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THE INFLUENCE OF THE MODEL PARAMETERS OF LI-ION BATTERIES ON THE WIRING HARNESS PERFORMANCE OF EVTOL AIRCRAFT

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Abstract

This paper deals with the influence of the shape of the discharge curve of Lithium Ion battery cells on the wiring harness of electrical vertical take-off and landing aircraft. A simulation framework is presented which enables a detailed simulation of the wiring harness performance over the complete mission of an aircraft. Three common reference aircraft configurations are used for the simulation to compare different harness architectures. Different possible models for predicting the voltage of single battery cells are introduced. With the selected battery model, a sensitivity study to the simulation outcome of the model coefficients is performed and discussed. The paper concludes with the general discussion about how the shape of the discharge curve of the battery influences the wiring harness performance.

Keywords: eVTOL, Wiring Harness, Optimization, Battery Model, Numerical Simulation

Nomenclature

eVTOL electrical vertical takeoff and landing

LiIon Lithium Ion

ODE Ordinary Differential Equation

SoC State of Charge

SoD State of Discharge

1. Introduction

The wiring harness of an electric aircraft plays an extended role compared to the wiring harness of a fuel-powered aircraft. In the fuel powered aircraft, the wiring harness is used to supply the electrical systems and to transmit signals. The main focus here is to save mass and make redundant connections. In an electric aircraft, the wiring harness gets an additional function. It is used to distribute the main propulsion power to the different propulsion systems. The wiring harness is then a part of the drive train and its power loss inherently determines the propulsion efficiency of the drive train. Therefore, in the design of an electric aircraft, the wiring harness gains a higher influence on the system performance than in a fuel powered aircraft.

In electrical vertical takeoff and landing (eVTOL) aircraft, the lift for takeoff and landing is produced by the electric propulsion systems of the vehicle. These so called “hover flight” phases take a higher amount of power compared to the forward flight phases of an eVTOL aircraft, where the main lift is produced by the wing of the aircraft. The hover flight phases can be longer or shorter depending on the mission profile of the vehicle. The influence of the wiring harness on the propulsion efficiency is increased during the hover flight phases due to the increased power consumption.

Among the mission profile, the system voltage level used for the propulsion system determines the performance of the wiring harness. The power transmission within the wire gets more efficient when the voltage level is increased and gets less efficient when the voltage level is decreased [1]. A common approach to estimate the preliminary mission performance of electric aircraft is to estimate a constant cell voltage which results in the same integrated amount of energy when multiplied by the battery current compared to a variable cell voltage. The battery endurance for constant discharge power can then be calculated directly without the need for numerical integration.
When applying a variable battery voltage model to the mission simulation, the battery voltage will decrease with lower State of Charges (SoCs) and also decreases with higher currents [2]. As a result, the power transmission efficiency will decrease during the mission and the simulation becomes numerically costlier, because the discharged battery energy has to be calculated by integrating the discharge power. The proposed paper implements the constant voltage approach as well as the variable voltage approach in its simulation for estimating the performance of eVTOL aircraft and shows the difference in the resulting optimal wiring harness and aircraft performance.
The paper focuses on Lithium Ion (LiIon) batteries as they are the state of the art in the design of electrical aircraft at the moment. They are established in the industry and easily available [3].

2. Battery Models

There are several equivalent battery circuits available to model the discharge behavior of batteries. Common models suited for LiIon batteries are collected and presented in [2]. In this paper, the models for the discharge curve of LiIon batteries are based on the Rint equivalent circuit. The parameters of the models can depend on different values. In [4] an accurate model for predicting temperature and dynamic behavior of a battery cell under load is presented. The results show that the cell discharge voltage is mainly dependent on the load current and the SoC of the cell. Those two dependencies can be split into two components:

- a SoC dependent cell voltage, the so-called open circuit voltage U_{OC}
- a series resistance which can be SoC dependent

