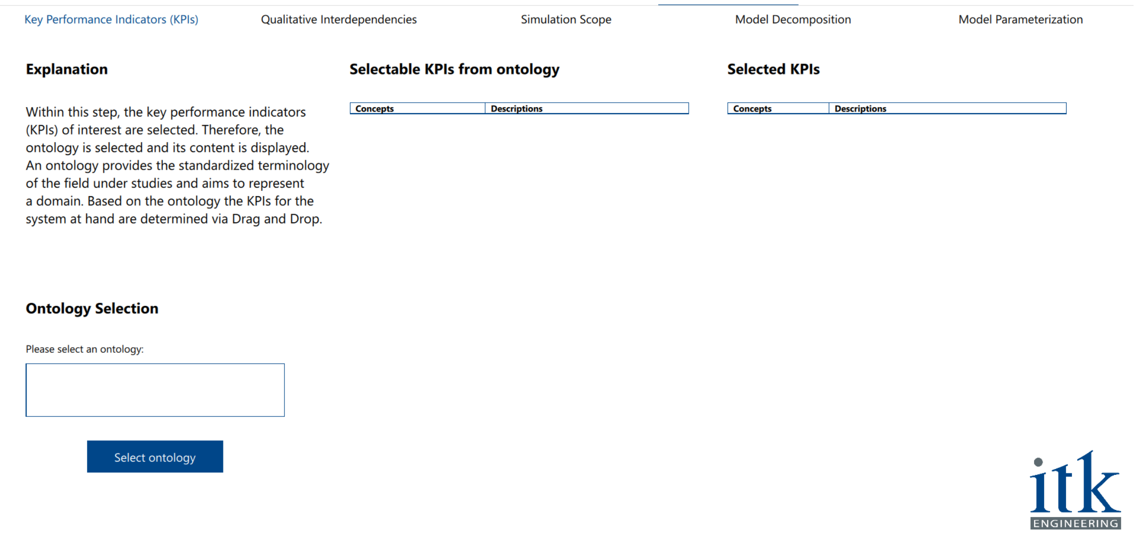
6.1. Definition of KPIs

In this subsection the first configuration layer is introduced: The KPI level. On this level, the general aims to be investigated are defined. It starts with the choice of a suitable domain ontology to the field of study which covers its relevant concepts and relations, ideally an established and broad ontology of the field. The variables for selectable and defined KPIs are instantiated as empty sets and subsequently, the concepts of the ontology are successively added to the variable od selectable KPIs. Only units and relations from the ontology are excluded for this step. From this set of ontology concepts, the KPIs are selected. The minimal number of KPIs is one with no further limit to the maximal amount. Conclusively, this step is done independent on the concrete system or its artefacts and serves as the first configuration step. At the end of this step, the ontology building the terminological and conceptual base for the system configuration is defined beside the KPIs which shall be investigated. The procedure is summarized in Algorithm 2. With the domain ontology, a first external artefact is selected which is further used in the configuration process.

Algorithm 2 KPI Level

```
                                                        ▷ Ontology selected by user
$Ontology := \{Regular\ Concepts \cup Units \cup Relations\} \leftarrow Input()$
$Selectable\ KPIs := \{\,\}$
$Defined\ KPIs := \{\,\}$

for $each\ Concept \in Ontology$ do
    if $Concept \notin Units\ AND\ Concept \notin Relation$ then
        $Selectable\ KPI \leftarrow \{Name\ of\ Concept,\ Description\ of\ Concept\}$
        $Selectable\ KPIs = Selectable\ KPIs \cup Selectable\ KPI$
    fi
od

$Input() \rightarrow Defined\ KPIs \subset Selectable\ KPIs$

Ensure: $Defined\ KPIs \neq \{\,\}, Ontology \neq \{\,\}$
$return :=\ Defined\ KPIs,\ Ontology$
```

Regarding the front end, the KPI level is represented in the first frame as illustrated in Figure 31. The user can select the ontology from which the KPIs shall be selected. By clicking the button "Select ontology" a pop-up window opens which allows the user to browse for the corresponding file and confirm the choice. The content of the ontology is displayed with all selectable concepts and the belonging descriptions.



Explanation

Within this step, the key performance indicators (KPIs) of interest are selected. Therefore, the ontology is selected and its content is displayed. An ontology provides the standardized terminology of the field under studies and aims to represent a domain. Based on the ontology the KPIs for the system at hand are determined via Drag and Drop.

Ontology Selection

Please select an ontology:

Figure 31: Configuration step: KPI level

Thereby, the user gets all selectable KPIs including the details given in the ontology as an overview and can check in parallel the feasibility of the ontology for one's intended purpose. Via drag and drop functionality single KPIs can be selected and dropped in the third column with the selected KPIs. All selected KPIs are displayed in the third column and are deleted from the view of the selectable KPIs. The selected KPIs with their descriptions are stored in the back end as well as the parsed ontology for their further usage.

6.2. Qualitative Interdependencies

Afterwards the level of qualitative interdependencies is described on which interdependencies are defined that relate to individual prior-defined KPIs. The interdependencies are instantiated as an empty set. Each qualitative interdependency consists of one related KPI and two influencing factors. Whereas the KPIs necessarily base on the ontology's concepts, the influencing factor can be defined independent on vocabulary restrictions. Thereby, the influencing factors can either describe a combination of concepts or can express different quantities or shares.

There are two restrictions that do apply: First, for each prior-defined KPI, at least one interdependency must be defined. Second, each interdependency comprises two influencing factors. Consequently, if a chain of multiple influencing factors shall be expressed, several interdependencies must be defined. Therefore, it is allowed to reuse an influencing factor multiple times. After the user's definition of the interdependencies, an analysis of possibly chained interdependencies is conducted as described in Algorithm 3.

The solely input of the function are the defined interdependencies. At the start of the function, the two variables checked and chained interdependencies are instantiated as empty sets. For each interdependency it is checked whether another defined interdependency contains either the same KPI or an identical factor. Conclusively, a chained interdependency consists of at least two interdependencies. The minimal number of chained interdependencies is zero for defined interdependencies without any overlapping regarding KPIs or factors.

On the other side, at maximum all defined interdependencies can be related to each other. In the end the function returns the identified chained interdependencies as a set which is possibly empty as explained above. Thereafter, a redundancy check of the interdependencies is conducted. At the end of the actual process step the qualitative interdependencies are defined that shall be considered by the simulation system under configuration. Consequently, the step returns the defined interdependencies and the chained interdependencies. The belonging procedure is summarized in Algorithm 4.

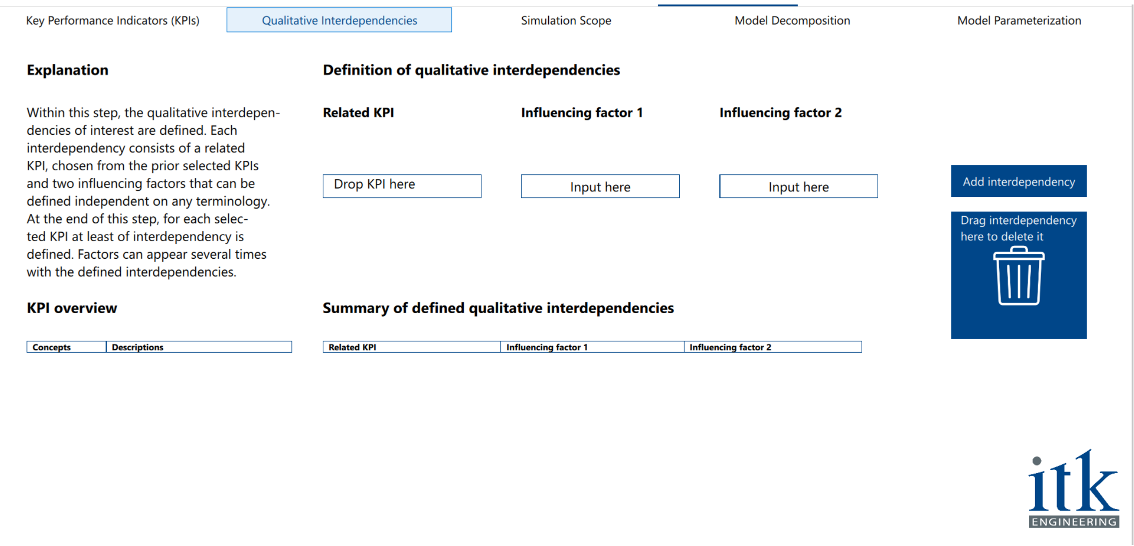
Algorithm 3 Function: Analysis of Chained Interdependencies

```
function ANALYSE CHAINED INTERDEPENDENCIES(Interdependencies)
                                ▷ Interdependencies abbreviated as $Interdep.$ here-after
    $Checked\,Interdeps. := \{\,\}$
    $Chained\,Interdeps. := \{\,\}$        ▷ Abbreviated as $Chai.Interdeps.$ here-after

    for $each\,Interdep._1 \in Interdeps.$ do
        for $each\,Interdep._2 \in Checked\,Interdeps.$ do

            if $KPI\;of\;Interdep._1 \equiv KPI\;of\;Interdep._2$ then
                if $KPI \in Chai.\,Interdeps.$ then                ▷ Complement chain
                    $Chai.\,Interdep._{\mathsf{KPI}} = Chai.\,Interdep._{\mathsf{KPI}} \cup Interdeps_1$
                fi
            else                                                   ▷ Create new chain
                $Chai.\,Interdeps. = Chai.\,Interdeps. \cup \{Interdep._1\,,\;Interdep._2\}$
            fi

            if any $Factor\;of\;Interdep._1 \equiv$ any $Factor\;of\;Interdep._2$ then
                if $Factor \in Chai.\,Interdeps.$ then
                    $Chai.\,Interdep._{\mathsf{Factor}} = Chai.\,Interdep._{\mathsf{Factor}} \cup Interdep._1$
                fi
            else
                $Chai.\,Interdeps. = Chai.\,Interdeps. \cup \{Interdep._1,\;Interdep._2\}$
            fi
        od

        $Checked\,Interdeps. = Checked\,Interdeps. \cup Interdep._1$
    od

    $return := Chai.\,Interdeps.$
end function
```

The front end (see Figure 32) is designed as follows: In the left column the priorly selected KPIs are displayed beside the explanation field for this configuration step. The definition of the qualitative interdependencies requires the definition of one related KPI and two influencing factors as explained above.

Algorithm 4 Qualitative Interdependencies Level

```
                                ▷ Factors can be defined free from any vocabulary restrictions
Require: Defined KPIs from KPI Level
$\{KPI,\ Factor_1,\ Factor_2\} \rightarrow Interdependency$
$Interdependencies := \{\ \}$

for $each\ KPI \in Defined\,KPIs$ do
    while User wants to define further Interdependency do
        $KPI \rightarrow KPI_{\text{Interdependency}}$
        $Input() \rightarrow Factor1_{\text{Interdependency}}$
        $Input() \rightarrow Factor2_{\text{Interdependency}}$
        $Interdependencies = Interdependencies \cup Interdependency$
    od
od

                                ▷ Analysis of relations between interdependencies
Chained Interdependencies = Analyse Chained Interdependencies(Interdepends.)

                                ▷ No interdependency is doubled
Ensure: $Interdependency \notin Interdependencies \setminus Interdependency$
$return := Interdependencies, ChainedInterdependencies$
```



Explanation

Within this step, the qualitative interdependencies of interest are defined. Each interdependency consists of a related KPI, chosen from the prior selected KPIs and two influencing factors that can be defined independent on any terminology. At the end of this step, for each selected KPI at least of interdependency is defined. Factors can appear several times with the defined interdependencies.

Definition of qualitative interdependencies

Related KPI | **Influencing factor 1** | **Influencing factor 2**

KPI overview

Concepts	Descriptions

Summary of defined qualitative interdependencies

Related KPI	Influencing factor 1	Influencing factor 2

Figure 32: Configuration step: Qualitative interdependencies

The related KPI is selected by drag and drop from the KPI overview into the corresponding field for definition. As multiple interdependencies can be defined relating to the same KPI, a one-time selected KPI is not deleted from the overview. When the user has selected the related KPI and has put it, the two influencing factors, the definition of this specific interdependency is confirmed by pressing the button "Add interdependency". Subsequently, the interdependencies appear in the summary below. If a defined qualitative interdependency shall be deleted, it can be dragged from the summary view and dropped in the corresponding field for deletion at the right. The step is finished when for each KPI at least one interdependency is defined. The chained interdependencies are processed automatically in the back end.

6.3. Simulation Scope

It follows the definition of the simulation scope which comprises the selection of suitable pre-defined scenarios and the models that shall form together the co-simulation. The step requires the defined interdependencies and the parsed ontology as inputs. The factors contained in the defined interdependencies are extracted and the model assignments are instantiated as an empty set. The scenarios contained in the scenario file define the scope and settings that are possibly evaluated by the help of the simulation system. The scenario file shall base on the domain ontology which is priorly selected to ensure it matches its concepts. Thereby, the scenario file restricts the simulation scope to a certain set of combined parameter values, the so-called scenarios. The scenario shall match the models' content, but do not necessarily comprise every parameter nor variable of the models. Although, such a coverage would be required for a fully automated process, this requirement is not applied here to broaden the applicability of existing artefacts such as defined scenarios or models. Nonetheless, the scenarios must contain the relevant parameters and values which are of high importance for the field under investigation.

Furthermore, the models are selected which form together the co-simulation system. The incorporated models are chosen with regard to the prior-defined influencing factors. It applies the restriction that each model must represent at least one influencing factor which is stored in the variable model assignments. The maximal amount of influencing factors represented by one model is not restricted. Thereby, an interdependency can be either broken down into the interaction of two models or can be entirely represented by one model.

At the end of the simulation scope, the scenario file is selected which defines the parameter space for the later simulation runs and the models forming the simulation system are selected and mapped to the influencing factors under consideration. Thereby, the artefacts that are used for simulation execution are defined within this configuration step. The algorithm is summarized in Algorithm 5.

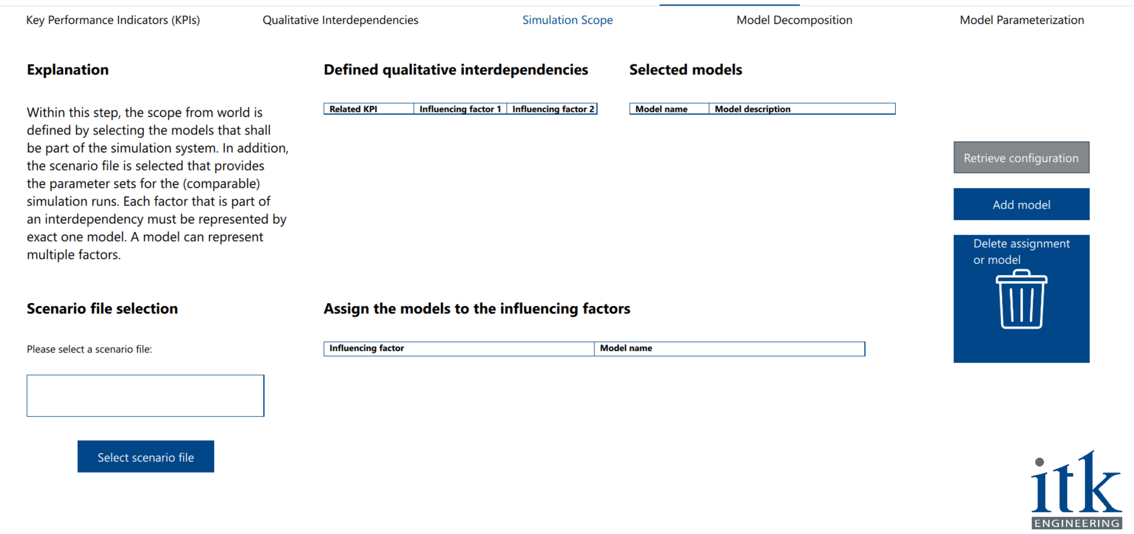
Algorithm 5 Simulation Scope

```
Require: Defined Interdependencies from Qualitative Interdependency level
Require: Ontology from KPI level

$Factors \in Defined\,Interdependencies \to All\ Factors$          ▷ Extract all factors
$Model\ Assignments := \{\ \}$
$Factor,\ Simulation\,Model \to Model\ Assignment$

for $each\,Factor \in All\ Factors$ do
    $Input() \to Model$                                             ▷ User choice
    $Factor,\ Model \to ModelAssignment_{\mathsf{Factor}}$
    $Model\ Assignments = Model\ Assignments \cup Model\ Assignment_{\mathsf{Factor}}$
od

$Scenarios := \{\ \}$
$Input() \to Scenario\,File$                                        ▷ User selects scenario file

Ensure: $One\,Model \to Each\,Factor$
$return := Model\ Assignments,\ Scenario\,File$
```

The belonging front end starts with the selection of the scenario file in the left column as illustrated in Figure 33. When clicking the "Select scenario file" button, a pop-up window opens in which the user can browse for the corresponding file and confirm its choice. Having selected a scenario file, the contained scenarios are parsed and stored in the back end. In the frame's centre the defined qualitative interdependencies from the prior view are displayed. By the button "Add model" a pop-up window opens in which the user can browse for the model in FMU-format to be selected and confirm its choice. By the confirmation, the model is automatically unzipped and its model description is parsed with the content being stored in the back end. From this information, the model name and the description attribute of the model description is added to the displayed overview about the selected models.

