# *Model Based Systems Engineering High Level Design of a Sustainable Electric Vehicle Charging and Swapping Station Using Discrete Event Simulation*

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***Abstract*—In line with the spate of technological advances, the transportation industry has also witnessed an increase in the adoption of Electric Vehicles (E.Vs). However, there has been and are still some underlying negating factors to the wide spread acceptance of these electric vehicles; one of note is the unavailability and inaccessibility of adequate charging infrastructure, long charging times, limited driving ranges, costs of the vehicles etc. These and many more characteristics lead to a trend popularly known as "range anxiety".**

**One of the major strengths of electric vehicles are their ability to be powered by electric energy via stored chemical energy in rechargeable batteries. Some electric vehicles run solely on batteries (Battery Electric Vehicle – BEVs), while others are a hybrid of the electric vehicles and the internal combustion engines (Plug-in Hybrid Electric Vehicles –PHEVs, and Hybrid Electric Vehicles – HEVs). However, since these electric vehicles lean towards reducing atmospheric pollution (Carbon monoxide, hydrocarbons etc.) caused by internal combustion engines, it also follows that the means of recharging these electric vehicles should also be geared towards reducing pollution to some degree. Hence, the concept of renewable energy sources powered recharging stations.**

**However, before a lot of resources are committed into building such an infrastructure, a model should be developed which will take into account certain key factors such as storage capacity, type and size of the renewable sources, facility layout, policies and other identified stakeholders requirements which are evaluated and used in trade-off and decision analysis. However, the status-quo involves around a document-centric methodology of system development. This methodology carries with it challenging characteristics such as poor communication of data between and within interested parties, inability to contain complexities inherent in today's projects, stored data becoming prone to damage as a result of storage or usage and sometimes, inaccessibility of data. In line with current systems engineering practice, we propose a model-centric approach of the system development life-cycle, which will negate some of the drawbacks of the document-centric approach.**

**In this work, a two-level approach is proposed: First, the model based systems engineering (MBSE) framework approach is implemented utilizing the systems modeling language (SysML) to formulate and show different views and architecture of the system in question. The objectives of this MBSE approach in addition to offering different views of the model are also to aid in real-time communication and collaboration of designs which links to understanding change configurations and impact, requirements verification, and traceability. In the second approach, a discrete-event simulation (Arena) tool is used as the reference simulation optimization tool for the model's architectural analysis.**

**The discrete-event simulation (DES) models a hypothetical renewable-energy powered charging and swapping station with the objective of maximizing the electric vehicle's throughput (amount of EVs successfully recharging and swapping batteries in the facility). Certain constraints such as the allowable area for the solar panels, operating budget, amount of energy to purchase from the main grid etc., are included to account for a realistic adaptation of the facility, which is in line with the concept of the renewable energy sources powered recharging stations previously mentioned.**

**Statistical analysis are performed on the optimized architectures to evaluate and compare the design configurations based on the stakeholder's requirements. The optimized parameters are then used to verify and validate the requirements. These categorization of events support the**

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**application of MBSE and simulation to the early stages of the system life cycle development of the high level design of an electric vehicle charging and swapping station**

***Keywords—MBSE, SysML, Discrete-Event Simulation***

## I. Introduction

The implemented procedure in this work consists of two approaches: the first approach uses the SysML-MBSE approach to present several holistic views of the hypothetical system while the second approach uses the model parameters from the views for optimization via the Arena (discrete-event simulation) model[19]. Statistical analysis are then performed on the optimized architectures to evaluate the results, which are then fed back to the MBSE platform and subsequently used for verification analysis.

In the Arena model, the proposed hypothetical model assumes a unidirectional metered connection, whereby the facility can only purchase energy from the grid as opposed to a bi-directional scenario where the facility can sell or purchase energy to and from the grid. In the normal operational scenario, deficient renewable energy generation (if any) is supplemented either with energy from the grid, from the battery storage system, or from the backup source (Diesel generator), or a combination of the energy sources. The percentage of extracted energy (one of the model parameters to be evaluated) from each source is sized and optimized in the Arena model which is in line with the stakeholders' requirements (budget, sustainability etc.).

