Parametrizing Complex Co-Simulations to Support Decision Making in Mobility

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Abstract: The radical change in mobility calls for the simulative support of decision making for large-scale projects which asks for the simultaneous consideration of multiple stakeholders additionally. The major challenge in such simulation systems is nowadays the consistent and modifiable tool-independent parameterization to enable scenario analysis by systematic parameter variation and reach reliable support for those extensive decisions. Taking the example of public charging infrastructure, a holistic co-simulation framework is proposed, in which an approach for the central parameterization as well as the belonging scenario analysis tool take part. Necessary functionalities as well as the belonging interfaces are revealed. Proposing a loop of mainly getting and setting parameters automatically, a domain ontology is required to reach standardization of naming conventions. With this work, a research gap in the filled of co-simulation is addressed by proposing a framework which allows the central parametrization of such systems to enable decision support.

Keywords: Co-Simulation, Central Parameterization, Decision support, Electric Mobility, Charging Infrastructure

1 Introduction

1.1 Motivation and Aim

Currently the mobility undergoes changes in manifold directions: Intermodal connections, the change of user behaviour as well as technological changes due to political decisions and technical progress. Regarding the high required invest and the long-term implications to evolve mobility systems, decisions have to be taken carefully and under consideration of relevant interdependencies, although an uncertainty will remain. As future developments cannot be experienced economically in real-life on a large-scale base, simulative analysis to support decisions and regard foreseeable scenarios is a suitable approach.

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Those foreseeable scenarios shall cover the realistic range of future developments, which is technically a parameter space consisting of the modelled behaviour of the stakeholders and their interdependencies. From this parameter space, the relevant combinations have to be derived as scenarios for the simulation. The consideration of different scenarios within the same simulation can be described as scenario variation and calls for the ability of the used simulation environment for systematic parameter variation. Only this systematic parameter variation enables the aimed decision support by analyzing and comparing different scenarios.

Simulation is widely established in the mobility domain, e. g. regarding traffic [Lo18, MDC19] or vehicle relocation in car sharing [Ke09], which allows the visualization and analysis of certain developments and changes.

Within this domain, the simulative approach is challenging due to multiple stakeholders and required adaptations to local circumstances. Therefore, the approach must be flexible, adoptable and calls for a high reliability of the results to meet the demand of such cyber-physical systems.

Co-simulation meets the described challenges: First, it allows the domain-specific modelling for the stakeholders' perspectives. Second, models can be exchanged within reasonable effort to make local adaptations or to later add a further model. Moreover, models can be reused for different purposes: E. g. a traffic simulation can be not only used for traffic light optimization but as well to identify the demand for car parks time- and location-specifically.

The challenge arises when a co-simulation shall be enabled for scenario variation and therefore, parameter variation respectively. By the example of planning public charging infrastructure for electric vehicles (EV), the needs as well as the challenges are revealed. To overcome EV drivers' concerns such as range anxiety and necessary detours for charging [KKS13, AG20], public charging infrastructure is regarded as a crucial point for the market penetration of EVs and is therefore in political focus as an urgent issue [Bu19, Be19, KKS13]. Only with sufficient public charging infrastructure, the emissions associated with individual mobility as established nowadays can decrease with the desired speed.

In general, the framework enables careful decision making in the mobility sector under consideration of multiple relevant aspects. This facilitates necessary adaptations in the mobility sector to meet the demands of climate change and changing users' request. Consequently, it contributes to the field of green software. The concrete benefits of the presented approach depend on the concrete application. Therefore, the benefits regarding environmental and sustainable aspects are explained by the example of planning public charging infrastructure in the following.

The efficient location of charging infrastructure ensures several point: The charging points are frequently used, as they are placed according to the driver's behavior and under consideration of specific local circumstances. In contrast to private or semi-public charging points, the accessibility is not restricted. Without restrictions, the achievable capacity utilization is higher and the overall amount of charging points can be reduced. Moreover, the simulation allows an enhanced precision of necessary charging stations, which prevents the authorities from installing too many charging stations. As the production and installation process of such charging systems asks for significant use of resources and investments, the improved planning procedure helps to decrease the environmental impact caused.