Finally, the assignment of the models to the influencing factors is conducted. All influencing factors that take part in the defined qualitative interdependencies are displayed as a list to which the selected models are assigned via drag and drop. This results in an overview of the assignments in the centre bottom of the frame.

If an assignment needs to be corrected, it can be deleted via drag and drop to the corresponding field at the right, in analogy to the prior frame with the qualitative interdependencies. The assignments are stored in the back end and the configuration step is completed, when a scenario file is selected and a model is assigned to each influencing factor.



Within this step, the scope from world is defined by selecting the models that shall be part of the simulation system. In addition, the scenario file is selected that provides the parameter sets for the (comparable) simulation runs. Each factor that is part of an interdependency must be represented by exact one model. A model can represent multiple factors.

Please select a scenario file:

Figure 33: Configuration step: Simulation scope

Additionally to the manual selection of the scenario file and the models, a "Retrieve configuration" button is intended. This function shall enable the reuse of a priorly defined configuration, as each configuration is intended to be stored automatically when the simulation is started. With the retrieve of a configuration, the subsequent steps of model decomposition and model parametrisation are conducted automatically as well. This retrieve functionality is helpful e. g. a model bug was fixed without the need of facade changes.

At this point in the process of system configuration, the transition is made between the derivation of a simulation system composition on the one side and an executable and consistently parametrised simulation system on the other. To reach the simulation system composition, KPIs and qualitative interdependencies have been defined which are then reflected in the selected simulation models. These selected simulation models together build the simulation system which is finally executed for one or multiple scenarios from the scenario file. The realisation of the executable simulation system is described in the following Section 7.

7. System Configuration: Realising the Executable System

This chapter deals with the final two steps of the proposed simulation system configuration, "Model Decomposition" and "Model Parametrisation". Starting point is the simulation system composed by simulation models from which an executable co-simulation system is derived. Required artefacts from the previous steps comprise an ontology, defined KPIs and qualitative interdependencies as well as the assignment of simulation models to the factors within the interdependencies. As the step of "Model Decomposition" strongly relies on the application of NLP to match variables to their belonging ontology concepts, the fundamentals of the NLP application in this work are introduced at first.

7.1. Matching Variables to Ontology Concepts

A major step towards a consistent parametrisation is the clustering of the models' parameters and variables to the concepts of the domain ontology at hand. This challenge is part of the field of semantic interoperability. The ontology is here defined and regarded as a representative entity for the domain and therefore it builds the fundament to which the models are mapped by NLP. The task to be solved by NLP can be summarized as identifying the concept from the ontology from which a model's variable or parameter is an instance of.

Within the FMU standard, the available data of a model is available in a (semi-)structured form. The so-called modelDescription.xml is part of each FMU and provides information about the parameters, inputs and outputs of the model as well about the model itself, an exemplary extract, besides an ontology extract, is illustrated in Figure 34. The latter can be interpreted as meta-model. An important distinction has to be made between mandatory and optional fields for which details can be found in the FMI specification [43]. For the matching itself, only variable or parameter specific data is analysed with the two fields of (variable) name and its corresponding description. Further (optional) data, such as variable type or its unit are analysed at another point.

With the methodology an automated switch between the processing of general and domain-specific language is performed. A domain-specific fine-tuning of transformer models is conducted to account for the limited available training data from the domain of the use-case. The differentiation between general and domain-specific languages demonstrates an increased matching precision compared to out-of-the-box models. The performance evaluation has been conducted in comparison to traditional string-matching algorithms.

The choice for NLP lies in the limited availability of information in general with a majority of information being available in form of text which does not necessarily provide a structure. For the practical work with the here-developed framework, a full automation is highly questionable for matching. The provided information quality and precision by variable names and there description highly differs as both fields are filled by the model's developer without further restrictions. Meaningful variable names are good practise but first not mandatory and second, might leave room for interpretation due to different terminology in a company or domain. Consequently, a variable naming along a suitable domain ontology is recommended.

Due to the varying information available about the individual parameters and variables, the matching can only overcome a limited amount of inconsistency which can be hardly specified or quantified. In particular, variable names with different meanings in different contexts, so-called homonyms, can be only differed by a meaningful accompanying description. An example for a homonym is objective which can either mean a goal or a camera lens. Therefore, the matching mainly serves a user support with the aim to partially automate the matching processing.

```
<? xml verison = "1.0" encoding
  = "UTF-8"2>
< fmiModelDescription
   < ModelVariables >
      < ScalarVariable
           name = "capacity in kw"
           valueReference = "1234"
           description = "indicates
            the battery
capacity of
           an electric vehicle in kw"
           causality = "parameter"
           variability = "fixed"
            < Real unit = "kW"
          start = "40.0"/>
     </ScalarVariable >
```

```
< owl: Class rdf: about = "ParkingArea" >
   < rdfs: subClassOf rdf: resource =
      "ParkingOntology Thing"/>
   < owl: Restriction >
      < owl: onProperty rdf:resource =
               "hasChargingStations"/>
      < owl: onDataRange rdf: datatype =
         "Integer"/>
   </owl: Restriction >
   < owl: Restriction >
      < owl: onProperty rdf: resource =
         "hasParkingPolicy"/>
      < owl: allValuesFrom rdf: resource =
        "ParkingPolicy"/>
   </owl: Restriction >
  < rdfs: label xml: lang = "en"> Parking
       Area </rdfs: label >
  < rdfs: comment xml: lang = "en "> A
             Parking Area refers to some
             area that eneables parking of
             Vehicles.</rdfs:comment>
</owl: Class>
```

Figure 34: Exemplary comparison of structure between model description and ontology

The characteristics of the available model and ontology data are compared and summarized in Figure 35. The comparison of available information is a major step to connect information from heterogeneous systems, e. g. the data type can be only considered for analysis if this piece of information is available in both systems. From the comparison it can be concluded that information regarding values, value range and variability cannot be compared due to a lack of available information. Therefore, the matching uses the information about label, description, data types and units.

Characteristics	**Model Description**	**Ontology Data**
Markup Language	Extensible Markup Language (XML)	Web Ontology Language (OWL)
Degree of Abstraction	Low, Detailed	High, Abstract
Relations	None	Parent-child, Properties, Associations
Organisation	None	Hierarchy
Language	English	Multilingual
Label	One Label	Preferred and Optional
Style	Lower Case, Singular	Upper Case, Plural

Figure 35: Comparison of characteristics between ontology and model data

In addition to the NLP-based matching, further provided information concerning the parameters and variables is analysed. This refers to the field of constraint-based matching. For NLP the information about label and description is taken, whereas for the further analysis the data types and units are used. Such information is here processed in a secondary way as this information accounts more for exclusion of possible matches than selecting a specific match between the ontology's concept and a model's variable.

As the task of matching models with an ontology is similar to that of matching multiple ontologies to each other, established techniques from this field are adopted. Heterogeneity in terms of syntactic, terminological, pragmatical and conceptual heterogeneity have to be overcome. The conceptual heterogeneity is mainly caused by the different degrees of abstraction with the models' parameters as instances whereas the ontology defines classes. Terminological heterogeneity results from the (partly) different naming for elements with the same meaning. The focus of the developed solution mainly deals with these two types of heterogeneity. Whereas syntactical heterogeneity can be easily overcome by NLP and is therefore not in focus, pragmatic heterogeneity is a limit of the automated matching process. Examples for the conceptual and terminological heterogeneity between the model data and domain ontology at hand is provided model-wise in Figure 36.

Model	**Model Variable**		**Ontology**
	Terminological Heterogeneity		
CPO	Charging Point Operator	→	Operated by
	Is Not Private	→	Valid for Public
Grid	Start Date	→	Time Start Value
	Charging Session Duration	→	Recharge Time in Min
User	Alternating Current Connection Point	→	Current Type AC
	Customer of	→	Service User
	Conceptual Heterogeneity		
CPO	Maximum Parking hours	→	Duration Description
	Latitude/Longitude	→	Location
Grid	Renewable Energy	→	Energy Source
	Structure Operational	→	Supply Equipment Record
User	CHAdeMO	→	Connector Standard
	Mini-compact A-segment	→	Vehicle Type

Figure 36: Examples for terminological and conceptual heterogeneity model-wise

For the element-wise matching, the ontology consisting of classes (c), data properties (p) and individuals (ind) is summarized to one entity as well as all entries of one model to another entity. For each element of the first entity, a candidate from entity 2 is determined sequentially by the criterion of highest similarity. The model elements label and description are analysed separately from each other. The similarity of the labels and the description are then combined to the overall similarity assessment.

The procedure for the similarity assessment is differed in general information and domain-specific information. The classification is conducted by the help of a context-independent embedding model. If the label of the element is not part of this embedding model, it is considered Out of Vocabulary (OOV) and is treated with a domain-specific approach. This domain-specific approach solely differs in the processing of the description.

The implementation is realised in Python [222] by using the following packages. The extraction of the ontology's information is conducted with Owlready2 [238]; for the model descriptions' extraction ElementTree [222] is used. For the further processing of the label and corresponding descriptions punctuation, upper cases and space characters are deleted as these are not needed in the following process.

Stop words, e. g. articles and conjunctions, are only deleted for the processing in word embeddings, but needed for the processing by the transformer models. In contrast to parts of the related work, numerical characters are not excluded as they may have importance e. g. to differentiate between different plug types.

Whereas the model description does not provide structural information, the domain ontology does. This information is processed as follows: For each element of the ontology, a label chain is built consisting of the corresponding super and sub classes of the class under analysis. This information is only processed if at least one super and one sub class is available. The processing of the label chain is conducted by pandas [239]. Further information is taken from the label chains of data properties. If such a data property is matched to a model element, its related class as well as its associated data type is analysed. The data type forms a constraint that allows the exclusion of options rather than allowing the initial identification of a match. Nonetheless, its incorporation increases the overall matching quality.

For the realisation of the context-sensitive transformer models, the SBERT [240] as base model is trained in two ways, one time supervised and the other unsupervised. This so-called fine tuning is realised by the package PyTorch and Transformers [241], [242] with data from Semantic Scholar [243]. For the supervised training, the same set of data is used. The additionally required target variables are acquired as follows: For each of the publication's abstract, the contained sentences are combined to pairs and labelled positively. All other combinations of sentences that appear across papers are labelled negatively.

The comparison of data types and units are realised by a conservative distance function. The distance is determined by the function sequenceMatcher of the package difflib [222]. The analysis of available units is realised analogously with a further step of standardization by the package Pint. The result of this additional information is not directly incorporated in the matching result, but provided to the user in the user interface for the manual assessment of the automated matching process.

For the evaluation of the developed matching algorithm, a representative model is created based on the ontology Open Mobility Vocabulary (MobiVoc) which deals with future-oriented mobility solutions [244]. To ensure the representativeness of the model, only the instances of the ontology are used for the set of model elements. The resulting model consists of 70 model parameters and variables with 29 of them being domain-specific and 41 general elements following human evaluation.

As established evaluation methods such as precision, recall and F1-score are not applicable due to the lacking ground truth [245], the algorithm's application to the representative model forms the evaluation. The accuracy (see formula below with n representing the amount of sentences to be analysed) of the matching assessed by human interpretation is analysed. The evaluation shows a decreased performance when incorporating structural information from the ontology.

$$Accuracy = \frac{true\,positives + true\,negatives}{n} \tag{2}$$

The clustering into domain-specific and general vocabulary works well with the word embedding models not assigning any domain-specific element to the general language. Although both tested embedding models did not cluster all of the human-defined 29 elements into the domain-specific cluster, this does not reduce the quality of the matching algorithm at all. As the fastText model performs slightly better, it is taken as the final word embedding in this work. Regarding the transformer models, the out-of-the-box model SBERT performs best in terms of accuracy and the model for the domain-specific data supervised pre-trained SBERT does so. For that defined combination the accuracy of the matching is assessed for different threshold values summarized in Table 2. The threshold value is here defined as the minimum value for which a match is incorporated on a scale from 0 (no match) to 1 (safe match). Conclusively, the best results are reached by equally combining the similarity assessment of labels and descriptions.

Operator	Threshold **0,6**	Threshold **0,8**	Maximum	Sum	Threshold **1,0** (without label)
Accuracy [%]	58,6	60,0	58,6	65,7	61,4

Table 2: Accuracy of different configurations of the matching between ontology and the representative model

The evaluation revealed five error types. First, the ontology contains redundant elements which results in a model element being compatible with multiple ontology elements. Second, inconsistencies do appear in the combined ontology. This results in the matching of an incorrect element because of its better fitting description. Third, the element's description lacks information. Fourth, insignificant and misleading information leads to mismatches. Fifth, the semantic was not processed correctly and comprehensively. A systematic bias might be caused by the training data as it origins from the scientific domain, more precisely from abstracts of scientific publications between 2015 and 2022. Recent development within the smart mobility domain are therefore not incorporated. Moreover, pragmatic heterogeneity cannot be overcome as language is interpreted differently by different persons.

The application within the given context is conducted as summarized in Algorithm 6 and explained in the following. The variable's name, the parsed ontology and optionally, the variable's description, are taken as inputs. The candidate, a concept from the ontology, is instantiated empty and the maximal similarity is set to 0.

For each concept from the ontology, the overall similarity, the name's similarity and the description's similarity are reset to 0. Afterwards, the name's similarity is compared to the ontology concept's name. If there is a description for the variable as well as for the ontology concept, the comparison is also conducted for these two descriptions. Consequently, the overall similarity is either the mean from name and description comparison or solely the name's similarity. If the overall similarity of the currently checked concept exceeds the value of the maximal similarity identified before, a new best candidate is identified and therefore assigned. The function returns the matched concept, as the candidate with highest similarity as well as the matching precision for this result. The application within the system configuration is conducted in the following Subsection 7.2.

Algorithm 6 Application of Natural Language Processing

```
function APPLYNLP(Name_Var, Ontology, optional: Description_Var)
    $Candidate := \{\}$
    $Maximal\ Similarity = 0$                    ▷ All similarity values between 0 and 1

    for $each\ Concept \in Ontology$ do
        $Overall\ Similarity := 0$
        $Similarity_{\mathsf{Name}} := 0$
        $Similarity_{\mathsf{Description}} := 0$
        $Similarity_{\mathsf{Name}} = compare(Name,\ Ontology\ Concept)$

        if $Description \neq ''\ '' \wedge Concept\ Description \neq ''\ ''$ then
            $Similarity_{\mathsf{Concept}} = compare(Description_{\mathsf{Var}}, Description_{\mathsf{Concept}})$
            $Overall\ Similarity = 0.5 \cdot Similarity_{\mathsf{Name}} + 0.5 \cdot Similarity_{\mathsf{Description}}$
        else
            $Overall\ Similarity = Similarity_{\mathsf{Name}}$
        fi

                                                 ▷ New best candidate identified
        if $Overall\ Similarity > Maximal\ Similarity$ then
            $Maximal\ Similarity = Overall\ Similarity$
            $Concept \rightarrow Candidate$
        fi
    od

    $Maximal\ Similarity \rightarrow Matching\ Precision$
    $Candidate \rightarrow Matched\ Concept$

    $return := Matched\ Concept,\ Matching\ Precision$
end function
```

7.2. Model Decomposition

Within the fourth step of system configuration the parameters and variables of the selected models are analysed and mapped to the concepts of the domain ontology. Details of the process and used technology for mapping are elaborated above in Subsection 7.1, whereas here the underlying idea is explained. As the models are assumed to come from different origins, a harmonized naming, already according to a single domain ontology cannot be requested. On the other side, their integration into one simulation system requires an understanding of the models' individual contents first, and moreover, the mapping of outputs from each model to the corresponding inputs of the further models. For both requirements, the following solution is pursued. The models' parameters and variables are matched to their corresponding concepts within the domain ontology. As the domain ontology aims to contain all relevant concepts, the mapping shall be possible, even the parameter or variable naming itself differs. Having mapped all parameters and variables to the domain ontology, the similarities in required parameters become evident as well as which inputs and outputs of the different models describe the same concept. Based on the mapped variables, the connections in form of the belonging inputs and outputs in the simulation system are automatically set.

The detailed procedure is summarized in Algorithm 7 requiring the model assignments and the scenario file from the simulation scope level and the ontology from the KPI level. At first, an empty set to collect all variables is instantiated. Subsequently, the scenarios in the scenario file are checked for their vocabulary as described in Algorithm 8. Therefore, each scenario is clustered for its name, e. g. "trend" or "optimistic" as well as the year it is describing, and finally parsed. Afterwards, for each descriptor in each scenario it is checked whether the descriptor is part of the ontology. If this case does not apply, the application of NLP is conducted in analogy to the procedure as applied for the matching of the models' variables. When not reaching a minimal matching precision of 0.8, a manual assignment is required.