In this model, certain real data [5][12], [22] were used to depict a real-world system. The facility's architecture in line with the stakeholder's requirements consists of electric vehicle charging stations (EVCS), an electric vehicle swapping station (EVCS), energy generation and backup systems (renewable energy, grid energy, and diesel energy), energy storage systems, and load elements.

The projected objectives this work aims to achieve are as follows:

- Formulating the requirements analysis and providing traceability
- Framing different views of the model in line with SysML syntax
- Providing real-time collaboration and communication of the model's characteristics via the MBSE framework
- Analyzing the different model architecture with Arena (via optimization)
- Performing a statistical analysis on the optimized architectures

Based on the simulation results, the stakeholders can make informed decision on the design of the charging and swapping station.

## II. Model Formulation

### A. Model Application

As stated earlier, this work proposes a model based systems engineering (MBSE) approach to formulating and presenting different views of the model to the stakeholders. The model parameters (system level requirements) to be simulated are derived from the stakeholder's requirements and several model architectures are developed in the MBSE model. The Arena simulation tool [19], is then used for optimizing the architectures after which statistical analysis are performed on the optimized results to aid in the decision analysis process. These sequence of steps, though not exhaustive shows the application of MBSE and simulation to the high level design (which is usually utilized in the concept, design, and development phases) of a sustainable EV charging and swapping station.

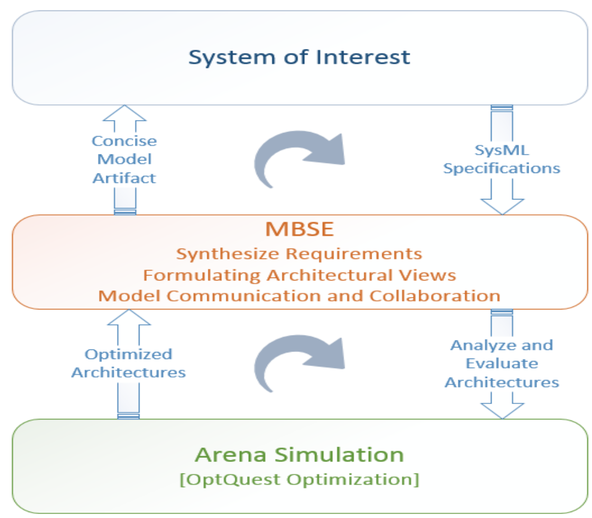


**Figure 1 Proposed Model Concept**

Figure 1 above shows the proposed concept for the application of MBSE and simulation in designing the facility. The systems engineering methodology will be utilized in identifying the stakeholders and eliciting their requirements, deriving the system level requirements, and subsequently, the component level requirements.

## III. Arena Model

In order to describe and understand how the Arena Model works, we will describe the model in terms of the major operational activities such as the arrival, charging and swapping, energy generation, and energy extraction phases. However, for this initial submission, we will limit our discussion to the Arrival and Charging Station Phases.

## *A. Arrival Phase*

In the arrival phase, EVs enter the facility based on an inter-arrival rate and random state-of-charge (S.O.C). The S.O.C is randomly assigned to each EV entering the facility using the assign assignment function.

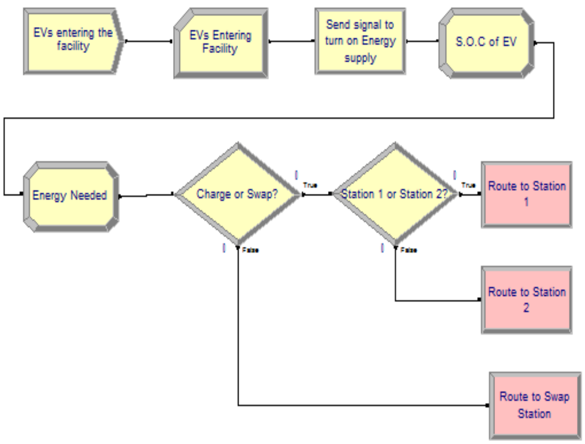


**Figure 2 EV Arrival and Routing Schema**

## *B. Charging Station Phase*

In the Arena model, the electric vehicle supply equipment will be modeled using the regulator block. However, before any EV can seize the resource (EVSE), a logic is implemented in Arena via the Decide module. The objective of the module is to determine if the required energy needed by the EV (which is an attribute assigned to every EV as it enters the facility by the assign module) is available.