1.2 Status Quo and Challenges in Co-Simulation

Cyberphysical systems call for the simultaneous analysis of relevant subsystems. Due to the heterogeneity a unified modelling or monolithic approach is not suitable. Instead, the use of specialized software packages and modelling approaches is promising. The necessary merge of those distributes models can then by reached by co-simulation. This is generally defined as a coupled simulation of independent black boxes with an orchestrator – hereafter master algorithm – to coordinate the simulation. [Pa17]

A co-simulation scenario is regarded as the obtaining of a correct co-simulation by providing the necessary information. This necessary information mainly compromises the inputs, outputs, and their experimental frames beside others. There are four main types of co-simulation which have to be considered within the domain: discrete-event (DE), continuous-time (CT) and hybrid approaches combining those two. Depending on the major coordination of the overall simulation, there are either called hybrid DE or hybrid CT simulations. [Go18] As time is the major unit in the mobility domain and there are both, discrete as well as continuous systems, the type of hybrid CT simulation is the most relevant here.

Standardization of co-simulation is aimed in multiple projects which results in several co-existing standards. The High Level Architecture (HLA) focuses on simulation interoperability by providing a runtime infrastructure and is also applicable on cyber-physical systems [Da97, Na19]. The functional mock-up interface (FMI) standard concentrates on the standardization of the model's interface by defining a model description standard to enable the exchange of simulation models as a container [Ma20]. Related to the FMI standard, the System Structure and Parameterization (SSP) standard aims to provide a tool independent standard to enable the parameterization of composed simulation systems. The SSP standard provides an opportunity to provide a container of several pre-defined FMUs to be used as a container. [Ma19] Next to the technical challenges to be overcome for co-simulation, the consideration of different sub-domains calls for the standardization of used terms to address semantic challenges in parameterization. Exemplary this is conducted in [Te20] in the related domain of power and energy systems.

The issue of systematic parameter variation for scenario analysis has been addressed in the context of automated driving among others. The field of safety assessment for automated driving calls for the analysis of a variety of defined scenarios which has to be conducted also in simulation. Therefore, in [Na19] an approach is presented, in which the parameter setting is conducted via a specific tool, from which the further application are supplied.

A related co-simulation approach towards the planning of charging infrastructure is proposed in [MBN16]. Montori et al. integrate "Simulation of Urban Mobility" (SUMO) as an urban traffic simulator with an electric power system simulator ElectroMagnetic Transient program (EMTP-rv) via the open-source simulation environment OMNeT++. The parameterization itself is not conducted centrally but rather model-individually, completed by a synchronization mechanism. Binder et al. pursues a buttom-up approach towards scenarios in co-simulation by creating comprehensive scenario descriptions from co-simulation runs using the smart grid co-simulation framework Mosaik [Bi20]. In the domain of planning charging infrastructure, known co-simulation frameworks build on decentralized approaches for parameterization [MBN16, Na19], which limits their value for scenario analysis and decision support.

Having summarized the state of the art, the challenges to be overcome are introduced. There is mainly the reuse of existing models, the manifold synchronization of models and finally, the systematic parameter variation to enable the scenario analysis and the subsequent optimization for decision support.

Model Reuse

Models have been developed once to serve in a specific environment and a defined purpose. In the context of mobility, this might be a grid model originally developed to plan a factory location which should be now used for charging infrastructure. Therefore, it is necessary to find ways which allow the reuse with only small adaption which can be ideally conducted without expert-knowledge on the model. Regarding the parametrization several issues might occur:

Variable only part in a specific model: If a variable can be only found within one model which is not supported by the other included models, this variable must be handled via the parameterization. Either by setting a constant value or by a function which uses further variables from the participating models. If a parameter is only part of a specific model this can be directly handled via the central parameterization without regarding any interdependencies.

Variable names different: Either exchanged variables as well as parameters might occur in different models with different names. Furthermore, the variables should possibly appear with a more user-friendly name than it is handled internally in the simulation analysis tool. Those naming differences have to be recognized and solved for the actual simulation runs.