For the belonging unit of the descriptor, its appearance in the ontology is also checked. If the assignment was unsuccessful, the user is required to input a unit conversion of the descriptor's unit as a combination of units which is known by the ontology. The function returns the processed scenarios in which the original descriptors are replaced by their belonging concepts from the ontology.

The procedure of the step "Model Decomposition" continues with the parsing of the models. For each model, the model variables are reset to an empty set and the modelDescription.xml is parsed. For each variable within this file, the following attributes are stored: the model to which the variable belongs, the variable's name, its description, the type (parameter, input or output) as well as the variable's unit. Having parsed all variables of one model, the set of variables with their attributes are stored in "All Variables".

Algorithm 7 Model Decomposition

```
Require: Model Assignments and Scenario File from Simulation Scope Level
Require: Ontology from KPI Level
$All\,Variables := \{\,\}$

                    ▷ Check if vocabulary in scenario file matches ontology concepts
Scenarios = Check Descriptors' Vocabulary(Scenario File)

                    ▷ Unpack models and create overview about contained variables
for $each\,Model \in Model\,Assignments$ do
    $Model\,Variables := \{\,\}$
    Model Description = unzipModel(modelDescription.xml)

                    ▷ Get type; either be parameter, input or output
    for $each\,Variable \in modelDescription$ do
        $Model_{\mathsf{Var}},\ Name_{\mathsf{Var}},\ Description_{\mathsf{Var}},\ Type_{\mathsf{Var}},\ Unit_{\mathsf{Var}} \rightarrow Attributes_{\mathsf{Variable}}$
        $Model\,Variables = Model\,Variables \cup Attributes_{\mathsf{Var}}$
    od

    $All\,Variables = All\,Variables \cup Model\,Variables$
od

                    ▷ Match model variables with ontology concepts
Model Variables = Match Models and Ontology(Ontology, Model Variables)

                    ▷ Set connections between inputs and outputs
Connections = Set Connections(Model Variables)

Ensure: $Ontology\,Concept \rightarrow each\,Variable$
Ensure: $Ontology\,Unit \bigvee Unit\,Conversion \rightarrow each\,Unit_{\mathsf{Var}}$
Ensure: $Output \rightarrow each\,Input$
$return := Matched\,Variables,\ Matched\,Units, Connections\,between\,Variables$
```

The two core functions comprise the matching of the models' variables to the ontology concepts (see Algorithm 9) and the setting of connections between inputs and outputs of the models (see Algorithm 10) which are further explained in the following.

The function to match models to ontology concepts takes the parsed ontology and the set of model variables as inputs. For each model variable it is checked first whether an ontology concept is semantically identical with the variable. In this case no further processing is required as the variable directly matches a concept of the ontology. In the other case, NLP as described in Algorithm 6 is applied.

Algorithm 8 Function: Check Descriptors' Vocabulary

```
function CHECK DESCRIPTORS' VOCABULARY(Scenario File)
    for $each\ Scenario \in Scenario\ File$ do
        $Scenario\ Name,\ Described\ Year \rightarrow Attributes_{\text{Scenario}}$
        Scenario Descriptors = ParseScenario(Scenario)

        for $each\ Descriptor \in ScenarioDescriptors$ do
            if any $Ontology\ Concept \equiv Descriptor$ then
                pass                    ▷ Descriptor matches concept of ontology
            else
                Mat. Concept, Mat. Precision = applyNLP(Descriptor, Ontology)
                if $Matching\ Precision \geq 0.8$ then
                    $Matched\ Concept \rightarrow Descriptor$
                else                    ▷ User selects concept from ontology
                    $Input() \rightarrow Matched\ Concept$
                fi
            fi

            if any $Unit\ in\ Ontology \equiv Unit\ of\ Descriptor$ then
                pass                    ▷ Unit of descriptor is in ontology
            else                        ▷ User defines conversion into units in ontology
                $Input() \rightarrow Unit\ Conversion$
                $Unit\ Conversion \rightarrow Descriptor$
            fi

        od
        $Scenarios = Scenarios \cup Scenario$
    od

    $return := Scenarios$
end function
```

Assuming the case of a sufficient matching precision of at least 0.8, the matched concept is added as a further attribute to the variable. Otherwise, the user is requested to select the matching concept manually from the ontology. Subsequently, the variable's unit is treated. At first, its appearance in the ontology is checked. If the unit is not part of the ontology, the user is requested to provide a unit conversion into units which are part of the ontology. In case, a unit conversion is required, it is added to the variable's attributes. Finally, the function returns the model variables including the additional information as described above.

Algorithm 9 Function: Match Models and Ontology

```
function MATCH MODELS AND ONTOLOGY(Ontology, Model Variables)
    for $each\,Variable \in Model\,Variables$ do
        if any $Ontology\,Concept \equiv Variable$ then
            pass                                  ▷ Variable matches concept of ontology
        else
            Matched Concept, Matched Precision
              = applyNLP(Name$_{Var}$, Descrip$_{Var}$, Ontology)

            if $Matching\,Precision \geq 0.8$ then
                $Matched\,Concept \rightarrow Variable$
            else
                $Input() \rightarrow Matched\,Concept$       ▷ User select concept from ontology
            fi
        fi

        if any $Unit\,in\,Ontology \equiv Unit\,of\,Variable$ then
            pass                                  ▷ Unit of variable is in ontology
        else                                      ▷ User defines conversion into units in ontology
            $Input() \rightarrow Unit\,Conversion$
            $Unit\,Conversion \rightarrow Attributes_{Var}$
        fi
    od

    $return := Model\,Variables$
end function
```

The second core function (see Algorithm 10) sets the connections between the models' inputs and outputs. The model variables, processed by the matching function described in Algorithm 9, are taken as the input and the connections are instantiated as an empty set. For each model the procedure starts with the extraction of the input variables. In the following, the outputs within the remaining models are extracted.

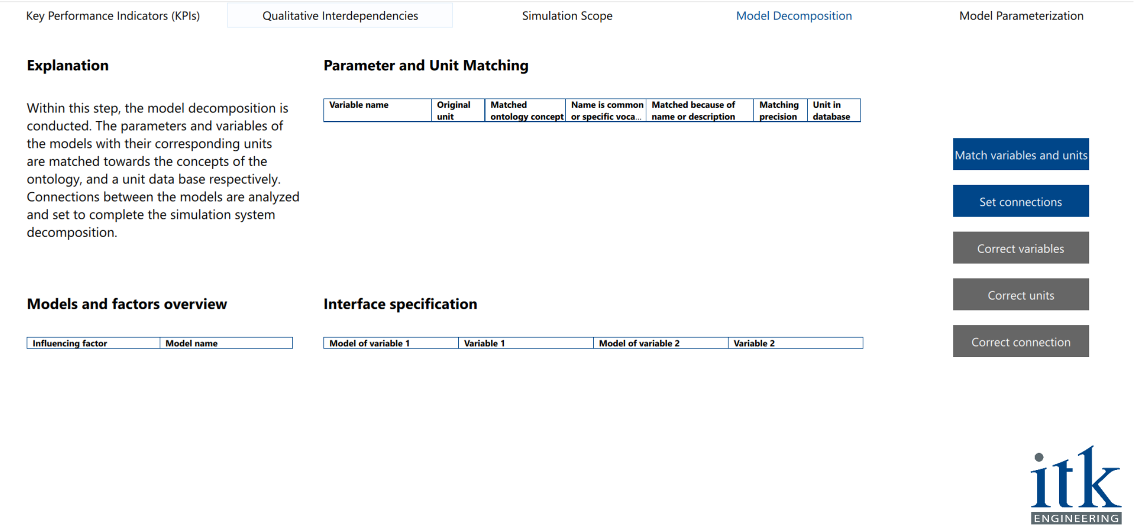
All outputs that were priorly matched to the same ontology concept as the input are assigned as individual connections. To define the specific output which shall serve the analysed input, three cases are distinct: First, if exactly one connection was identified, the participating output is also the serving output and no further definition is made. In the case that no connection was identified, a warning is displayed and the user is requested to select the serving input manually. Finally, in case of multiple individual connections, the user selects the output which shall serve the input for the specific configuration. The function returns the set of connections.

Algorithm 10 Function: Set Connections

```
function SET CONNECTIONS(Model Variables)
    $Connections := \{\}$
    for $each\ Model\ 1 \in Model\ Assignments$ do
        Inputs$_{\text{Model 1}}$ = extractInputs(All Variables$_{\text{Model 1}}$)
        for $each\ Model\ 2 \in Model\ Assignments \setminus Model 1$ do
            Outputs$_{\text{Model 2}}$ = extractOutputs(All Variables$_{\text{Model 2}}$)
        od

        for $each\ Input \in Model\ 1$ do
            $Individual\ Connections := \{\}$
            if $Input_{\text{Concept}} \equiv Output_{\text{Concept}}$ then
                $Ind.\ Connections = Ind.\ Connections \cup \{Input,\ Output\}$
            fi
            if $Number\ of\ Connections \equiv 1$ then
                                        ▷ Exactly one output identified to serve input
                $Output \rightarrow Serving\ Output$

            else if $Number\ of\ Connections \equiv 0$ then
                                        ▷ No output found to serve input
                $Input() \rightarrow Serving\ Output$          ▷ User choice

            else
                                        ▷ Multiple outputs require user choice
                $Input() \rightarrow Serving\ Output$          ▷ User choice
            fi
            $Input,\ Serving\ Output \rightarrow Connections$
        od
    od

    $return := Connections$
end function
```

Finally it is ensured that each variable has an ontology concept assigned, each variable's unit has either an assigned ontology unit or a belonging unit conversion and that each model's input is served. The matched variables, matched units and connections between the variables are returned by this process step. By the end of the end of this step, the simulation system is decomposed with the models' parameters and variables being mapped to the ontology and the connections between the models being specified.

The front end is implemented as illustrated in Figure 37: In the left column the assigned models to the influencing factors are displayed according to the prior selection in simulation scope, beside the explanation of the current step. The core tasks of this step comprises the parameter and unit matching first, and second, the interface specification.



Explanation

Within this step, the model decomposition is conducted. The parameters and variables of the models with their corresponding units are matched towards the concepts of the ontology, and a unit data base respectively. Connections between the models are analyzed and set to complete the simulation system decomposition.

Parameter and Unit Matching

Variable name	Original unit	Matched ontology concept	Name is common or specific voca...	Matched because of name or description	Matching precision	Unit in database

Models and factors overview

Influencing factor	Model name

Interface specification

Model of variable 1	Variable 1	Model of variable 2	Variable 2

Figure 37: Configuration step: Model decomposition

The view comprises the variable's or parameter's name, its original unit according to the model description, and its pendant from the ontology ("matched ontology concept"). Furthermore, details on the matching process are given to provide insights from the back end process. This information starts with the information whether the variable name was identified as part of common or specific vocabulary in the sense of the underlying language models. This distinction is further elaborated in Section 7.1. Second, it is stated whether the matching between variable and ontology concept bases on the variable's name or its description, as both are analysed regarding similarity by the back end functionality.

Third, the matching precision is given as a number between zero and one with a higher number indicating a higher matching precision. This serves as a user's hint whether a manual check or correction shall be conducted. Last for the overview, the corresponding unit from the ontology or a separate unit database is displayed.

The purpose of the mapping process is to analyse the models' content regarding the provided interface specification and compare it to the domain ontology at hand. Thereby, the models' content is reflected in the standardized terminology within the domain and the overlapping, similarities and differences between the models become evident. Furthermore, the gained information including the units are required for the following step of model parametrisation.

The view on the interface specification contains the belonging model of a variable and its name, first for the input and second for the output. Consequently, the view provides the information which input variable is served by which output with each giving model and variable name. The automated functionality is steered by the button column to the right. The first button "match variables and units" starts the corresponding mapping to the ontology and the units whereas the second button "Set connections" specifies the inputs and outputs that belong to each other. Further functionalities are intended for manual correction of the mapping to the ontology's concepts, the assigned units as well as the set connections.

7.3. Model Parametrisation

The final configuration step is the model parametrisation in which a composed simulation system is parametrised for one concrete simulation run or a defined bundle of simulation runs. Based on the analysed variables and parameters of the models from the prior step of model decomposition, the simulation system is consistently parametrised by the help of scenarios from the scenario file. Thereby, the parameter values of the models are defined for the models' current instances for the aimed simulation run. Therefore, the parsed ontology, the scenarios and models as well as the matched variables, units and set connections are required for this step. The procedure is summarized in Algorithm 11.

At first, the user defines whether a specific scenario or a set of scenarios shall be simulated. In the here-given context either an iteration over scenario types, e. g. "optimistic" or "pessimistic" is foreseen or the iteration over multiple considered years. If a full iteration is requested no further scenario-related definition is required. Otherwise, three cases are distinguished: First, if the iteration over types is requested, a scenario year to be simulated must be defined by the user. In analogy, the scenario type must be defined if an iteration over the scenario years is requested. Finally, if a single scenario shall be executed, the user must specify both, scenario year and type to be simulated.

In the following, the actual assignment of the concrete values is conducted for each scenario to be simulated as described in Algorithm 12. Taking the model variables, and the scenario year and type of the concrete simulation run as an input, the descriptors of the selected scenario are treated as follows:

From the individual descriptor's attributes, the ontology concept, value, unit and if applicable the unit conversion are extracted and an empty set for the belonging variables from the models is instantiated. Subsequently, from all models, the matching variables are collected with their attributes matched concept, unit and optionally the unit conversion.

Algorithm 11 Model Parametrisation

```
Require: Ontology from KPI level
Require: Scenarios, Models from Simulation Scope level
Require: Matched Variables, Matched Units, Connections between Variables from Model Decomposition level

                                        ▷ Define scenario(s) that shall be simulated
$Input() \rightarrow Iteration\ Scenario\ Types\ (Yes/No)$          ▷ User choice
$Input() \rightarrow Iteration\ Scenario\ Years\ (Yes/No)$          ▷ User choice

if $Iteration\ Scenario\ Types$ is True $\wedge$ $Iteration\ Scenario\ Years$ is True then
    pass                                                              ▷ Full iteration
else if $Iteration\ Scenario\ Types$ is True $\wedge$ $Iteration\ Scenario\ Years$ is False then
    $Input() \rightarrow Scenario\ Year$
else if $Iteration\ Scenario\ Types$ is False $\wedge$ $Iteration\ Scenario\ Years$ is True then
    $Input() \rightarrow Scenario\ Type$
else if $Iteration\ Scenario\ Types$ is False $\wedge$ $Iteration\ Scenario\ Years$ is False then
    $Input() \rightarrow Scenario\ Year$
    $Input() \rightarrow Scenario\ Type$
fi

▷ The procedure below assigning the concrete values is repeated for each scenario to be simulated
Apply Scenario Values(Model Variables, Scenario Year, Scenario Type)

Ensure: Each variable is parametrised with a value from the scenario
$return := Parameterised\ Models,\ Executable\ Simulation\ System,\ Started\ Simulation\ Run(s)$
```

Depending on the necessity of a unit conversion, the model variables' values are directly set to the descriptor value, or a unit conversion is applied on either the side of the descriptor or the variable. Further parameter transformation between scales as described in Section 5.3 are foreseen to be part of this process step.

Besides the application of the scenario values, the optimisation criteria for the specific field of application are selected here. The actual configuration of the optimisation in terms of population and variation minima and maxima is out of scope of the system configuration concept at hand and therefore not considered here. The process step returns for each scenario to be simulated the following entities: The parametrised models, the executable simulation system and the started simulation run.

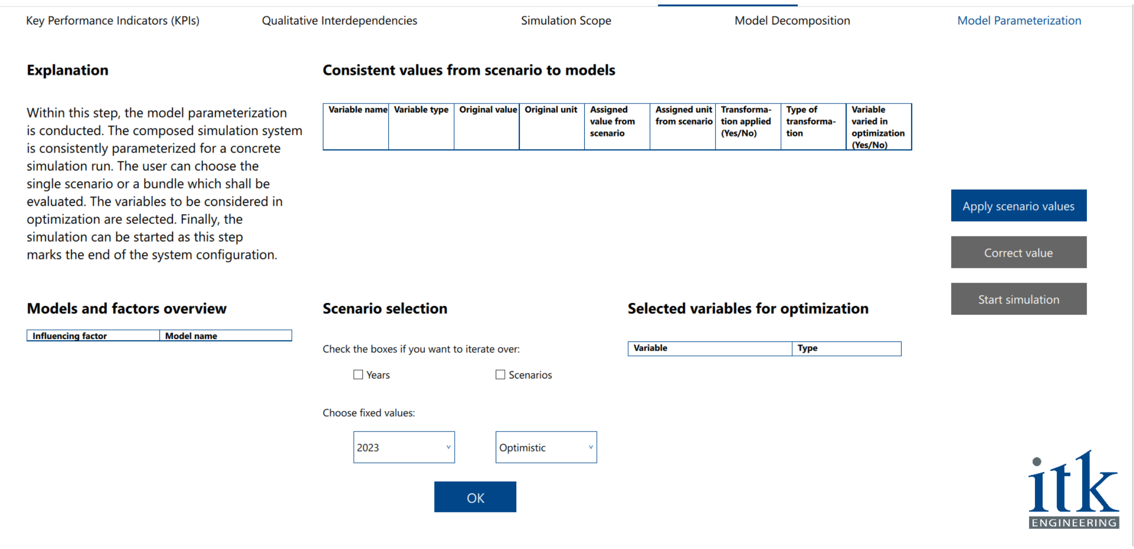
The functionality is transferred into the front end as illustrated in Figure 38 and explained in the following: In the left column, an explanation of the current step and the assignment of influencing factors and models are displayed.