There are different approaches on how to model the two components of the Rint equivalent circuit. The required parameters of a resulting model are usually fitted to measurement data. Since different cell types show different behavior, such a model has to be refitted for each cell type. Key aspects of the battery model are how quickly those parameters can be fitted to measured data and as which physical properties those parameters can be interpreted as, so that the model can be understood intuitively and be compared to other models.
The first model which is investigated is the model by Tremblay [5]. It directly predicts the cell voltage under load including the series resistance. The model as proposed by Tremblay is dependent on the discharged capacity and the cell current. This can be transformed to a dependency on SoC as the total cell capacity Q is already part of the initial model.
The second battery model is proposed by Chen [6]. This approach models the open circuit voltage and series resistance separately. This model was already used in [7] to simulate the performance of an universally electric aircraft.
Both models are compared against measured data of modern cells in Fig. 1. The models are used with the cell parameters as they are proposed in their corresponding papers. As can be seen, both models predict a similar shape of the discharge curve, but they cannot predict the performance of modern cells out of the box. The open circuit voltage of modern cells is higher at the beginning of the discharge curve and is rather linear in the major part of the discharge curve. The steep drop towards the end is similar in both models.
This means that the models have to be fitted to the modern cells properties before they can be used in the simulation framework. The results of this fitting process and a comparison the results can be seen in Section 6. .

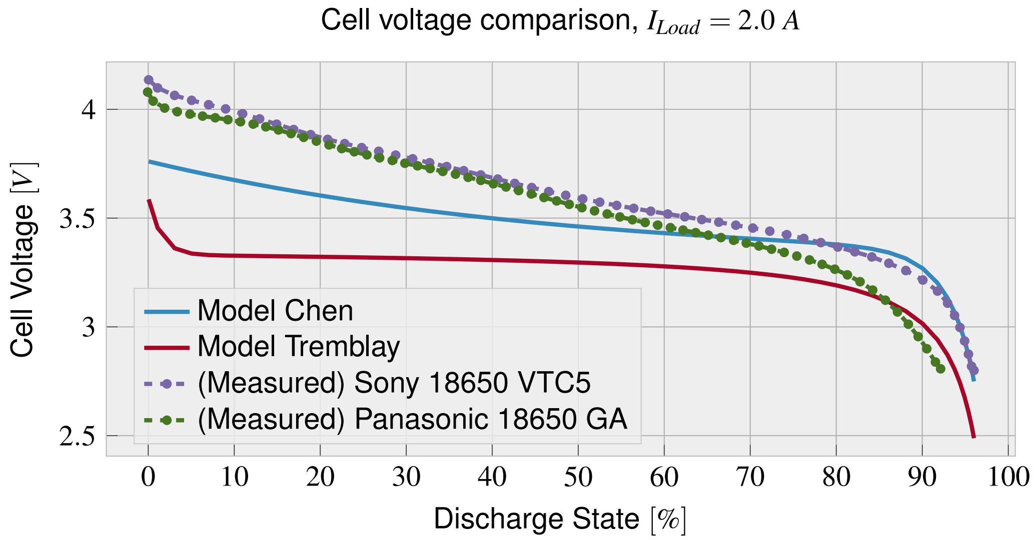


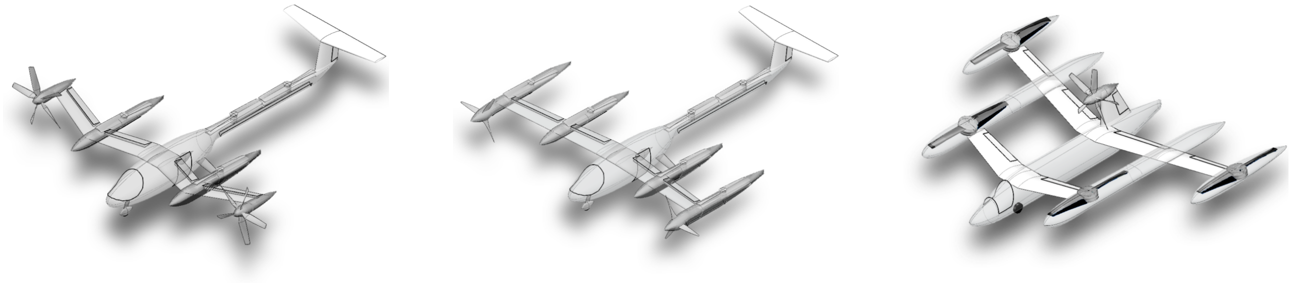
Figure 1 – Comparison of modeled and measured cell voltages