Model Exchangeability

The model exchangeability is closely related to the model reuse. When it is aimed to reuse existing models, e. g. for local adaptations or the consideration of a specific stakeholder, those models shall be integrated with limited effort required. Therefore, the framework should deal with different degrees of models' accuracy, scope, and interfaces. Models' accuracy means the outputs' resolution in terms of details, e. g. spatially, as well as the calculation frequency or step size. With the models' scope, its included content is meant. E. g. if a model only considers technical or technical and financial aspects. The models' interfaces are relevant for the connection of inputs and outputs between the participating models within the framework.

Models' Synchronization

In recent research the simultaneous time progress has been widely addressed. Regarding the parameterization, it is important to ensure that all models have the same values for identical parameters (see above). In the given context the pricing for electric energy have to be consistent for all models. In particular with to regard to the systematic scenario variation it has to be ensured that all variables and parameters are adopted consistently to the scenario. Furthermore, during simulation runs the variables have to be exchanged to all relevant parts of the simulation framework according to a determined order.

Systematic Parameter Variation for Scenario Analysis

This hypothesis is closely related to the models' synchronization above. The systematic parameter variation has two major challenges: The technical aspect of setting and getting the parameter values and the content-wise related perspective towards the parameter values and realistic combinations of them. Therefore, the values' variation between the parameters in distinct simulation runs have to be defined for the parameters or a group of parameters depending on the domain. Afterwards, the decision on how to vary the combination of parameters efficiently has to be taken. Due to the high number of parameters within mobility issues full-factorial plans are unlikely to be suitable.

1.3 Main Contribution and Paper Structure

This paper reveals the required functionalities to overcome the aforementioned challenges in parameterization and embed them in a general, modular, and tool-independent co-simulation framework that serves the decision support in current mobility issues. Exemplary explained by the field of planning public charging infrastructure, the required functionalities, their interaction and remaining challenges regarding implementation and adaptation are addressed.

Hereafter, the framework for decision support by co-simulation introduced. This includes the presentation of its aim, components, and workflow.

Thereafter, the concrete functionalities divided into the simulation preparation to ensure a consistent parameterization and the simulation and analysis section are elaborated. In parallel the belonging interactions and support concepts are introduced as they appear. This contribution concludes with a discussion and conclusion of the work followed by an outlook on future work.

2 Framework for Decision Support by Co-Simulation

The presented work is summarized in figure 1. Overall components and the major division are shown in blue, the concrete required functionalities and components in grey. The details on this framework are given in the following. The main information and workflow are highlighted with bold arrows, whereas the others represent supporting functionalities.