Algorithm 12 Function: Apply Scenario Values

```
procedure APPLY SCENARIO VALUES(Model Variables, Scenario Year, Scenario Type)
    for $each\ Descriptor \in Selected\ Scenario$ do
        $Attributes_{\text{Descriptor}} \rightarrow Ontology\ Concept, Value, Unit, (Unit\ Conversion)$
        $Variables_{\text{Descriptor}} := \{\}$

        for $each\ Model \in Models$ do
            $Variables_{\text{Mod, Descrip}} := \{\}$
            $Matched\ Concepts, Units, (Unit\ Conversions) \rightarrow Variables_{\text{Mod, Descrip}}$
            $Variables_{\text{Descriptor}} = Variables_{\text{Descriptor}} \cup Variables_{\text{Model, Descriptor}}$
        od

        if $Descriptor$ requires $Unit\ Conversion$ then
            $Conversion(Descriptor\ Value) \rightarrow Applied\ Value$
        else
            $Descriptor\ Value \rightarrow Applied\ Value$
        fi

        for $Variable \in Variables_{\text{Descrip}}$ do
            if $Variable$ requires $Unit\ Conversion$ then
                $Conversion(Applied\ Value) \rightarrow Variable\ Value$
            else
                $Applied\ Value \rightarrow Variable\ Value$
            fi
        od

    od
end procedure
```

The latter is again displayed as it provides user guidance for the selection of variables to be considered in optimisation. The four options of scenario selection are displayed as follows: Via check boxes the user can choose whether an iteration shall be conducted regarding the year or the scenario types. Depending on the selection of the check boxes, the drop-down menu to choose fixed values is enabled or not. The user selection is stored in the back end by confirming with the "OK" button.

Subsequently, the user can press "Apply scenario values" from the right button column to apply the prior-taken choice to the decomposed simulation system. The view "Consistent values from scenario to models" contains nine columns with details on the consistent parametrisation: First the variable name as provided by the model description is displayed followed by the variable type, its default value and unit. All this information is provided by the models themselves.



Explanation

Within this step, the model parameterization is conducted. The composed simulation system is consistently parameterized for a concrete simulation run. The user can choose the single scenario or a bundle which shall be evaluated. The variables to be considered in optimization are selected. Finally, the simulation can be started as this step marks the end of the system configuration.

Consistent values from scenario to models

Variable name	Variable type	Original value	Original unit	Assigned value from scenario	Assigned unit from scenario	Transforma-tion applied (Yes/No)	Type of transforma-tion	Variable varied in optimization (Yes/No)

Models and factors overview

Influencing factor	Model name

Scenario selection

Check the boxes if you want to iterate over:

☐ Years ☐ Scenarios

Choose fixed values:

2023 Optimistic

Selected variables for optimization

Variable	Type

Figure 38: Configuration step: Model parametrisation

The following two columns of the view provide the assigned value from the scenario and its unit within the scenario if applicable. Assigned values can be either parameter values or start values for variables as both need to be set consistently. Next, the two following columns deal with possibly applying transformation. First, it is assigned, whether a transformation in terms of scale or unit is necessary to apply the scenario values to the models. Second, the possibly applying type of transformation, e. g. linear transformation, is displayed.

Finally, a column for selecting the variables to be considered in the optimisation is displayed. By default, none of the variables are selected and the user can select the variables by double-clicking in the corresponding field of a row with the variable. The so-selected variables for optimisation are marked two-fold: First, in the last column of the selected variable, it is marked with a "Yes" and second, a separate view below provides a summary of the selected variables for optimisation with its name and type. Further intended functionalities comprise the manual correction of assigned values and the final start of simulation execution, as the system configuration is finished by completing the step of model parametrisation.

Conclusively, the proposed system configuration comprises the derivation of a concrete executable simulation system from top-level KPIs including the formal transitions between the different layers of abstraction. Having reached the executable simulation system the system configuration is finished with the actual execution going beyond the scope of this work. Therefore, the following chapter deals with the application of the system configuration for its usage in decision support focusing on the relation between the system configuration artefacts on the one side and the results on the other side.

8. Application of System Configuration

This section deals with the application of the proposed system configuration in the context of optimisation, specifically applying it to the use case at hand, the planning of public charging infrastructure. At first, an exemplary application is conducted providing concrete instantiations for different steps of the system configuration process. In the following, the reuse of configuration and artefacts as well as the replacement of a model are discussed and demonstrated. Thereafter, the traceability focusing on the interplay of system configuration and belonging results is set in focus and the usage of the system configuration in the context of solution space exploration is elaborated.

8.1. Application and Reusability

Within this section the application to the field of planning public charging infrastructure within the presented demonstrator is introduced. As an ontology, the merged ontology as explained in Subsection 4.3 is used containing 179 concepts. From this selection, the top-level KPIs to be pursued are selected. The "ElectricPowerDistribution" concept reflects the characteristics and constraints associated with electric power supply. Second, the "UsageSession" reflects in general the utilisation rate of a resource. Third, the "pricePerMonthCharge" reflects the associated costs of an individual for fulfilling its charging demands within a month. Thereby, three top-level KPIs are defined, for which qualitative interdependencies are defined in the following.

In contrast, to the KPIs, the qualitative interdependencies are not restricted to the vocabulary provided by the ontology for two main reasons: First, this decision is made according to the models which are also not necessarily based on the vocabulary of the ontology and can be therefore described as OOV compared to the ontology. Consequently, the interdependencies which build the base with their influencing factors, also need to be wider than the actual ontology. The second main reason is the concretisation of the KPI to possibly a share of the chosen KPI.

In the example at hand, the following interdependencies are defined:

- "ElectricPowerDistribution" - Number of public charging stations - Local grid
- "UsageSession" - Share of charging in public - Available power of public chargers
- "pricePerMonthCharge" - Share of charging in public - Price models of CPO

Thereby, the minimum of interdependencies are defined as to each KPI one qualitative interdependency is required by the system configuration. As the "Share of charging in public" is part of two interdependencies, the choice at hand results in five influencing factors and a chain of the two interdependencies. Conclusively, the latter two interdependencies are chained and demonstrate how the concept at hand deals with multiple factors depending on each other.

It follows the step of simulation scope, in which the scenario file is selected first. Here the scenario file is used which contains the scenarios as described in Subsection 4.4. Second, the models are selected. For the demonstration purpose, the three models as described in Subsection 4.2, are simplified into facades with less parameters and variables, but aiming for the same content compared to the actual use case. Conclusively, the incorporated models comprise a grid model, an EV driver model and a CPO model. These models are now assigned to the individual influencing factors that they do represent. The assignments are summarized in the following:

- Number of public charging stations - CPO model
- Local grid - Grid model
- Share of charging in public - EV Driver model
- available power of public chargers - Grid model
- Price models of cCPO - CPO model

With regard to the interdependencies defined before, the first is investigated by the combination of the CPO and grid model, the second by the combination of the EV driver model and the grid model and the last by the combination of the EV driver model and the CPO model. Consequently, also the KPIs are analysed by two models each. In a different context it would be also feasible, that an interdependency is analysed within the same model and therefore, a KPI is also analysed by only one model of a simulation system. The use case at hand also shows the need for incorporating different perspectives on phenomena in a structured manner and demonstrates the full traceability within the concept at hand.

In the following step of model decomposition the models' content regarding variables and parameters is analysed. By the help of the NLP algorithm as explained in Subsection 7.1, the agent-individual variables are analysed as specific vocabulary whereas parameters such as "electricity costs" are marked as common vocabulary. All variables and parameters (in total 26 here) are mapped to their corresponding ontology concept based on the matching between variable description and the concepts' comments with a matching precision between 0.4 and 0.6. Consequently, a manual check is recommended and in parallel, all variables and parameters' units have been found in the used unit database called pint. The relatively low matching precision can be explained by the different terminology used in the demonstration models compared to the ontology. Based on the matched ontology concepts, the corresponding inputs and outputs are matched with all connections being served in this demonstration case.

In the final step of model parametrisation the concrete scenario "optimistic" is selected for the year 2030. The application to the demo models at hand comprises the costs for electricity, the relative share of public charging compared to private charging and the demand of charge power by the agents.

Whereas this charge power is given in ”kW” and thereby in the same unit as required in the models, the costs of electricity and the share of public charging are linearly transformed to another unit (€/MWh to €/kWh and percentage to decimal).

Last, the variables for optimisation are selected. In contrast to the KPIs these variables are concrete values which are calculated within the simulation and are considered for the generation of the subsequent population of the optimisation algorithm. For the example at hand, the line utilisation of the grid is chosen beside the monthly revenue of the CPO and the loaded energy of both modelled agents. This marks the final step of the system configuration whose finish allows the start of a simulation run. The application shows the concretion and demonstrates the traceability of the configuration steps at hand.

Reuse of configuration and artefacts

Having introduced the exemplary application of the system configuration, the reuse of a configuration and single artefacts is elaborated as it is one of the motivations behind this work. For the reuse, the distinction is made between the artefacts which are used in the system configuration and those that are defined within the configuration itself.

The first group comprises the ontology, the scenario file and the models themselves. The domain ontology and the scenarios aim to cover all relevant aspects of smart mobility and are therefore reusable not only for different configurations within the given context, but also for further fields of application related to smart mobility. The models themselves are regarded as partially externally developed which leads to their reuse already by the usage in the context at hand, e. g. an existing grid model. The reuse of a model is mainly restricted by its fit to other models regarding the required inputs and the given outputs, as the connections are crucial to build up a plausible and meaningful co-simulation.

The second group comprises in order to the belonging configuration step:

- KPI level: Selected KPIs
- Interdependency level: Defined qualitative interdependencies
- Simulation scope: Selected models, assignment of factors to models
- Model decomposition: Results from parameter and unit matching and the interface specification
- Model parametrisation: Selected scenario, consistent parametrisation, selected variables for optimisation

As a concretisation is pursued with each subsequent configuration step, the reuse of defined artefacts depends on the decisions taken in the prior configuration steps. Therefore, selected KPIs can be reused e. g. as a general set for a user when planning mobility ecosystems even beyond the scope of charging infrastructure.

The defined qualitative interdependencies can be only reused if the KPIs are identical because the KPIs are an essential part of the defined interdependencies. Subsequently, the influencing factors participating in the interdependencies are assigned to one of the selected models. There, a reuse of defined artefacts is first possible for the selected KPIs and the further defined qualitative interdependencies and second, the reuse of a set of models which matches the prior defined influencing factors. With the identical set of models, the interface specification can be reused as well as the mapping to the ontology concepts under the assumption of reusing the domain ontology.

The reuse of the consistent parametrisation is also feasible if the configuration down to that step is comparable, but such a reuse has only limited applicability in practise: When the configuration is reused down to the model parametrisation, the results shall be available as well, unless an error occurred during run time or an internal model error, e. g. regarding model-internal calculation accuracy had to be fixed.

The analysis of the reusability reveals a high degree for the external artefacts in general with a slightly higher degree for the scenarios and ontologies. Regarding the internally defined artefacts, the reusability is also given, but dependencies have to be considered. The practical applicability and value of reuse tends to decrease with each concretisation step, as more prerequisites have to be fulfilled and the granularity of the artefacts tends to increase in parallel. Therefore, the configuration reuse is more useful for technical development purposes with repeated model refinement rather than its application in the context of decision support for infrastructure.

In this section a concept for configuration of a simulation system has been introduced consisting of the five steps KPI definition, qualitative interdependencies, simulation scope, model decomposition and model parametrisation. Its implementation and exemplary application have been elaborated and demonstrated. Finally, the discussion on the artefacts' reuse show the advantages of such a structured approach towards simulation system configuration.

8.2. Model Replacement

The replacement of a model affects the levels of simulation scope and below. The belonging procedures are introduced in the following. Starting with the simulation scope level, the models' assignments to the factors are checked based on the model names. If a model name is not longer found, the model assignment is deleted. Subsequently, the user can choose alternate models for those factors for which two cases are distinct:

First, the user can select another model which was not part of the simulation system before or the user selects a model representing the factor which is part of the remaining models. In both cases, the newly assigned model is assigned to a variable to collect all models which are either new or used in a different manner. This procedure is summarized in Algorithm 13.

Algorithm 13 Model Replacement: Check Assignments

```
Require: Model Assignments
for $each\ Model\ Assigment \in Model\ Assignments$ do
    if $Model\ Name \in Model\ Assignments$ then          ▷ Model name still exists
        pass                          ▷ No automatic adoption of model assignments
    else
        $Model = ""$
    fi
od

for $each\ Model\ Assigment \in Model\ Assignments$ do
    New Models := $\{\}$
    if $Model\ Field$ is empty then
        $Input() \rightarrow Model$                      ▷ User assigns from loaded models
        $Model \rightarrow Model\ Assignment$
        if $Model \notin New\ Models$ then
            $Model \rightarrow NewModels$
        fi
    fi
od
```

After the reassignment of the models to the factors, it follows the check of the variables which belong to the level of model decomposition. The belonging procedure is summarized in Algorithm 14 and requires the model assignments, the set with all variables and the set of new models. At first, all variables belonging to a model, which was deleted, are removed from the set of all variables. In the following each new model is parsed and unzipped. In analogy to the regular procedure on the model decomposition level, the attributes of the new model's variables are added to the model's individual set of model variables. Subsequently, a check is conducted whether the analysed model variables were part of the interface in the prior configuration. Thereby, it can be distinguished the cases of identical and non-identical model facades for the latter connection setting. In case that no facade change was identified, the overall set of model variables is not changed. Otherwise, the newly-parsed model variables replace the former model facade entirely.

Algorithm 14 Model Replacement: Variables

```
Require: Model Assignments, All Variables, New Models

for $Variable \in All\,Variables$ do
    if $Model_{\mathsf{Var}} \notin ModelAssignments$ then
        $All\,Variables = All\,Variables \setminus Variable$
    fi
od

for $each\,Model \in New\,Models$ do
    Model Variables := $\{\}$
    Model Description = unzipModel(modelDescription.xml)

    for $each\,Variable \in Model\,Description$ do
        $Model_{\mathsf{Var}},\ Name_{\mathsf{Var}},\ Description_{\mathsf{Var}},\ Type_{\mathsf{Var}},\ Unit_{\mathsf{Var}} \rightarrow Attributes_{\mathsf{Variable}}$
        $ModelVariables = ModelVariables \cup Attributes_{\mathsf{Var}}$
    od

    $Check\,Variable := 0$  ▷ Check if model interface is changed due to replacement
    for $each\,Variable \in Model\,Variables$ do
        if $Attributes_{\mathsf{Var}} \in All\,Variables\,with\,Model_{\mathsf{Var}} \equiv Model$ then
            pass
        else                                        ▷ Attributes of variable differ
            $Check\,Variable = 1$
        fi

        if $Check\,Variable \equiv 0$ then      ▷ All attributes of interface have been found
            pass
        else                        ▷ Delete old model variables and replace them by new
            $All\,Variables = All\,Variables \setminus Variables\,with\,Model_{\mathsf{Var}} \equiv Model$
            $All\,Variables = All\,Variables \cup Model\,Variables$
        fi
    od
od
```

The final step of model replacement is the setting of the connections between inputs and outputs which is described in Algorithm 15. At first, all connections are deleted in which variables take part which are not longer found in the set of all variables. Subsequently, analogous to the initial connection setting, each input shall be served by an output. Therefore, it is checked for each input if it is part of any connection and therefore served by an output. If a connection is found, no adoptions are made.

Algorithm 15 Model Replacement: Connections

```
Require: Connections

for $Connection \in Connections$ do
    if $Input \notin All\,Variables \vee Output \notin All\,Variables$ then
        $Connections = Connections \setminus Connection$
    fi
od

for $each\ Model\,1 \in Model\ Assignments$ do
    $\text{Inputs}_{\text{Model 1}} = \textbf{extractInputs}(\text{All Variables}_{\text{Model 1}})$
    for $each\ Model\,2 \in Model\ Assignments \setminus Model\,1$ do
        $\text{Outputs}_{\text{Model 2}} = \textbf{extractOutputs}(\text{All Variables}_{\text{Model 2}})$
    od

    for $each\ Input \in Model\,1$ do
        if $Input \in Conncetions$ then                          ▷ Connection already defined
            pass

        else                        ▷ Definition of connection as for initial configuration
            $Individual\ Connections := \{\}$
            if $Input_{\text{Concept}} \equiv Output_{\text{Concept}}$ then
                $Ind.\,Connections = Ind.\,Connections \cup \{Input,\ Output\}$
            fi
            if $Number\ of\ Connections \equiv 1$ then
                                          ▷ Exactly one output identified to serve input
                $Output \rightarrow Serving\,Output$

            else if $Number\ of\ Connections \equiv 0$ then
                                                  ▷ No output found to serve input
                $Input() \rightarrow Serving\,Output$                    ▷ User choice

            else
                                              ▷ Multiple outputs require user choice
                $Input() \rightarrow Serving\,Output$                    ▷ User choice
            fi
            $Input,\ Serving\,Output \rightarrow Connection$
            $Connections = Connetions \cup Connection$
        fi
    od
od
```

Otherwise, the definition of the connection is conducted comparable to the initial configuration. The parametrisation is conducted in analogy to the initial configuration and is therefore not further explained here. Conclusively, the discussion on the model replacement reveals the advantages of the presented simulation configuration system: The integration of a different model or model version follows the same structured approach as the initial simulation configuration and spans the steps from simulation scope to model parametrisation. In parallel, the discussion demonstrated the importance of the model's interface for such a process. Whereas a model variant with the same interface requires a check of the reused artefacts, an updated interface leads to comparable steps as the initial configuration.