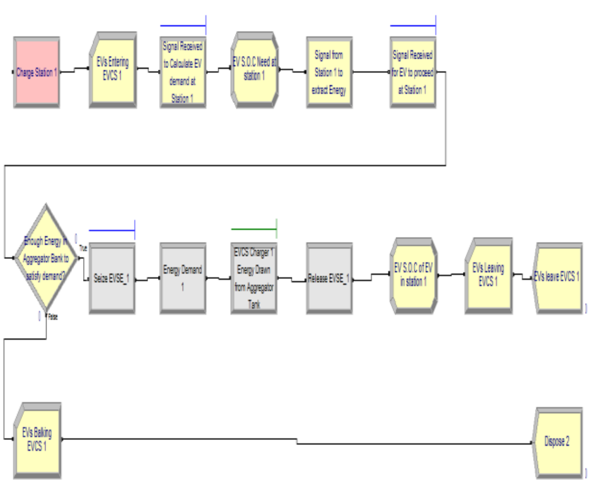


**Figure 3 EVCS Schema**

The logic is given by the Arena value:

TankLevel(Aggregator Tank) >= EV S.O.C Need at EVCS 1

If the above value results in a true logic, the EV seizes the EVSE. Else, it balks (departs with an unsatisfied or unmet demand) the system. The blocks modeling the charging station are shown.

The detailed description of the phases including the schema for the logic implemented in each block will be discussed in depth in the final draft.

## IV. MBSE APPROACH

The figure below compliments Figure 1 on how this work will proceed. The 4 pillars of SysML will be discussed in regards to the facility concept, using the various views to capture the model elements and architecture.

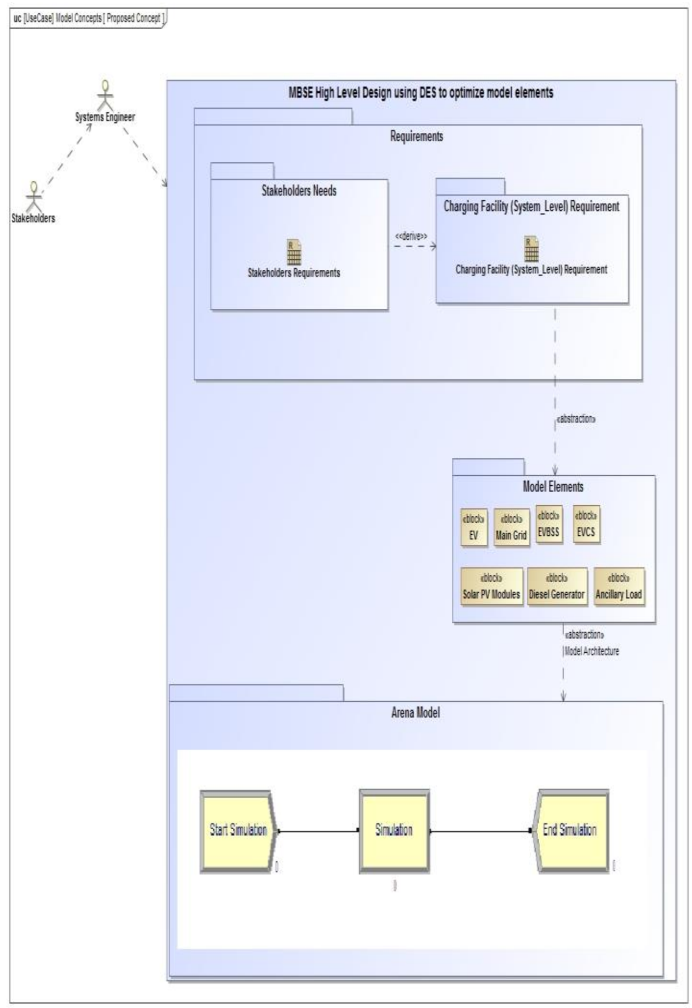


**Figure 4 Arena Model Concept**

Accordingly, the structure, parametric, behavior and requirement diagrams will be used in capturing the essential model architecture. The system and component level requirements will be used in the Arena simulation model for optimization with OptQuest. The requirements are updated and the traceability matrix is developed to show which requirements have been satisfied.