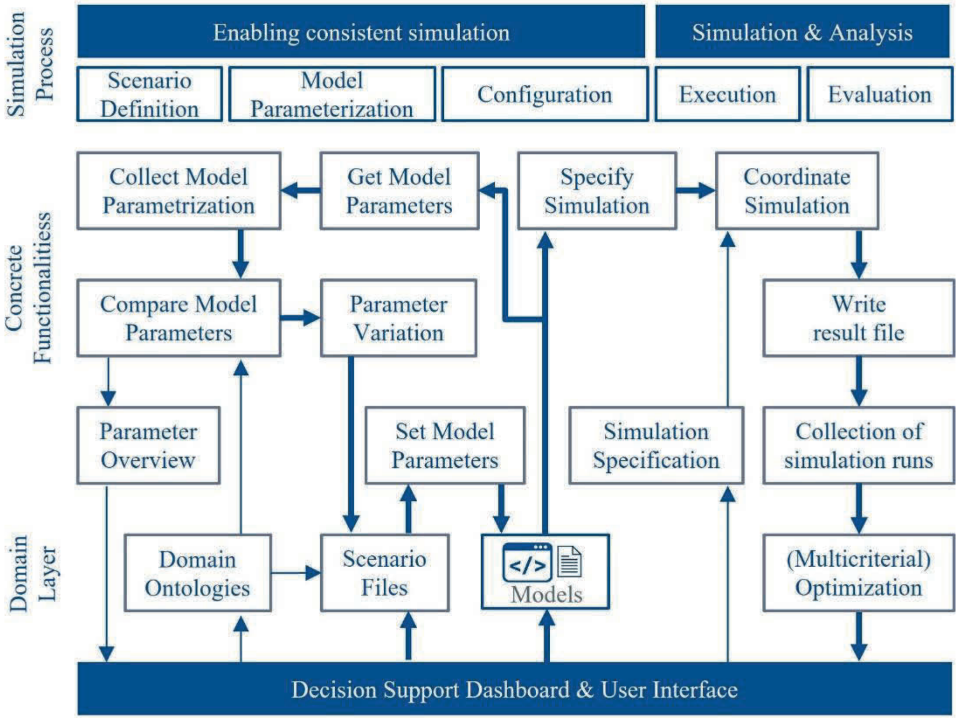

Fig. 1: Framework for Decision Support by Co-Simulation

The proposed framework should overall support decisions in the mobility sector which do require the consideration of multiple stakeholders. Their interests, relevant behaviour and causalities usually are modelled separately from each other due to the heterogeneity in tooling and content-wise focus. To overcome existing differences in terms of parameters, such as default-values, naming and required interconnections, this framework provides the required functionalities and additionally and analyses the user's interaction.

The framework is organized as a matrix with the procedure horizontally and the layers vertically clustering the contents for each step: First, there are the generally applicable layers with the simulation process and the concrete functionalities addressing the arising challenges. Second, it follows the domain layer which is context-specific and includes the user interface as well as the decision support dashboard.

Horizontally, the framework has two major segments spanning the range from starting with models and scenario ideas until reaching optimized results and comparison between different simulation runs: At first, the pre-simulation section to ensure the consistent parameterization needs to be handled. The scenario definition, the model parameterization and partly, the simulation configuration are belonging steps. It follows the simulation and analysis part which mainly contains the simulation execution and the evaluation. Details on the framework's components are elaborated in the following sections, separated in the pre-simulation side "Enabling Consistent Simulation" and its (post-)simulation counterpart "Simulation and Analysis for Decision Support".

3 Enabling Consistent Simulation

Beginning with the consistent parameterization, the required functionalities are presented which incorporate the process steps of scenario definition, model parameterization and partly the simulation configuration. Required inputs from user's side compromise the models to be included, the first approach of the scenario files and the domain ontology.

In the beginning, the types of variables to be handled must be defined. Within the framework, there are three main types of variables to be regarded: Constants, Model inputs and outputs as well as variables for analysis.

Constants are those simulation variables, which are not changed during a simulation run. An example for this type in the context of charging infrastructure is the price for energy. To reach a consistent parameterization, a defined price must be set in all participating models which include that parameter. Consequently, this type of simulation variable must be modifiable during the initialization of the simulation run and fixed afterwards.

The models' inputs and outputs must be served and routed during the entire simulation run. An example is this context, is the current power flow at a specific charging point. For those variables, it is important that the exchanged values match all the same time stamp at any time during the simulation run between the models. Regarding the central parameterization, the initial values must be set accordingly. In parallel to the constants, the aim of consistent parameterization calls for concise initial values between all models.

Moreover, it might be necessary to define an order, in which the models are executed and exchange those variables. This task is conducted by the master algorithm.

As a third type of simulation variables, the class of analysis variables must be considered. Those variables are not directly used within the simulation run, but are required for sophisticated analysis towards decision support. An example could be the average daily degree of capacity utilisation of a charging point. Whereas during the simulation run, the status quo of the charging point might be exchanged, the decision support can be further enhanced by investigating the daily situation based on weekdays. Therefore, the desired analysis variables have to be defined in advance, then the necessary information has to be made available in the individual model and last, this information must be prepared for analysis.

For the consistent parameterization, the variable types constants and the initial values for the models' input are most relevant. Therefore, those parameters have to be identified with the relevant information. This compromises their name, initial or fixed value and, if applicable, the unit. The difficulty of this step lies in the potential limited accessibility of black-box-models' variables. Therefore, the successful application of the proposed framework requires the visibility of all relevant parameters as well as their accessibility to overwrite values for consistency across models. The implementation of this function depends on the models' standard.

The second required functionality is the collection of the models' parameters in a structured manner with the aforementioned scope. This does not necessarily require the format of an external standard as this is internal within the simulation framework. The domain ontology supports this function by revealing potential overlapping parameters. From this status, a user overview is provided which enables the user to further intervene or analyse overlapping and similar parameter. Optionally, the naming of the parameters can be standardized via the application of the domain ontology.