8.3. Traceability and Mapping

Within this subsection the consistency is addressed in terms of traceability and mapping of the simulation configuration, the applied scenarios and the belonging results. The focus lies on the use of simulation systems in context of optimisation for design space exploration and decision support, for which the use case at hand, the planning of public charging infrastructure is an example for. Therefore, the issues of traceability and mapping are use-case-driven approached. The participating artefacts and relations are summarized in Figure 39. This subsection describes the qualitative part of enabling decision support by simulation in the work at hand.

Regarding the artefacts, a forth-fold distinction is made for traceability and mapping: First, the scope from world defined by the KPIs and defined interdependencies restricts the field of study in an abstract manner. It follows the configuration of the simulation system as a subspace of the prior-taken abstract definition. This definition comprises the artefacts of participating models in a specific version, their matching towards the ontology as well as the connections between inputs and outputs, complemented by the unit and scenario data base. Third comes the level of an optimisation run which includes the concretely evaluated scenarios, the parameters for which an optimal solution is searched, here a pair of numbers for AC and DC charging points, and the criteria which are evaluated to assess a simulation run's result. Finally, a single simulation run is defined by the concrete scenario and the concrete optimisation parameter combination.

The results are mapped accordingly to the four levels: For a single simulation run, the simulation results, e. g. the output values, and in particular the values of the optimisation criteria are stored. In the application at hand, the peak voltage deviation, the share of fulfilled charging desires and the monthly revenue for the CPO are evaluated which are also direct outputs from the participating models.

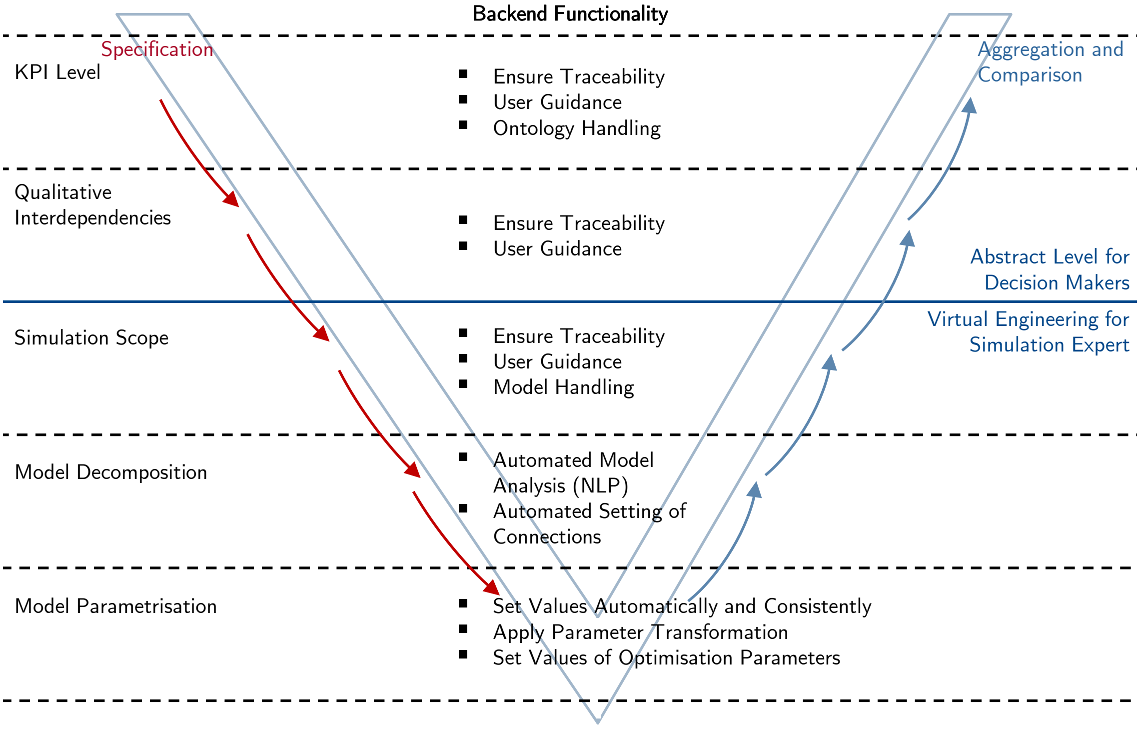


Figure 39: Traceability with the usage of simulation for decision support

On the level of an optimisation run, the results from the simulation runs are compared with each other and the non dominated solutions, here the pair of AC and DC charging points, for each of the evaluated scenarios are derived. Concretely, when evaluating a defined city, multiple optimisation runs are conducted, to find the best pair of AC and DC charging points for different years and different scenarios, e. g. for the pessimistic, trend and optimistic scenario, each calculated for 2030 and 2035. A further adoption is thinkable regarding the applied optimisation. Whereas a change of the optimisation algorithm would exceed the configuration options, also the variation of number of generations or the population size as well as the applied restriction to the solution space are thinkable. Moreover, the considered criteria could be varied to emphasize certain aspects.

On the higher level of the simulation system, the solutions are set in context and the non dominated solutions of the assessed scenarios are compared. In the application at hand, this is e. g. the timely development of charging infrastructure and the comparison between the non-dominated solutions in different scenarios to assess the variance of feasible layouts. E. g. charging points that are most likely to be needed in 2035 are identified and it is analysed if they are also possibly valuable already in 2030. Thereby, not only decision support for a defined time stamp is reached but also the development over time is supported under consideration of diverging circumstances represented by the scenarios.

The results of this comparison on the level of the simulation system are further aggregated as single parts for the evaluation of the scope from world defined by KPIs and interdependencies. In the context at hand, the simulation system of a city regarding charging infrastructure is then one part on the scope from world which could be e. g. the mobility system of that city or the usage of public space. Thereby, further aspects can be evaluated by simulation and the different recommendations can then be discussed on a higher level solving possible trade-offs such as the usage of public space.

The classification of the artefacts for traceability and mapping stands not in concurrence to the simulation configuration steps, but open another dimension which complements the simulation configuration as it maps the results, aggregated results and thereby derived knowledge to the different levels of decision support by simulation. Thereby, the result organization and usage is structured in a similar manner to reach decision support on different levels of abstraction compared to the simulation configuration and accounts for a central idea of the simulation configuration: Each concretisation is a choice within the range of possible paths spanned by the next higher level of abstraction. For the results, the opposite direction applies: With each next higher level of abstraction, the knowledge of the next lower level is aggregated and further processed.

Algorithm 16 summarizes the formal assignments and routings to realise the traceability. For each instantiation on the model parametrisation level, a simulation result returns from the simulation execution. An instantiation on the model decomposition level can contain multiple model parametrisations and belonging results. On a higher level of abstraction, the instantiation of a simulation scope comprises all analysed decompositions. The interpretation and extraction from the analysed scope to evaluate the individual factors requires expert knowledge which are described as results for a factor in the following as part of the high-level results. For the results on the level of qualitative interdependencies, the interplay of the high-level results for the two belonging factors is evaluated as the result for an interdependency. Finally, the results on the KPI level are the analysed results of all interdependencies in which the KPI itself takes part.

Algorithm 16 Traceability

```
  Instantiation i of Model Parametrisation =: $\mathsf{P_i}$
  Simulation Result for $\mathsf{P_i}$ := $\mathsf{R_i}$
  Model Decomposition containing $\{\mathsf{P_i}, \mathsf{R_i}\}$:= $\mathsf{D_i}$
  Simulation Scope containing $\mathsf{D_i}$ := $\mathsf{S_i}$
  Qualitative Interdependencies containing $\mathsf{S_i}$:= $\mathsf{I_i}$
  KPIs containing $\mathsf{I_i}$ := $\mathsf{KPI_i}$

  $\mathsf{D_i} = \{\{\mathsf{P_1}, \mathsf{R_1}\}, \{\mathsf{P_2}, \mathsf{R_2}\}\}$
  $Analysed\ Decomposition:\ D_{\mathsf{i}} = \sum_{n=1}^{Number\ Simulation\ Runs}\{P_{\mathsf{n}}, R_{\mathsf{n}}\}$

  $Analysed\ Scope:\ S_{\mathsf{i}} = \sum_{d=1}^{NumberofDecompositions} D_{\mathsf{d}}$

  High-Level Results := {}
  for $each\ Factor \in Model\ Assignments$ do
                              ▷ Interpretation and Extraction requires expert knowledge
      $extractFromResultFile() \rightarrow Results\ for\ Factor$
      $High-Level\ Results = High-Level\ Results \cup Results\ for\ Factor$
  od

  Results Interdependencies = {}
  for $each\ Interdepedency \in Interdependencies$ do
      $Results\ for\ Factor\ 1 \in High-Level\ Results \rightarrow Results\ Factor\ 1$
      $Results\ for\ Factor\ 2 \in High-Level\ Results \rightarrow Results\ Factor\ 2$
      $KPI_{\mathsf{Interdependency}}, Results\ Factor\ 1, Results\ Factor\ 2 \rightarrow ResultsInterdependency$
      $Results\ Interdependencies = Results\ Interdependencies \cup Results\ Interdependency$
  od

  Results KPIs = {}
  for $each\ KPI \in KPIs$ do Result KPI = {}
      for $eachResultsInterdependency \in ResultsInterdependencies$ do
          if KPI = $\mathsf{KPI_{Interdependency}}$ then
              $Results\ KPI = Results\ KPI \cup Results\ Interdependency$
          fi
          $Results\ KPIs = Results\ KPIs \cup Results\ KPI$
      od
  od
```

8.4. Exploration of Solution Space

Having explained the traceability and mapping between simulation configuration and the results on different levels of abstraction and aggregation, the exploration of the solution space describes the quantitative part of enabling decision support by simulation in this work. The participating models within this work are considered to be grey-box as their interface specification is provided by the model description, but not every detail of the models is assumed as accessible. Conclusively, the systematization is limited to the given parameters, inputs and the resulting outputs, whereas the inner model behaviour can only be studied indirectly.

For the input side, the model parametrisation by the scenarios and the optimisation configuration have to be studied. The scenarios were developed based on state-of-the-art literature with an established methodology for scenario development as described in Subsection 4.4. This procedure includes also the expert-knowledge-based judgement of influences and their interdependencies in form of a consistency matrix. The result of the scenario technique is a set of scenarios which aims for the comprehensive description of the development in the field for subsequent years. Thereby, the parameters are consistently defined for one scenario type, e. g. an optimistic scenario, also in their timely evolvement.

Assuming that the scenarios cover the foreseeable range of developments, the parametrisation based on the scenarios allow the structured variation of the model's parametrisation. Regarding future developments, the scenario technique has the restriction that only foreseeable developments are considered and therefore technology leaps, e. g. in terms of battery technology, do not take part in the scenarios at hand.

From those scenarios, a choice can be taken to be considered for one's real-world decision problem. This can be either based on a logical approach taking e. g. the pessimistic, trend and optimistic scenarios to consider the boundaries and the most likely-development. Or a choice of a different scenario-bundle is made based on expert-knowledge reflecting the local situation based or considering prior-taken decisions or implicit restrictions e. g. by political stakeholders. For the choice of the scenarios, a further path is the definition of the relative distance between the scenarios bundle and the subsequent choice of resolution which is aimed for the decision problem at hand.

In addition to the parametrisation, the optimisation variables are set as inputs, here a pair of numbers of AC and DC which also calls for a systematic approach. Due to the assumed limited knowledge on the model behaviour, an a-posteriori evaluation of the chosen values for the optimisation variables is conducted for the use case at hand. The initialization is conducted randomly within the defined solution space.

As the NSGA-II is an evolutionary algorithm, the systematization of the optimisation parameter's mainly depends on the resulting values for the assessed criteria. Thereby, the algorithm converge over generations towards better solutions, but does not necessarily reach the mathematical optimal solution.

On the other side, this algorithm has the advantage that a full-factorial exploration of the possible design is not required, but nearly-optimal solutions can be identified within reasonable calculation time. Therefore, the here-presented framework does not necessarily result in the mathematically optimal solution, but leads to solutions which are well-evaluated from different perspectives and nearly-optimal, as for these future-oriented decisions logically remains a level of uncertainty.

The definition of the solution space is done by expert-knowledge based on the political framework and in dependence of the considered number of households from which the number of electrical vehicles is derived. Thereby, the solution space is restricted by expert-knowledge and literature values. In this context a trade-off must be solved between a restrictive solution space definition for its detailed evaluation on the one side and the broad searched range of possible solutions to identify even not directly foreseeable nearly-optimal solutions on the other side.

A further influencing factor is the choice of number of optimisation criteria as the multi-criteria optimisation identifies solutions that are not dominated by any other. With not dominated meaning that an increase of a criteria fulfilment cannot be reached without a decrease of another criteria, the number of not dominated solutions arises with each added criteria to be taken into account. Furthermore, the handling and actual knowledge generation becomes more complex with an increasing number of assessed scenarios, criteria combinations and evaluated optimisation variables.

Having discussed the input side, the exploration of the solution space shall be elaborated for the results in addition to the traceability aspects as discussed in Subsection 8.3. In accordance with the possible approaches for the input and configuration definition, the comparison and aggregation of the results can be either pursued based on expert-knowledge or by using metrics such as the relative distance between multiple results. By defining e. g. a relative minimal distance in which results are analysed as practically identical, the assessed solutions can be reduced to the dimensions in which their performance differ significantly.

Moreover, within this step, the solution space can be eased by incorporating a-posteriori restriction, e. g. in the given context a minimal profitability of the public charging infrastructure to only consider solutions that are attractive for private investors. The same direction is pursued by assigning different weights to the assessed criteria which adds a different dimension of exploring the design space as it allows to test the solutions for robustness in terms of trade-offs between different stakeholders' perspectives.

Furthermore, the closing of the loop is thinkable between the achieved variation in the assessed options (as pairs of optimisation variable values) and the variation of input parameters. In particular under the assumed limited knowledge about the models, the knowledge generation of what the biggest influencing factors are, lead to an improved usage of the simulation system over time.

With the exploration of the solution space for decision support, it remains the uncertainty from future development along with further restrictions from real world: Each simulation model has restrictions and limits of applicability. The evolvement in real world leads most likely to some differences between the simulation results and the practical applicability when dealing with infrastructure decisions such as public charging infrastructure.

9. Evaluation

This section starts with a technical reflection of the methodology and its associated limits. Afterwards, the plausibility of the use case at hand for the individual models as well as the overall simulation system is evaluated based on exemplary results. Three semi-structured expert interviews build the core of the evaluation for this work. The corresponding interview guide is introduced followed by the presentation and discussion of the interviews' results. Furthermore, the applicability of the developed artefacts and framework to further fields of interest is discussed.

9.1. Limits of Methodology

The technical reflection is divided into the process-related aspects for simulation configuration as well as result aggregation on the one side and the discussion on participating artefacts such as the simulation models and the ontology on the other.

Configuration Process

On the first two levels of KPI and qualitative interdependencies definition, a distinction is made between the ontology-based KPIs and the OOV factors for the qualitative interdependencies. Thereby, the user is enabled to break down KPIs even beyond the provided concepts from the ontology, but also a lack of standardization results: First, multiple users in a corporate environment may express the same factors differently which leads to redundant configurations. Second, the understanding of expressions may vary which leads to misunderstandings or misinterpretations. Based on these OOV factors the simulation models are selected and indirectly assigned to the KPIs. Although this assignment integrates uncertainty into the configuration process, the step is important to reflect dependencies that shall be evaluated in the simulation. Moreover, such interdependencies can thereby cover partial concepts or effects that are related to a share, e. g. the grid stability in a certain sub-area.

The analysis of the models' content is conducted for the first time on the model decomposition level in which the models' interfaces are analysed regarding incorporated parameters, inputs and outputs. Conclusively, the model fit can be evaluated first after the model selection process has been finished. A lack of model fit can be avoided by expert knowledge when selecting the models or by re-engineering of the prior process step.

For variable transformation, the details have been discussed in Subsection 5.3. In general, the conversion within a scale or to a scale with less information is feasible and has been implemented for demonstration. It remains an issue at a point where the model description does not provide sufficient information about a variable, e. g. when the unit is not given.