3. Simulation Framework

In this paper, the influence of the battery voltage level on the performance of an eVTOL wiring harness is investigated. Based on the simulation framework proposed in [8] and extended in [9], the performance of an aircraft is calculated applying the different battery models. The framework includes a detailed wire model for the wire mass and thermal behavior under load, a mass estimation of the different aircraft components on a preliminary level, and a simulation model to calculate the mission performance of the vehicle. This framework enables the simulation to predict the performance of an aircraft and its wiring harness under different operating conditions. The simulation models for the mass and mission performance are performed on a preliminary level to decrease computing time, but they are detailed enough to roughly estimate the influence of all major design parameters of an eVTOL aircraft.
The simulation framework models the power components using their equivalent circuits:

- **Battery**: Constant Voltage Source + Constant Series resistance
- **Wire/Harness Link**: Temperature Dependent Resistance (Temperature is current dependent)
- **Propulsion System**: Constant Power $\rightarrow$ Voltage Dependent Resistor

The resulting electrical network of this abstraction only consists of voltage sources and resistors. The current flow within the network can be solved by applying Kirchhoff's voltage and current law. The framework uses graph theory to assemble the network equation which then is solved iteratively until the power flow within the network converges, see [9].
The initial battery model uses a constant cell voltage to compute the pack voltage during the mission. In the scope of this paper, the simulation framework is extended with a battery model with variable voltage. The resulting mission simulation then becomes an Ordinary Differential Equation (ODE) which is not constant over time and has to be solved numerically. The mission simulation is therefore extended with a numerical ODE solver which is based on a Runge-Kutta method.
The investigated aircraft configurations are the three common reference models (eCRM) proposed by Uber Elevate in [10]. These models provide an overview of current eVTOL aircraft configurations and contain tilt rotors as well as fixed rotor propulsion systems as can be seen in Fig. 2. The mission parameters are taken from the UberAir mission requirements in [11] to fit the simulated mission to the configuration. The harness architecture and performance parameters are the same as presented in [9].



eCRM-001 eCRM-002 eCRM-003

Figure 2 – Overview *Uber* Common Reference Models

4. Optimization

Using the simulation framework with the detailed wire model and the simplifications described in the previous chapter, an optimization for the optimal wire gauges of the wiring harness of an aircraft can be performed. The optimization is implemented in such a way, that multiple objectives can be addressed. This is achieved by using an objective function, which can be set to different optimization targets. The two main targets this paper focuses on are:

- minimizing the total wiring harness mass of an aircraft
- and maximizing the endurance of an aircraft.

Two different optimization strategies are implemented to optimize for each of the two targets. For the wiring harness mass, a gradient based optimizer yields good results. Based on a feasible start solution, this optimizer computes a single order gradient for each optimization parameter and steps into the steepest direction until there is no improvement of the objective function. For this target, this strategy does not get stuck in local minima and reliably finds the minimum wire gauge for the lightest possible harness.
For the second optimization strategy, to maximize the endurance, a search-based strategy is used. This strategy computes the objective value in the direct neighborhood of the current iteration step.The neighborhood is defined by changing one parameter by one step, all parameters by one step, and all possible permutations in between. The number of neighborhood points is 2^n when using n parameters for the optimization. The parameter permutation which yields the best objective value is taken for the next iteration step until there is no better objective value or parameter set found. This requires more evaluations of the objective function for one iteration step, but it ensures that the optimizer does not get stuck in local minima, which happens when using the gradient based strategy for this objective target.