Having created and cleared the parameters' overview, the preparation for the scenario analysis is required. Besides the parameter overview, the scenario files are necessary inputs. At first, a comparison and following adjustment of the prepared scenario files has to be conducted. Potentially, parameters were defined in the scenario files and are not included in the models or vice versa. An adoption of units and related conversion might be necessary. After balancing possible inconsistencies, the user can adjust the scenarios to be simulated according to the aim.

At this point, the required preparation for the simulation runs is mainly finished. For each simulation run, a comprehensive scenario file has to be selected and the parameter values as well as initial values have to be automatically set in the participating models. Therefore, the steps of scenario definition and model parameterization have been completed.

4 Simulation and Analysis for Decision Support

The simulation and analysis part starts with the final steps of simulation configuration and further compromises the simulation execution and its evaluation. Besides the models and their parameterization, the simulation specification is a necessary input for a simulation run. In contrast to the models' parameter variation by the scenario files, the simulation specification should be fixed for all simulation runs within a given context to ensure consistent results. It should compromise the model execution order, the models' step size, the time to be simulated and general specifications such as the participating models. With the twofold simulation input of parameterized models and the simulation specification, the actual simulation can be executed. The coordination functionality is mainly provided by a master algorithm which can be chosen considering the application scope and the amount of data to be exchanged. Generally, the requirements for a master algorithm in this decision support context are limited.

From the simulation execution the results are stored. They comprise the models output and optionally, analysis variables. In the following the result files from each simulation execution are collected and an optimization according to the domain and the user's desire is conducted. This information is then provided to the user in a decision support dashboard.

Besides the technical aspects within the framework, the users' interaction as well as the aimed decision support itself shall be discussed here. A major issue to reach decision support is the definition of a suitable objective function. Regarding the manifold stakeholders, a multicriteria objective function seems adequate. These objectives have to be defined specifically for an application in advance, but the weight of individual components might also be a field of study. Therefore, sensitivity analysis is relevant, equally for parameters in simulation and the weight of objectives regarding the simulation results. Therefore, the result can be either a specifically optimized solution or a set of similar optimal configurations.

5 Conclusion

In this paper an approach towards the central parametrization of distributed simulations for decision support in future mobility was presented. Decision support by simulation is required due to the high uncertainty of the upcoming development, the large time horizon and the high invest. Due to multiple stakeholders from different domain, a co-simulation approach is suitable to enable the model reuse and take advantage of varied modelling approaches. This work contributes to fill a gap in the state of the art in co-simulations as it ensures consistency with the included simulation models and enables the framework for efficient parameter studies in the context of scenario variation.

Limits of the proposed idea lay in the necessary information regarding the included parameters in black-box models. Furthermore, the presented approach highly benefits from a common domain ontology for the included simulation models, but shortages have to be resolved here. For the specific domain application of charging infrastructure this would include at least electrical engineering, economics and individual mobility. Moreover, a concise definition has to be taken of which models to include. Moreover, those models must provide a certain fit to each other to enable the analysis of interdependencies between stakeholders.

Implementation-wise, there is no general solution for central parametrization in simulation. This can be only achieved in a defined context, as different standards require different implementations. A further issue is the fix setting of parameters in models when they are not tuneable. In case such a parameter needs to be edited for a specific scenario, it is required to change the model settings and then to rebuild the model for simulation. Therefore, the models to be used do not require content-wise adaptions to be handled by the framework but it is mandatory to set some model properties according to the requirements of the proposed framework.

As the planning of charging infrastructure has a long-time horizon and no high-frequently changing simulation parts, numerical stability is not necessarily in scope for such a decision-support-tool. Nonetheless, this might be relevant when aiming for a detailed grid model with the physical modelling of plugging an EV. Whereas the idea of a central parameterization is not related to this, the tooling of the simulation framework might need further adaptations then.

Further fields of application within the mobility domain could be the positioning of car-sharing stations, the placement of mobile charging stations according to local events and the placement of battery swapping stations, e. g. for micro mobility offers like E-scooters.

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