Furthermore, the knowledge about the scale of a parameter can only be determined either by detailed information or by knowledge about the model's functionality. The issue of variable transformation to a scale requiring more information cannot be solved to full extent because the procedure is case-individual, and requires user interaction or other additional information. Within the step of model decomposition, the issue of redundancies in exchange variables can arise as treated in Subsection 7.2. These redundancies lead to multiple possible connections and thereby to different simulation system configurations which are not differentiable as these are internally within the model decomposition and not further marked.

On the model parametrisation level, the assignment of different values to variables reflecting the same ontology concept is not foreseen. This becomes relevant e. g. for agent-based models in which a variable such as the SOC at initialization shall be varied. Instead, those values are all consistently parametrised automatically. If the user wants to change certain agents' attributes, heavy manual effort would arise. Furthermore, all models are treated equally regarding consistent parametrisation (one value for one ontology concept independent on its frequence of appearance). Also for connections, all models are treated equally, therefore closed subsystems are not foreseen. Those subsystems are characterised by models that have numerous connections with each other and own different connections to models which are not part of the subsystem. As the procedure for connection setting analyses the matched ontology concept for a variable and its type, the corresponding connections for models for a subsystem would be searched within all assigned models.

Finally, the automatisation of the necessary steps and transitions is limited at certain points: If naming conventions are not met, the user has to confirm the automated matching or has to assign ontology concepts to the variables of a model. Moreover, the evaluation of the fit of models for simulation purpose and a simulation system is limited in its possible degree of automation.

Result Aggregation and Interpretation

On the result side, the aggregation from model parametrisation level via model decomposition level to simulation scope does nor require expert knowledge nor manual interaction as these steps simply collect combinations of configurations and their belonging results. In contrast, the further transitions require interpretation based on expert-knowledge and can further reveal lacking information in the aggregated simulation results. Either the DSE is not sophisticated or the transition from available outputs does not lead to holistic conclusions regarding the KPIs. Regarding the DSE, e. g. an insufficient variation of future occurring charging power within the electric fleet could lead to a lack of detail what impact these charging powers would have on the electrical grid. Conclusively, even a large number of simulation runs compared with each other would not lead to a comprehensive impact analysis as relevant configurations were not included on the input side.

Regarding the available outputs, e. g. the grid stability can be measured by values such as voltage deviation, occurring peak power or the line utilisation. For such values again, different measures can be taken as reference, e. g. maximal, minimal or average values. The first issue might be the lack of one of those values although all of them are important to finally evaluate the KPI. During the configuration process there is neither a set requirement nor an automated check if the KPI is that well reflected during the transition process from KPI via the OOV interdependencies to the model assignments. Even when the simulation expert considers the integration of all values into the corresponding models, further double-checks would be necessary with the decision makers if the measure, e. g. the average, is appropriate for evaluation. Such cross-checks lead to the need for interactions between the levels to ensure that downstream decisions match the intention of the upstream decisions which were taken before.

Finally application-wise, the term of decision support implies that simulation can not overtake decisions, but help in the process to find the best-possible decision. The planning tool for public charging infrastructure aims to compare data-driven several options with each other. At the same time, its precision depends on the quality of the developed models and the given data. Furthermore, the type of criteria to assess the different options as well as their individual relative weight can be only defined by experts. The role of simulation and the presented framework lies in the data-driven evaluation within a human-defined scope with an increased degree of automation compared to the state of the art.

Suitable Domain Ontology

The core of the presented concepts and implementation is a suitable domain ontology that covers all terms (concepts) and its relations as well as realistic restrictions. This is reflected by the wide usage of the ontology across the levels of KPI definition to the model decomposition. In Subsection 4.3 it is elaborated that a suitable domain ontology for smart mobility or more specific, the field of public charging infrastructure, is still pending. The developed ontology which is a merge of four previously developed ontologies aims to reach the highest achievable degree of standardization for terminology. Nonetheless, even the used sub-ontologies do not have the ranking of an industry-standard.

Without an established ontology, the terminology which is used for model development highly differs. Up to a certain degree, naming differences can be overcome automatically by NLP approaches as demonstrated. Nonetheless, each matching tends to need a manual confirmation and limits are reached when variables are not meaningful named, e. g. "variable1" instead of "electricity tariff".

Furthermore, the adoption of a domain ontology takes time either for model refactoring or until models are available following the updated convention. Therefore, terminology harmonization is a pressing issue to enable model reuse and bottom-up-developed simulation systems.

Characteristics of Simulation Models

The characteristics of simulation models highly determine the feasibility of the proposed system configuration approach. Basic requirement for the implementation at hand is the usage of the FMI standard. The advantages and reasons for this choice are discussed in Subsection 5.4. The simulation system's composition highly depends on the model description, as it provides information about the model itself and its variables. The implementation of the presented concepts is made specifically for the FMI standard and requires adoptions when using different model interfaces. A major prerequisite is the manipulation of the parameter values, as given by the option "tunable" in the FMI standard. Even for FMI-conformed models, the set of "tunable" values is prerequisite to realise a consistent model parametrisation. Moreover, optional fields within the standard, such as unit and description shall be used to give the user sufficient details for the configuration process including the manual user choices. In general, implementation-independent, the model interface must account for information availability, modifiable values and co-simulation functionality.

Within the proposed concept, the analysis of the model's content is limited to the interface with parameters, inputs and outputs. The model behaviour is black-box and therefore, aspects such as internal resolution cannot be considered e. g. to determine the output which shall serve a specific input. E. g. if there are two variables in a model which match the same ontology concept, e. g. charging power, and another model demands the charging power as an input, the internal calculation and suitability of the outputs cannot be assessed without further expert knowledge about the model itself. In best case situation the description of the variable provides such valuable information, but even then its consideration must be manually overtaken by the simulation expert and is neither conducted automatically nor explicitly considered in the process. The better the models' variables match the concepts of the ontology, the less adoptions are necessary.

Besides the models' individual characteristics, the fit of the simulation models between each other is highly important. In Section 7.2, the connection setting between inputs and outputs is discussed. The belonging concepts require the service of each model input by a suitable output which requires matching interface variables.

Scenarios

The structural derivation of suitable scenarios is out of scope for the methodological part in this work and has been exemplary conducted for the use case at hand, the planning of public charging infrastructure. The scenario factors shall base on the ontology's concepts but a matching of OOV content is foreseen as explained in Section 7.2. Moreover, the scenarios shall match the content of the participating simulation models. This fit is not automatically checked, but fully based on expert knowledge.

Furthermore, the development of scenarios has a significant impact on the assessment of the design space. By setting the parameter values and their combination, the assessment can be highly determined by setting parameters to suitable values, and covering a sophisticated range of individual parameters as well as parameter combinations over multiple scenarios. The feasibility of the simulated configuration is only checked for inherent consistency regarding connections, units and parametrisation, but domain-specific checks remain a task for the simulation expert.

The term scenario is here used for the domain-specific concrete scenarios representing a future thinkable state of several factors. Thereby, the scenario is first introduced on the simulation scope level and mainly applied for the model parametrisation. On the result aggregation side, the scenario marks an important milestone as the result assignment to an evaluated scenario is conducted automatically and therefore fully traceable.

In conclusion the major limits of the methodology lie at those points that require a user interaction and are therefore neither completely structured nor traceable. On the other side, those points account with their flexibility for a wide applicability of the proposed simulation system configuration. Regarding the artefacts simulation models, domain ontology and scenarios, their fit to each other highly determines the manual effort within the process as well as the resulting quality for decision support. As the models are assumed as black-box, an automated process is not feasible and information availability limits also the usage of expert knowledge.

9.2. Model Check for Plausibility

The model check for plausibility aims to compare the individual model behaviour with expert-knowledge and the state of the art from literature at first. Subsequently, the comparison is pursued for the overall simulation system's behaviour. The analysed values are summarised in Figure 40. This approach is pursued as model validation is not feasible in the given context and would exceed the scope of this work due to the focus on methodology with an exemplary application.

The grid model bases on the load profiles and representative grid layouts from SimBench which have been validated within the research project. When using multiple low-voltage standard nets in parallel, the simultaneity factor of the original standard net is taken as a reference for the overall simultaneity factor. In addition, the amount of consumed energy is kept constant in analogy to the reference data from SimBench. The load profile modified by changing winter or summer days with each other and by shifting reference loads by 1.5 hours in maximum. Thereby, two aims are pursued in parallel:

First, the overall simultaneity factor between several subnets does not exceed the simultaneity factor as expected by the higher voltage level. Second, the reference data is only randomized in the smallest and from an expert-knowledge-view foreseeable way to do not loose the level of validation as reached in SimBench.

For the mid-voltage, no randomization is pursued as the parallelization of multiple standard nets is only required in a small range in which the simultaneity factor is not regarded as critical.

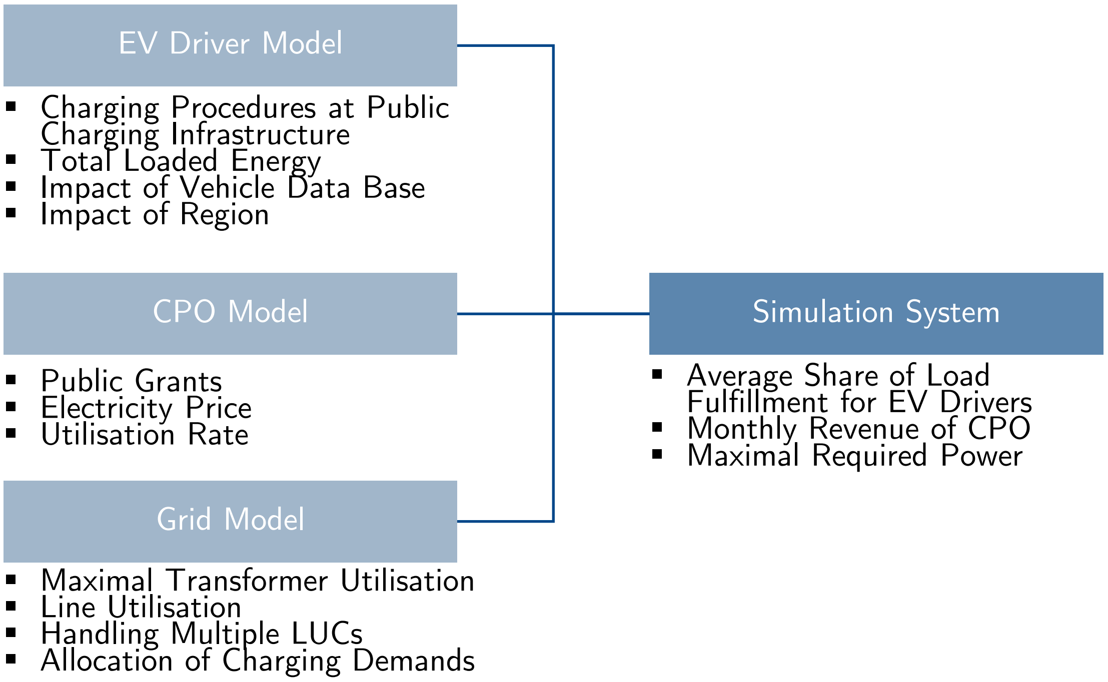


Figure 40: Analysed values for check of plausibility

The scenario-based extension is done based on the scenarios as presented in Subsection 4.4 in relation to the current situation as reflected in the standard grids by pre-factors e. g. for the share of renewable energy in form of Photovoltaic (PV). The steering of the grid has been implemented according to the norms Association of Electrical, Electronic & Information Technologies (VDE) 4100, 4105 and 4110 [246], [247], [248]. The model check for plausibility has been conducted by two scenarios for 2035 and an analysis of the current situation for 2023 for the mid-voltage level. For each scenario, the maximal transformer utilisation is between 14.6% and 16.6%, the maximal line utilisation between 48.7% and 55% and the maximal current deviation between 0.0116 and 0.0137 per Unit. All values show a correlation with an increasing simulated EV market penetration, but remain within a realistic range without critical values. Therefore, the steering functions have been separately tested by a high-power heat pump in the low voltage area with the result that critical values have been successfully prevented.

Further function tests comprised the allocation of more charging demands than charging points available and the handling of multiple LUCs. Model limits do occur when it comes to the spatial resolution of charging points within the grid and a partially too harsh restriction of charging power due to the implemented steering.

The models for the user behaviour and the CPO have been checked for plausibility with their application to Kassel. The resulting charging procedures in public differs between approximately 700 and 900 for the trend scenario of EV market penetration compared to an optimistic scenario. Whereas the relation between the absolute number of vehicles in Germany differ by less than 20% (10.2M compared to 12M), the charging procedures in public differ by approximately 25%. This result is in accordance to the increasing importance of public charging infrastructure for an accelerated EV market penetration as the number of EV drivers without a private charging opportunity raises relatively faster. This is also reflected in the share of usage in the model when classifying users according to one's availability of a private charging point: The users without a private charging opportunity are responsible for more than 80% of the charging procedures in public.

The loaded energy at public charging infrastructure shows the same difference between trend and optimistic EV penetration which shows one of the model's limitations: As the EV data base is fixed, the technical progress in terms of range and battery capacity is not reflected appropriately. Therefore, a model enhancement is suggested for future work that incorporates the evolvement in this field, at least by the help of factors. The need for a broad EV data base is justified by sensitivity analysis between the sole utilisation of a Volkswagen ID.3 in comparison to the entire EV data base: The amount of loaded energy is approximately 20% lower with the exclusive usage of the ID.3.

For the analysis of the influence of the regional type, a rural area is compared to Kassel as a mid-size city. The comparison reveals a higher share of charging procedures at private charging points with a difference of approximately 15 percentage points.

Further values which are checked for plausibility comprise the mapping of the loaded energy to the LUCs 1 to 7. For public charging infrastructure, the LUC 7 (roadside parking) has a significant higher share than the LUC 4 (inner-city hubs) which can be explained by the focus of the model on the inhabitants of a city while neglecting travel axes and commuter. When comparing the modelled LUCs 1 to 3 (private charging and employer charging) with the share at public charging infrastructure (LUC 4 and 7), about two third of the loaded energy is charged at private charging infrastructure.

Having checked for plausibility the grid and user model, the CPO model is discussed. The role of public grants is evaluated ceteris paribus by the consequence analysis of the program "Ladeinfrastruktur vor Ort" which supports an investment of public charging infrastructure by at maximum 200K €. Whereas without the public grant an average yearly loss of 20K € results, the public grant turns the average yearly revenue slightly above 0. Consequently, a public grant highly affects the investment decision and is seen as necessary to support the ramp-up of public charging infrastructure.

The highest influence on the CPO's profitability has the electricity price which the CPO has to pay for the electrical energy. A ceteris paribus comparison of four different electricity prices in three-cents-steps between 0.26 and 0.35 €/kWh is conducted. With the lower two prices, a significant profit is reached, whereas the other two would cause losses. Further significant impact is made by the tariffs that the CPO charges its customers and the utilisation rate of the charging points. This model behaviour is in accordance with the expected behaviour that the utilisation rate and revenue contribution of the charging procedures highly influences the CPO's rentability.

For the overall simulation system it can be stated that the scenarios and their implications are solely partially reflected in the individual models' behaviour and therefore also only to a limited extent in the simulation system with its current status. For check for plausibility of the entire simulation system, neither AC nor DC charging points are given as an input to analyse the models' behaviour. The simulation system behaves as expected with no charging procedures being conducted in public which leads to agents running out of energy when they do not have access to private charging infrastructure.

For the system's check for plausibility, the results of the same simulation run as described in 4.6 using a pessimistic scenario for 2030, are analysed. For the 10th generation, the dependencies between the given number of AC and DC charging points on the one side and the following variables on the other side are analysed: The monthly revenue of the CPO, the average peak power deviation within the mid-voltage grid, the occurring peak power, the average monthly costs of the EV drivers and the average share of available charge power compared to the EV driver's desired charge power. For the check for plausibility, not only the non dominated solutions are of interest, but all results as the variety of system behaviour is of interest.

For the monthly revenue of the CPO a strong correlation is observable between the total number of public charging points and the CPO's profitability. As the utilisation rate of public charging points is regarded as a crucial point for the infrastructure's profitability, a correlation between the amount of public charging infrastructure and the CPO's profitability is expected. The profitability is here represented by the monthly revenue of the CPO, as the depreciation for its invest is incorporated. As the number of EV driver and their charging behaviour is fixed for a given year and scenario, the utilisation rate of the analysed number of charging points mainly depends on the total amount of public charging points. The expected strong correlation is confirmed with the three highest numbers of analysed charging points lead to the highest CPO's losses. On the other side, the CPO's profitability is negative for all assessed pairs of AC and DC points.

First, this can be explained by the high degree of parallel charging demands which leads to a relatively low average utilisation rate. Second, the CPO model assesses its profitability without public grants which stresses the need for grants, in particular in case of a slow ramp-up of EVs.