5. Impact of variable voltage model

Several mission simulations using the discussed battery models are performed with the simulation framework. The simulated mission which is based on [11] is summarized by a vertical take-off phase, followed by a cruise segment and ends with a vertical landing. The vertical flight segments are fixed to a duration of $60s$ for takeoff and $30s$ for landing. The cruise segment is active until the battery is depleted to a SoC of 0.2. Each segment is assumed to have a constant power demand by the propulsion systems. This results in a constant power consumption during each segment. The power consumption of the vertical flight segments are equal. Figure 3 gives an overview of the mission power requirements.
In this example, the simulation results of the *eCRM-001* vehicle are used to discuss the impact of the variable battery voltage. Two simulations are performed. One simulation uses the constant voltage model for the battery voltage and the other uses the variable voltage model. Otherwise, both

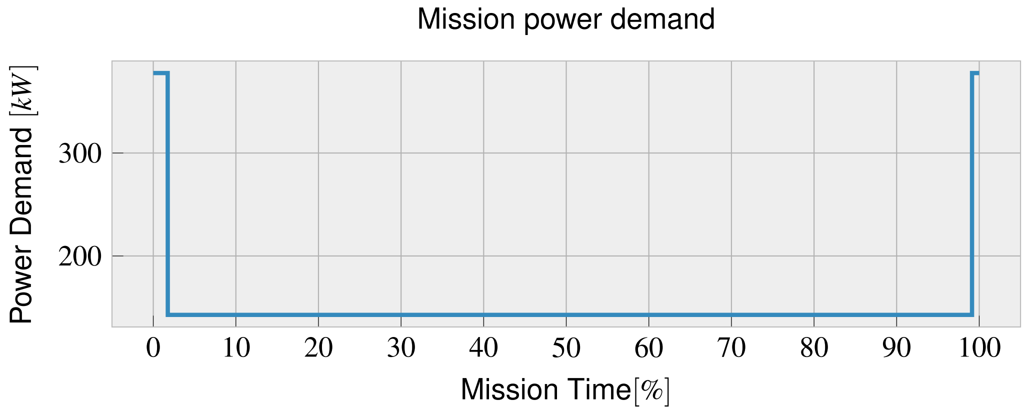


Figure 3 – Mission power requirements

simulations share the exact same boundary conditions. The wiring harness consists of the same wire gauges, the power requirements are the same and the mass and mission parameters are the same. In Fig. 4, you can see the battery voltage during a mission, when the constant voltage model is used in red (dashed line) and the variable voltage model in blue (solid line). It is to note that the voltage of the variable model drops significantly towards the end of the mission and in particular in the landing hover phase.