## V. RESULTS

Before running the model, we would like to determine the effects of the radiation value (gotten from two consecutive months) on the throughput (response variable). The reason behind this is to determine if the optimization model would be run separately with the two values or if one of the value would depict what would happen if the other values were used.

A design of experiment (simple comparative experiments [48]) approach would be used. The experiment is set up as thus:

Treatment 1= $\text{Scenario}_1$ (June Radiation Value)

Treatment 2= $\text{Scenario}_2$ (July Radiation Value)

The simple comparative experiment utilizes the statistical hypothesis test to compare the two treatments ($\text{Scenario}_1$, and $\text{Scenario}_2$) using:

$H_0: \mu_1 = \mu_2$

$H_1: \mu_1 \neq \mu_2$

The above equations can be rewritten as:

$H_0: \mu_1 - \mu_2 = 0$

$H_1: \mu_1 - \mu_2 \neq 0$

Where:

$\mu_1$=Mean throughput of treatment 1 ($\text{Scenario}_1$)

$\mu_2$=Mean throughput of treatment 2 ($\text{Scenario}_2$)

Visually comparing the two dot diagrams, it might be inferred that the mean throughput is greater in treatment 2, but is this statistically correct? The test statistic will verify or discredit this claim.

Using:

$$\text{Sample standard deviation } s_i^2 = \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x}_i)^2 \quad i=1,2$$

$S_1^2 = 0.57$

$S_2^2 = 1.2$

Since the sample standard deviations are not similar and we cannot assume that the population standard deviations are similar, we use the test statistic as follows:

$$\text{Test Statistic } t_0 = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} = 10.5$$

$$\text{degrees of freedom } df = \frac{\left[\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}\right]^2}{\frac{1}{n_1 - 1}\left[\frac{s_1^2}{n_1}\right] + \frac{1}{n_2 - 1}\left[\frac{s_2^2}{n_2}\right]} = 1.74$$

Using the student t-distribution chart, we obtain:

$$t_{\alpha/2} = t_{0.05/2} = t_{0.025,1} = 12.706$$

Since the test statistic $t_0=10.5$ does not fall into either critical regions (marked by the margin of error $t_{\alpha/2} = \pm 12.706$, we fail to reject the null hypothesis. In other words, there is no statistical difference to suggest that the average throughputs from the two treatments are different. Thus, we can use either radiation values for the simulation model.

**Table 1 Model Parameters in the Base and Optimized Cases**

| | Base Case | Optimized Case |
|---|---|---|
| **Throughput** | 29 | 38 |
| **Number of PV Modules** | 110 | 115 |
| **Number of Batteries in Battery Bank** | 90 | 92 |

Several analysis could be performed on the result (Table 1) to understand the dependencies between the response variable (Throughput) and the independent variables (Number of PV Modules, and Number of Batteries in Battery Bank). Such analysis could include factorial analysis, regression analysis etc. For our work, we choose regression analysis as the statistical method for interpreting the results.

The general form of a regression analysis, relating the response variable to the independent variables is given by:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k + \epsilon$$

Where:

$y$=Response Variable

$x_1, x_2$=Predictor/Regressors Variables

$\beta_j$=Regression Coefficients $j=0,1,\ldots,k$

The equation above (show equation) is called a multiple linear regression model with k regressor variables.

From the optimized model, we would like to determine the effects of the variables (number of PV Modules, and number of batteries in the battery bank) on the response variable.

Therefore fitting our model with the two quantitative predictors become:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \epsilon$$

Where:

$y$=Avg.Throughput

$x_1$=Number of PV Modules

$x_2$=Number of Batteries in Swap Station BatteryBank

$\beta_0, \beta_1, \beta_2$=unknown parameters to be estimated

The final result of the regression analysis is given below:

$$\hat{Y} = 23.6 + 0.11x_1 + 0.0114x_2$$

The work is completed with the MBSE model being updated with the optimized results using the RVTM module.

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