For the peak power deviation, no significant differences are observed as the medium voltage level is analysed with an absolute value of approximately 1%. Conclusively, there is no strong correlation observable between the number of analysed charging points and the occurring peak power deviation. A similar picture in terms of relative analysis is observable for the resulting peak power in the analysed medium voltage net with a value around 15 MW. In contrast to the peak power deviation, the absolute values differ by approximately 600 kW. Again, a correlation between the number of charging points and the peak power in the net is observable. Combining the results for the peak power deviation and the resulting absolute peak power, the number of charging points does not affect the grid stability (represented by the peak power deviation) significantly, but leads to remarkably higher peak powers. The resulting peak power for the medium voltage level is relatively feasible, but a detailed analysis of the low voltage grids downstream might reveal different results.

For the monthly costs of the EV drivers, the average costs correlate strongly with the number of analysed charging points. As the costs of public charging are modelled as higher than the costs of private charging, the increased share of public charging available with more charging points leads to higher costs. In parallel, the share of desired energy in comparison to the available energy at public charging infrastructure highly correlates with the number of charging points. As the simulation system counts a lack of availability as a 0% share, the system behaves as aspected.

9.3. Interview guide for expert interviews

The interview guide was developed with the intent to validate the assumptions and fundamentals of the conducted work at first, collect the opinions on emerging trends within the field and as the core, evaluate the concept and steps of the system configuration. As the interview guide was designed to collect individual views from multiple perspectives while ensuring comparability between the interviews, a semi-structured interview approach is taken with a mixture of open and closed questions. For the beginning of the interview, a short personal introduction of the interview partners was conducted without revealing details about the thesis to exclude a possible impact on the following answers to the general questions. As all interview partners are German native speakers, the interview guide was developed in German and the interviews themselves were conducted in German.

The first half of the interview guide deals with the fundamentals and emerging trends and is divided into four blocks. At first, a general entrance to the field of public charging infrastructure in Germany is taken with regard to current trends, participating stakeholders and recent planning procedures. It follows a block about the usage of simulation in the context of infrastructure. This block comprises the current application of simulation, foreseen challenges and questions regarding terminology standardization as well as model extension and refactoring.

Third, the set-up of simulation in context of infrastructure is put in focus. Modelling tools, data sources and handling as well as the tools and their collaboration for the experts and their organization are treated. The fourth and final block of the first half are closed questions in difference to the open questions before. Several aspects regarding the current planning of public charging infrastructure as well as simulation-specific aspects are taken into account. The scale is chosen in analogy to the German grade system from one to six with one being the best grade indicating an excellent level or a high importance respectively. These closed questions aim to cover those aspects which can be answered on a scale and therefore, are set-up for a comparison between the three experts.

The second half of the interview guide consists of the presentation of the demonstrator for the system configuration as introduced in Sections 6 and 7. During the presentation the upcoming questions of the interviewees regarding understanding were answered as an open discussion is foreseen during the actual demonstration. The open discussion is complemented by the latter closed questions, again with a scale in analogy to the German grade system. For each of the system configuration's process steps, a rating is asked for. In addition, the reusability, comprehensiveness as well as usability are analysed. At the end of the interview, an open question towards open or not touched points is foreseen. In total, the estimated interview duration is between 90 minutes and two hours with the presented structure and scope. The full interview guide is given in appendix A.

9.4. Results of the expert interviews

Three expert interviews were conducted with the goal of covering different stakeholders from industry and academia that work in related fields of the work at hand. The fist interviewee is a modelling expert for energy management, the second one a team coordinator for electric and process control engineering with a focus on sustainable energy solutions for neighbourhoods, and the third is a professor leading an institute for smart mobility. In order to facilitate the comparison of results, they are abbreviated as follows: modelling expert, team coordinator and professor. The results are discussed in the order of their appearance in the interview guide.

First, the general questions towards charging infrastructure for EVs are put in focus. The lack of sufficient charging infrastructure along travel axes was named twice as a current challenge. Moreover, the lack of the wide availability of public charging infrastructure leads to the situation that an own parking spot with a charging opportunity is regarded as highly recommended for EV drivers. Further named challenges comprise the compatibility between several CPOs, getting the permission for locations and the frequency as well as rentability of public charging infrastructure for the CPO. Regarding the load factor the team coordinator does not see a challenge when incorporating load management, whereas the professor sees a challenge, in particular when considering utility vehicles.

For the KPIs regarding public charging infrastructure, the costs and the related return on invest, a relative number of public charging points depending on the number of EVs in Germany and the placement of public charging stations at locations with high frequency, e. g. super markets are named. For the interdependencies to be considered, the different types of charging (private, public, employer) are brought up as well as the market penetration and the dependencies of regional mobility subsystems with their interaction. With a more technical focus, the team coordinator named the development and bonus systems related to bidirectional charging, as well as the interdependency with renewable energy such as PV.

Regarding the stakeholders that are considered nowadays for planning public charging infrastructure, a gap becomes apparent in comparison to the ideal state: Currently, the installers, public authority, the energy and grid provider as well as the possible property owner are considered. The users, private as well as business, are not adequately represented nowadays, but shall be considered according to all three experts.

For the integration of new charging points into existing systems, exemplary in a neighbourhood, the modelling expert and the professor answered solely the feasibility check of the grid and the corresponding maximal available power. The team coordinator also named this point of feasibility check, but offers an optimistic view into the future additionally: As increased modularity of electrical installation is nowadays required for new constructions and EV charging must be incorporated in planning, he sees a facilitated integration and ramp up path in the future.

Regarding the process for planning and installation, the modelling expert answered that the process depends on location and installer. The professor knows from his work in a commission that it starts with the goal definition on municipality level and is then executed by the locally responsible public authority. The team coordinator responded the current processes in neighbourhoods. There, it starts with the neighbourhood operator requesting an extension. His team derives details and gives a recommendation. The load factor is a major but yet unknown driver of the feasibility for installing charging infrastructure which can be compared with the situation of introduction of electric cooking.

The consideration of future uncertainty can be either conducted scenario-based complemented by local detail planning or by providing capability for future extension. Uncertainty remains partly difficult to estimate as technological advancement in combination with major incidents, e. g. COVID, and political decision cannot be foreseen nor quantified.

To align stakeholder interests, expert commissions in form of project-based meeting series, stakeholder forums or direct meetings between the directly participating parties (grid operator, installer, property owner) are named. Trade-offs in the process arise between the grid operator being responsible for secure energy supply on the one side and the installers and possible operators on the other.

This conflict arises when more charging power shall be installed than the grid operator allows. As the grid operator is the final instance regarding installed power, only technical solutions behind the grid connection point such as load management can be then used. Moreover, the equipment of parking lots with a charge point leads to a decreasing number of parking lots for conventional vehicles. Finally, the trade-off between charging power for fast charging, the grid connection point's dimension and installation costs has to be solved.

The second block deals with the usage of simulation in the context of infrastructure. Simulation is used for dimensioning the grid connection point, interdependencies in the context of infrastructure and to derive recommendations. Major challenges result from the data availability which was explicitly named by all three experts and the predictability of future developments. The model extension and refactoring depends on the used simulation tool chain. Whereas for Excel-based simulation, the parameters can be changed according to stochastic distributions, data-based model require a refactoring based on the new data. For further simulation tools, a time delay might occur due to the sequence of modelling, simulation, getting new data from real world and integrate this data or the derived knowledge again in the simulation tool.

For the naming of parameters and variables none of the experts uses external standards. Regarding the usage of simulation and the models during the operation phase e. g. in form of a digital twin, a similar picture results. So far, no digital twin is in usage although data is collected in real-world. A remaining question regarding digital twins is the extent to what this technique is needed. The professor remarks that infrastructure systems are mostly static which makes historic data sufficiently precise.

Simulation validation itself is a consensus by using real world data, only the systematization of this procedure reveals potential. Current challenges with simulation comprise the availability of meaningful data and therefore, also the development of suitable models. Moreover, numeric stability and simulation duration are challenges in practise. Regarding simulation tools, the professor sees no gap which cannot be closed by in-house-development. The modelling experts sees Graphical User Interface (GUI) development and usability in general, but also in particular for non-simulation experts. The team coordinator stresses the point of automated analysis during operation and the related prediction of optimal operation for the upcoming one or two hours.

The third block about the set-up of simulation in the context of infrastructure starts with the used simulation standards. Whereas the modelling expert uses the FMU standard, design pattern and development environments, the professor reports the use of agent-based frameworks and the team coordinator only reports the usage of in-house-developed tools without external modelling tools. On the other side, the modelling expert names a range of modelling tools, such as Matlab Simulink and AnyLogic.

All three experts make use of external data sources. In addition, the professor uses internal data as provided in research project and the team coordinator uses internal data from projects that are already in operation. For software solutions the modelling expert uses a mixture of self-developed and purchased software where the professor and the team coordinator use self-developed frameworks. But both also reported that they are constantly evaluating also purchased solutions. The hosting of the software is done in the cloud for the professor and mainly on-premise with the modelling expert and the team coordinator depending on the availability. Modelling and simulation is mainly done in-house with all three experts.

The processes diverge between the three experts. Whereas the professor uses established processes for data-driven modelling, the modelling expert starts with the problem definition, followed by tooling and modelling depth. Subsequently, he defines the required results and edits them for presentation. The team coordinator pursues an iterative approach which starts with a rough data analysis which is further detailed until an concrete offer can be derived. Finally, the distribution of tasks between simulation and application experts is evaluated. The modelling expert has a separation between simulation specialists and the surrounding work in his projects, a similar distribution is reported by the professor for the associated partners in research projects. The team coordinator has an expert for each tool, but the application experts use the simulation tools themselves.

In the final block of the first half regarding the general field, closed questions were foreseen. The modelling expert highly questioned that planning public charging infrastructure is conducted in a systematic manner and that the stakeholders are collaborating adequatly. On the other hand, the standardization of terminology is evaluated positively which stands in contrast to the not usage of standardized naming in daily work as reported before.

The deviation of comparable simulation results is evaluated also positively while the importance of extensibility and refactoring is also stressed. The protection of IP gets the highest rating of all questions which supports the assumptions of grey-box or black-box approaches for simulation models. Finally, the evaluation whether a holistic model or a modular simulation system is preferred, the answers diverge: Whereas the team coordinator tend to one holistic model, the two other aim for modularity.

Having concluded the first half of the interview, the different perspectives of the experts are compared: Whereas the modelling expert has the widest range of tooling and sees the challenges in making simulation accessible, the professor reports less methodological gaps and a state-of-the-art procedure. All three report that the collaboration and compromise finding between stakeholders leaves room for improvement. IP protection is a crucial point as well as the data availability for all three.

Whereas the standardization in terminology is regarded as well-developed, this standardization is not used in simulation yet. This stresses the importance to deal with models that do not follow a generally accepted naming convention for the variables and parameters. Moreover, a lack of systematization for integration of new knowledge as well as for the transition into the operation phase was reported.

Regarding the second half of the interview guide, the demonstration of the system configuration demonstrator was conducted as a hands-on with the interviewees deciding on e. g. selection of KPIs and the definition of the interdependencies. Thereby, the depth of the discussion was improved as the interviewees were part of the demonstration. All steps were explained by the interviewer and individual questions were answered. As the project was not introduced in detail a-priori to the demonstration, the further understanding of the work was reached by the demonstration and explanation. In the following the feedback which was given during the presentation is summarized for each individual step. The quantitative results are summarised in Figure 41.

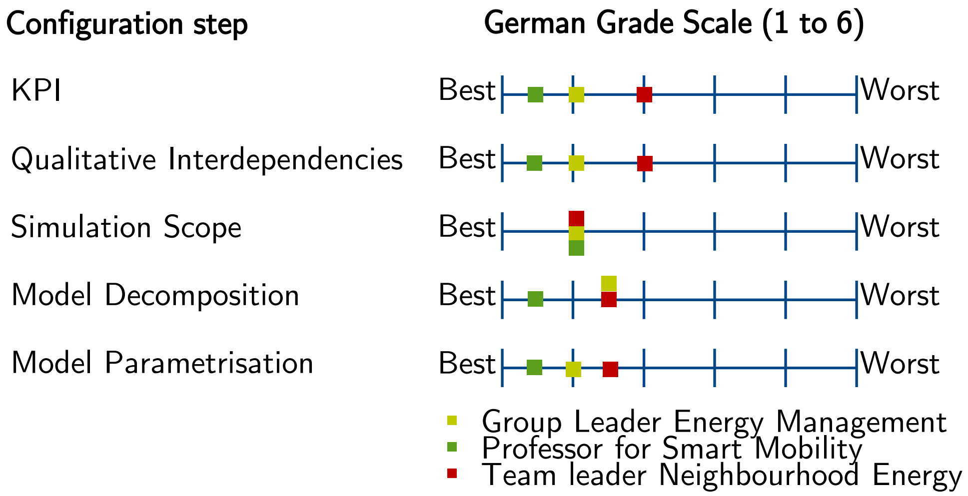


Figure 41: Quantitative results of expert interviews

First, the KPI level is discussed. The wording of "ontology" caused questions two times as its meaning in the given context for standardized and structured terminology was unknown. Regarding the view as a table with concept and description, the opinions were divided.

On the one hand, the professor would like to have an additional graph view to display the contained relations in the ontology. Further explanation was necessary that the KPIs are not necessarily the optimisation criteria in the actual simulation run. On the other hand, the team coordinator thinks that sets of KPIs would provide more user guidance. He recommended sets of KPIs for several use cases which could be than optionally adopted to specific needs based on the ontology.

For the second step of defining the qualitative interdependencies, questions arose because the influencing factors are defined by text input without any defined vocabulary. As this step is done to reflect the undefined model's vocabulary and to account for shares or subparts of an ontology's concept in parallel, the explanation could convince the interviewees. A further discussion step was the choice of exactly two influencing factors per interdependency. As factors can appear multiple times, chained interdependencies are possible by reusing the same factor. Again, the team coordinator proposed to define and display default sets according to the KPIs.

For simulation scope, the procedure and aim of the step did not need further explanation. The modelling expert wished to display the content of the scenario files with the contained data, whereas the team coordinator found the encapsulation appropriate. Due to the limited availability of demonstration models, the choice within this step was limited to the assignment of the models to the prior-defined factors.

The following step of "model decomposition" with the automated mapping of model variables and parameters to the ontology's concept was highly valued by the modelling expert, but too detailed for the team coordinator. He recommended that the user should only see the details if issues arise. The professor highly appreciated the possibility to integrate OOV models in an automated manner.

Finally, the step of model parametrisation was again judged as too detailed by the team coordinator and the modelling expert wished to get more insights about the possible scenario. The degree of automation was again appreciated and the added value of a fault-reducing automation and assignment of transformation was seen.

As the degree of detailing was at some points too high for the team coordinator, its rating for the configuration steps was on average slightly lower than e. g. that of the professor. The step of qualitative interdependencies diverged mostly between the professor and the team coordinator with the first giving his highest grade and the latter his lowest grade. The reusability of the artefacts was differentiated by the modelling expert: He judges the models as highly reusable within the framework, but the ontology and the scenarios slightly below in terms of reusability. Both other experts see an overall high reusability. The division of the configuration step seemed traceable and logical to all three experts as well as the sequence.

The comprehensiveness of the steps were seen by all three experts whereas the professor judged the clarity of the final two steps lower than the three steps at the beginning. The usability and added value for simulation experts was clearly stressed by all three experts, whereas an application expert would need more user guidance and a reduced level of detailing. Finally, the team coordinator stressed the need for traceability between the simulation configuration and the corresponding results. Conclusively, the expert interviews confirmed the underlying assumptions of this work with the need for traceability, user guidance and a methodological enrichment for virtual engineering.

Although the proposed system configuration needed explanation during demonstration, the experts' evaluation in the end showed that the concept was fully understandable and offers an added value by its comprehensiveness, user guidance and functionalities. Nonetheless diverging opinions on the level of detailing and user guidance appeared. Whereas the modelling expert and the professor tend to more details with a detailed view on the scenarios and the graphical representation of the ontology respectively, the team coordinator with a more application-oriented view recommends to reduce the level of detailing in particular within the last two steps.

9.5. Application to Further Fields of Interest

Within this subsection, the applicability of this work at hand for further use cases shall be discussed. The application within this work is conducted for public charging infrastructure in Germany as an essential part for the future mobility ecosystem. The application to further fields of interests has to be analysed in two dimensions: The methodological part with the framework, its addressed challenges and the simulation configuration on the one side and the usage of the artefacts, such as models, domain ontology and scenarios on the other. The high-level split of preprocessing for configuration, execution or run time and evaluation or post-processing is universally applicable and allows the mapping of a broad range of tasks from simulation and virtual engineering.

The framework was developed with a separation between the domain level, concrete functionalities and the process steps. The process steps are applicable to a wide range of fields for virtual engineering and simulation and are therefore neither limited to mobility nor to infrastructure. It is also applicable to the development of components by the help of simulation: The KPI level with the definition of the goals to be analysed also applies for the definition of test cases in general which are comparable to the scenario term as used here for infrastructure decision. The definition of interdependencies applies if an interplay with other components shall be analysed. Otherwise, for the development of a single component only internal interdependencies shall be defined.