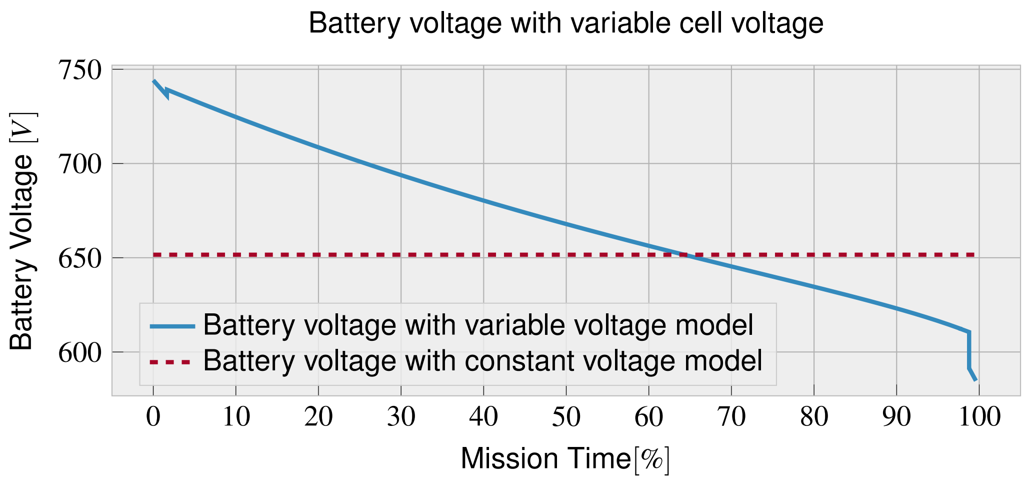


Figure 4 – Battery voltage during the mission

This effect immediately impacts the current consumption of the propulsion system because of the constant power assumption. This influence can be seen in Fig. 5. The figure shows the results for one harness link connecting the battery. This link is active in both the hover and cruise mission segments. The wire current in the simulation with the constant voltage source is constant throughout each mission segment. The wire current with the variable voltage source increases steadily in each segment.

The simulation framework uses the wire current to estimate the steady-state wire temperature during the mission. Hence, the wire temperature is also affected by the change in the wire current. The change is shown in Fig. 6. The key difference in the two wire temperature graphs is the temperature towards the end of the mission. The wire temperature in the constant voltage simulation is lower than the temperature in the variable voltage simulation. Moreover, the constant voltage case does not reach the maximum rated wire temperature. The wire temperature of the variable voltage case gets closer to the rated current/temperature of the wire in the last moments of the hover flight phase. As a result the wiring harness in the constant voltage case is evaluated as a fit for the mission and power requirements, whereas in the variable voltage case the wiring harness could fail in the last bit of the mission in certain scenarios.

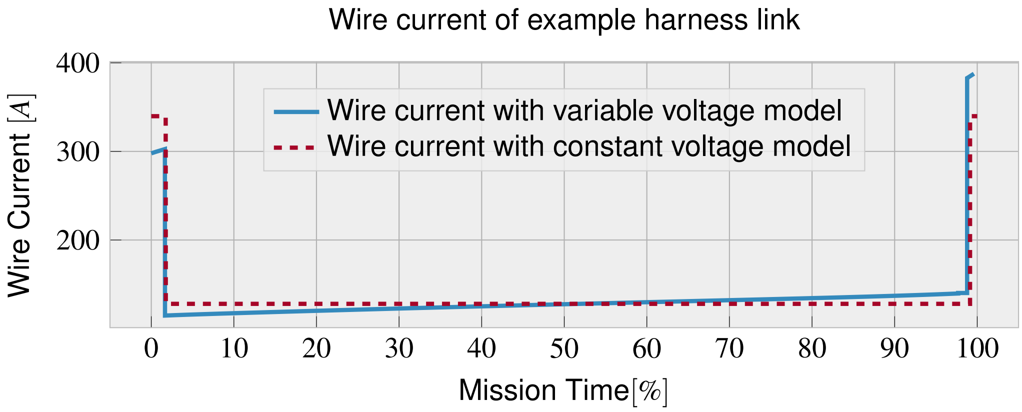


Figure 5 – Wire current during mission

This immediately impacts the outcome of the wiring harness optimization. When for example the optimization goal was to minimize the harness mass, the minimum found with the constant voltage case would result in a non feasible solution compared to the physically more accurate case with the variable voltage model.