Subsequently, the scenario file selection is conclusively the selection of the test case suite to be analysed. When developing a single component it is most likely to have a comprehensive simulation model which leads to the need of only one model to be selected. Nonetheless, the component's model could be also split into multiple submodels and in each case, the model variant needs to be selected for analysis. Consequently, the model selection also applies here. The assignment of the models to the influencing factor depends on the number of models to be integrated. The parameter and unit matching is universally applicable under the assumption of a suitable ontology. In the case of an internal development, the matching has a reduced importance as the model's content and naming can be conducted with regard to internal rules. Nonetheless, it provides support in large organizations or in collaboration with suppliers.

The interface specification only applies when multiple submodels are part of the development process. The final step of model parametrisation again does also apply for an individual model of a component with the selection of a test case from the test case suite instead of the scenario selection and the variables to be analysed for evaluation are also needed, even with a different approach of evaluation instead of the presented multi-criteria decision support.

Second, the concrete back end functionalities are also domain-independent, but are developed and mostly limited to their application to simulation systems. These simulation systems can be either applied for systems, such as mobility infrastructure, but also to the development of ecosystems and the interplay of components, as e. g. observable in the field of mobile devices. Nowadays, mobile devices such as smart watches, smartphones and earphones build together the ecosystem of an OEM and therefore, their interplay shall be ensured including the upwards and downwards compatibility. For such an application the major points such as analysis, comparison and setting of the simulation models also apply, but the tool chains and common standards differ between the industries. Therefore, the concrete functionalities do also apply, but their implementation has to be possibly adopted.

Third, the domain-specific artefacts are analysed separately in the categories of ontology, scenarios and simulation models. The domain ontology was self-developed because a comprehensive ontology for smart mobility and the related fields is still pending. It was specifically composed for the use case at hand, but can be also used for further applications in the mobility and transportation sector, e. g. the assignment of parking lots in general or the charging infrastructure for further vehicles, e. g. for micro mobility offers or for electrified buses as part of public transport.

The developed scenarios are developed with the aim to cover the CASE trends within the mobility domain and are therefore also applicable e. g. for the incorporation of autonomous vehicles or the analysis of implications caused by an increased proportion of shared mobility. On the other hand, the developed scenarios are limited to relatively high-level questions within the mobility domain as they do consist of 13 descriptors and are not applicable to questions outside the mobility domain and cover the situation in Germany mainly.

Finally, the reusability of the individual models is discussed: The EV driver model specifically models the mobility behaviour by cars in Germany and returns the charging requests. Whereas the model version including its inputs and outputs is closely limited to the application within this work, the adoption of the inputs and outputs would allow the analysis of further questions related to the individual mobility behaviour, such as the usage of shared mobility. Second, the CPO model is also limited to the application for public charging infrastructure within Germany. At least the EV driver model as well as the CPO model are designed for adoption to different German regions and scale by parametrisation which makes them at least flexible within the field of intended application.

The third model, covering the electrical grid is the most universal of the three models. It allows the modelling of low- and medium voltage level either based on a representative library of German net topology or based on real data to be incorporated. Moreover, the scope of the modelled grid is flexible and further electrical components can be integrated with a reasonable effort. Thereby, the grid model is also suitable e. g. to analyse required extensions for the increased share of renewable energy or the usage of buffer storages. Nonetheless, also the grid model requires adoptions in terms of its inputs and outputs for different fields of application.

Conclusively, the work at hand is applicable to further fields with a decreasing degree from the proposed steps, via the concrete functionalities to the domain-specific artefacts. It has been discussed that even for the virtual development of a single component the process steps also apply and most functionalities are required, even if their implementation needs to be adopted to meet different industry standards. The application to further questions within the mobility domain has been proved and the application to the distinguished field of mobile devices shows that the work at hand is valuable beyond the scope of the here-pursued application. Nonetheless, the domain-specific artefacts, in particular the models' interplay is limited to a specific field of application which reveals the importance of frameworks that account for the reuse and low-effort composition of simulation systems.

10. Summary

The work contributes to the field of simulation and virtual engineering by enhancing simulation methods, concretely co-simulation, for their usage in the context of mobility and related infrastructure to support decision-making. Co-simulation allows to incorporate existing models, use specialized tools to model different parts of a system and ensure modularity of the simulation system's composition. Thereby, interdependencies and foreseeable scenarios can be analysed on a large scale beyond the scope of real-world experiments.

Based on recent developments in the mobility domain, the aspects of thinking in systems, rapid development cycles, virtual engineering and the system's support throughout its life cycle serves as the fundament for the work at hand. By the example of planning sophisticated public charging infrastructure for electric mobility in Germany, the challenges for system configuration, handling and enabling decision support by simulation are discussed and approaches towards automation and user guidance are presented. The exemplary simulation system for charging infrastructure contains the three stakeholder perspectives of the EV drivers, the electrical grid with its technical installations, and finally the CPO. Thereby, bottom-up planning is enabled as a detailed analysis of scenarios and infrastructure options becomes possible.

The core of the work is to build a guided and highly automated system configuration to define and concretise a hybrid co-simulation system in a traceable way. A major challenge is the consistent parametrisation of the heterogeneous model system which is solved by the usage of NLP. Moreover, a flexible multi-criteria decision support system enables the comparison of the results from different simulation runs and their corresponding infrastructure configuration to support decision-making. Tackled challenges comprise the reuse and replacement of models, consistent parametrisation of simulation systems, and comparability between simulation configurations and runs. The system configuration was evaluated in expert interviews and the underlying assumptions of the research as well as application fields have been validated.

10.1. Contribution

The challenges for handling co-simulation systems are clustered into a three dot three matrix with one scale consisting of system configuration, run time and post processing, and the other of process step, required functionalities and domain-specific artefacts. Thereby, it can be systematically derived how a framework shall be set up including the derivation of required adoptions to specific domains. Moreover, the systematization of steps, artefacts and their interaction reveals the fundament for the aimed automation and guidance.

For system configuration, five consecutive abstraction layers are defined. First, the key performance indicators are chosen on a top-level from a selectable domain ontology, for which qualitative interdependencies consisting of a related KPI and two influencing factors are defined subsequently. It follows the step of simulation scope definition, in which the scenario data base and simulation models are chosen. Each of the influencing factors is assigned a simulation model which it covers. In the step of model decomposition, the models' parameters and variables are mapped to the concepts of the ontology and connections between the models are set, all highly automated. In the final step of model parametrisation, a consistent parametrisation based on a selected scenario is applied. Thereby, an executable simulation system is traceable derived with user guidance and a high degree of automation. The challenges of model reuse and replacement as well as consistent parameterization are addressed by the latter three abstraction layers. The automation facilitates the composing of the simulation system configuration and makes it accessible for application-oriented users as it requires less simulation know-how.

Within the system configuration, the automated mapping of the models' variables and parameters to an ontology in the step of simulation scope is an enhancement of the state of the art. Based on NLP, the variables' names are classified into specific and common vocabulary with the classification deciding on the NLP model used. Beside the variables' names, their description is also processed by NLP to enhance the precision of the method. With this automated mapping, the simulation system can integrate models that are out of vocabulary compared to the ontology in a highly automated manner which accounts in particular for the model reuse.

Furthermore, the protection of IP of the incorporated models can be ensured as only the model's interface is analysed in this step. The importance of IP protection has been stressed in the expert interviews. This model integration accounts for the model reuse, as well as model replacement and synchronisation in parallel in the context of co-simulation systems. The limits of automation and user guidance are discussed and boundaries are defined. The system configuration aims to combine the top-down definition of an executable simulation system with the ability to integrate existing models from outer scope which is referred to as rather a bottom-up approach. Finally, the aggregation and analysis of results is elaborated meeting the five proposed abstraction layers.

The application of a flexible multi-criteria optimisation and the integration of the co-simulation-system into this optimisation allows a detailed evaluation of feasible decisions. The result is a set of non-dominated solutions, here application-specific, a set of infrastructure alternatives which fits all stakeholder needs best possible. This optimisation framework is set-up domain independent, as only the decision criteria have to be defined based on the participating models.

10.2. Future Work

Finally, the corresponding future enhancement of the work at hand is discussed. A crucial point is the lack of a suitable domain ontology that accounts at first for comprehensiveness for the field of smart mobility and its infrastructure and second, is widely accepted within industry and academia and therefore, commonly used for model development.

Moreover, the models at hand only cover certain aspects related to charging infrastructure and have been chosen to cover the most important perspectives as recommended in literature. Consequently, the build-up of further models is recommended to cover more aspects and gain further precision in the simulation system.

The evaluation has shown that different user groups tend to have diverging opinions on the usage and corresponding detailing of the developed system configuration. Therefore, its application in practise require a detailed a-priori analysis of the aimed user group, the deviation of its corresponding requirements and the subsequent tool development for external usage including an automated installation.

An important motivation for the work at hand is the traceability within the simulation system which shall also allow the transition from a-priori simulation into a digital twin of the existing system. Challenges beside others comprise the data collection in real world, its incorporation into the models, and the structured derivation of learnings to be incorporated in decision support.

A. Interview Guide

The following interview guide was developed and applied for the interviews conducted for evaluation. The guide was applied identically for all three interviews to ensure comparability between the results.

Introduction to Field of Research and Charging Infrastructure

1. Welche Herausforderungen sehen Sie bei der öffentlichen Ladeinfrastruktur in Deutschland und Europa aktuell?
2. Welche Zielgrößen (KPIs) sind für Sie in der Planung öffentlicher Ladeinfrastruktur von besonderer Bedeutung? Nennen Sie drei bis fünf.
3. Welche Abhängigkeiten bzw. Wechselwirkungen in Bezug auf öffentliche Ladeinfrastruktur sind von besonderer Bedeutung?
4. Welche Stakeholderinteressen sind für die Ladeinfrastrukturplanung zu berücksichtigen? Nennen Sie drei bis fünf.
5. Welche Stakeholder partizipieren aktuell an der Planung öffentlicher Ladeinfrastruktur?
6. Wie erfolgt die Integration neuer Ladepunkte in bestehende Systeme (z. B. Netzanschluss)?
7. Wie beschreiben Sie den aktuellen Ablauf zur Planung öffentlicher Ladeinfrastruktur?
8. Wie wird die Unschärfe der Zukunft in der Planung öffentlicher Ladeinfrastruktur berücksichtigt (Stichwort Roadmap)?
9. Wie erfolgt die Abstimmung zwischen den Stakeholdern im Planungsprozess für öffentliche Ladeinfrastruktur (z. B. Gesprächsforen, weiterführende Kooperationen)?
10. Wie ist die Bereitschaft verschiedene (ggf. abweichende) Interessen bei der Planung von öffentlicher Ladeinfrastruktur zu berücksichtigen?

Usage of Simulation in Context of Infrastructure

1. Für welche Fragestellungen nutzen Sie Simulation bzw. sehen diese als wertvoll an im Kontext von Infrastruktur?
2. Welche Herausforderungen sehen Sie bei der Simulation im Kontext von Infrastruktur?
3. Wie erfolgt die Integration neuer Erkenntnisse in ihre Simulation (Erweiterung, Refactoring, etc.)?
4. Benutzen Sie externe Standards bei der Benamung von Variablen und Parametern?
5. Inwiefern wird die Simulation bzw. ihre Ergebnisse in der Betriebsphase genutzt (z. B. digitaler Zwilling)?
6. Validieren Sie Ihre Simulation bzw. Ergebnisse im Betrieb bzw. mit historischen Projekten?
7. Welche Herausforderungen bei der Simulation sind Ihnen in den vergangenen 12 Monaten begegnet?
8. Welche Methodik bzw. Simulationswerkzeuge fehlen Ihnen aktuell?

Set-up of Simulation in Context of Infrastructure

1. Welche Standards hinsichtlich Simulation sind Ihnen bekannt oder werden bei Ihnen im Haus genutzt?
2. Welche Modellierungstools werden bei Ihnen genutzt?
3. Welche Datenquellen werden im gegebenen Kontext genutzt (extern wie intern)?
4. Welche Datenformate nutzen Sie?
5. Setzen Sie auf eigene oder fremdentwickelte Softwarelösungen?
6. Wenn Software, dann cloud oder on-premise?
7. Externe Beauftragungen oder interne Bearbeitung?
8. Beschreiben Sie ihre Arbeitsschritte in der Simulation.
9. Wie beschreiben Sie die Aufteilung zwischen Fachexperten bzw. Projektierern und Simulationsexperten?

Closed General Questions

Scale from 1 (relevant, good) to 6 (irrelevant, bad)

1. Wie systematisch wird die Planung von öffentlicher Ladeinfrastruktur aktuell vorgenommen?
2. Wie bewerten Sie die Zusammenarbeit zwischen verschiedenen Stakeholdern öffentlicher Ladeinfrastruktur in Bezug auf den Austausch von Daten und Modellen?
3. Für wie gut erachten Sie die Simulationsexpertise bei Anwendern im Kontext Planung öffentlicher Ladeinfrastruktur?
4. Wie bewerten Sie den aktuellen Stand von Ontologien bzw. Begriffsstandardisierung im Kontext von Ladeinfrastruktur?
5. Wie leicht ist es im Kontext von Ladeinfrastrukturplanung übertragbare Aussagen aus der Simulation zu generieren?
6. Welche Bedeutung hat die Erweiterung und Anpassung in der Simulation in ihrem Arbeitskontext?
7. Welche Bedeutung hat der Schutz von Intellectual Property in Simulationen in ihrem Arbeitskontext?
8. Simulation: Lieber ein großes Modell (1) oder ein modularer Aufbau (6)?

Closed Questions after Demonstration

Scale from 1 (relevant, good) to 6 (irrelevant, bad)

1. Wie bewerten Sie die Wiederverwendbarkeit von Artefakten (Ontologie, Szenarien, Modellen) aus dem vorgestellten Tool?
2. Wie bewerten Sie die Aufteilung der verwendeten fünf Schritte für die Systemkonfiguration?
3. Wie bewerten Sie die Abfolge der verwendeten fünf Schritte zur Systemkonfiguration?
4. Wie bewerten Sie den Schritt „KPI“?
5. Wie bewerten Sie den Schritt „Qualitative Interdependencies“?
6. Wie bewerten Sie den Schritt „Simulation Scope“?
7. Wie bewerten Sie den Schritt „Model Decomposition“?
8. Wie bewerten Sie den Schritt „Model Parametrization“?
9. Wie bewerten Sie die Vollständigkeit und Nachvollziehbarkeit der Schritte zur Systemkonfiguration?
10. Welche Nutzbarkeit bringt das vorgestellte Tool für Simulationsexperten?
11. Welche Nutzbarkeit bringt das vorgestellte Tool für den Anwender?

Final Question

1. Gibt es noch Themen oder Aussagen, die Ihnen wichtig sind, aber bisher im Interview nicht ausreichend behandelt wurden?

Authored Publications

Conference Paper (peer-reviewed)

2022	Leonard Stepien, Sven Hallerbach, and Frank Köster, ”Accelerating Simulation-Enabled Engineering.” 2022 IEEE International Symposium on Systems Engineering (ISSE). IEEE, 2022.
2022	Leonard Stepien and Frank Köster, ”Flexible Model Exchange in Modelling Smart Mobility by Using Domain Ontologies.” 2022 IEEE International Systems Conference (SysCon). IEEE, 2022.
2021	Leonard Stepien and Frank Köster, ”Parametrizing Complex Co-Simulations to Support Decision Making in Mobility.” INFORMATIK 2021 (2021).

Further Publications

2023	Leonard Stepien, ”Bidirectional Charging in Residential Neighborhoods.” ATZ worldwide 125.9 (2023): 18-23.
2022	Leonard Stepien, „Zukunftsweisendes Energiemanagement im Quartier.“ Whitepaper ITK (2022)

Presentations

2023	Leonard Stepien, “Smart Charging Infrastructure Architect.” Power2Drive. München. (2023).
2022	Leonard Stepien, „Simulation for Infrastructure Development.” IAA Transportation. Hannover. (2022).
2022	Leonard Stepien, „Flächenknappheit auf der letzten Meile: Wie kann Simulation dabei unterstützen?“. Last Mile City Logistics. Berlin. (2022).
2022	Leonard Stepien, Robin Schmidtke, Frank Köster, „Planung öffentlicher Ladeinfrastruktur in Deutschland“ Hybrid- und Elektrotagung Gifhorn. (2022).

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Erklärung

Hiermit versichere ich, dass ich diese Arbeit selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

Die Dissertation hat weder in ihrer Gesamtheit noch in Teilen einer anderen wissenschaftlichen Hochschule zur Begutachtung in einem Promotionsverfahren vorgelegen.

Hiermit erkläre ich, dass mir die Leitlinien guter wissenschaftlicher Praxis der Carl von Ossietzky Universität Oldenburg bekannt sind und von mir befolgt wurden.

Hiermit erkläre ich, dass im Zusammenhang mit dem Promotionsvorhaben keine kommerziellen Vermittlungs- oder Beratungsdienste (Promotionsberatung) in Anspruch genommen worden sind.

Oldenburg, 16.11.2024 ....

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