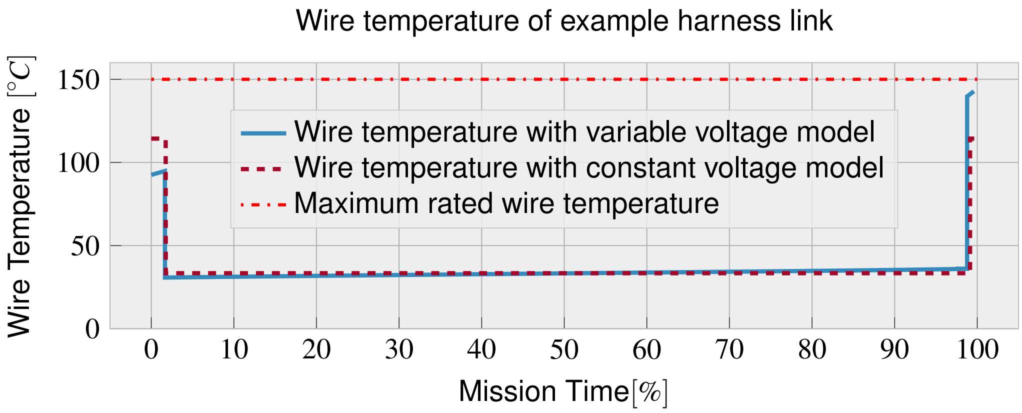


Figure 6 – Steady-State wire temperature during mission

6. Battery Model Fitting

As it was mentioned in Section 2. , the parameters of the used battery models have to be fitted against measurement data. The model is fitted against measurements performed with a *Sony VTC5* Li-Ion cell. The cell is discharged with a constant current at different C-rates to characterize the discharge behavior of the cell. In the following the fitting approach and results are explained.

6.1 Battery Model Selection

The battery model coefficients have to be fitted for the different C-rates. This makes the fitting process multi dimensional. In other the words, the model coefficients can be dependent on the C-rate. When the investigated battery models are used within the limit of their assumptions, those parameters should not be dependent on the C-rate, though. This is validated by using different approaches for fitting the coefficients.

The first approach is to fit one set of coefficients against all measured data. The second approach is to fit one set of coefficients individually for each C-rate. The third approach is to use the results of the second approach and then compute the mean for each coefficient. The residuals of the battery model to the measured data for each fitting approach are shown in Fig. 7.

The first result of this comparison is, that the model from Tremblay gives better fitting results compared to the model from Chen. The second result is, that the fit for each C-rate individual gives the lowest overall residuals. The reason for this becomes immediately evident when looking at the direct

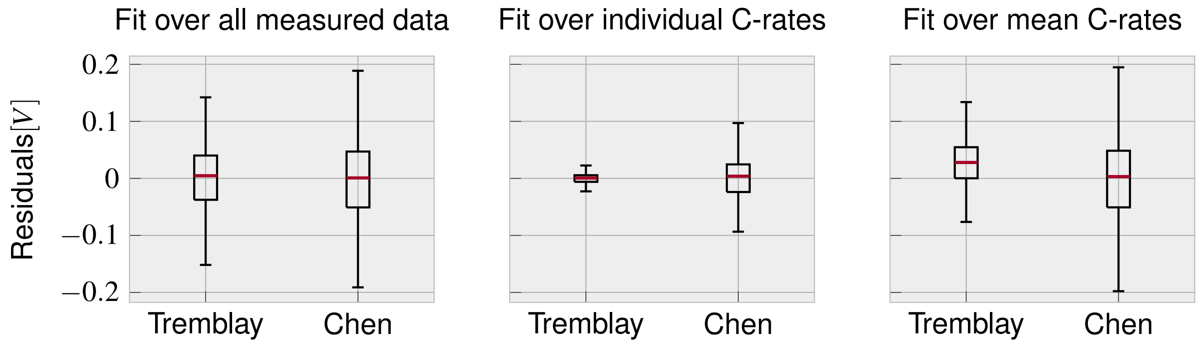


Figure 7 – Comparison of residuals for different fitting methods

comparison of the measured data to the fitted model in Fig. 8. For this comparison, the battery model from Tremblay was fitted against the measured data where the C-rate is 1.0. Each plot in Fig. 8 compares the fitted model to the measured data for each measured C-rate. For C-rates up to 5.0, the fitted model predicts the battery voltage well and shows small deviations to the measured data. At higher C-rates, the model assumptions, like constant series resistance or constant cell capacity with increasing load current, are no longer valid and the predicted voltage is overestimated especially at higher SoDs or lower SoCs.
The battery model of Tremblay is used for the simulation since it has less parameters than the model of Chen. This makes fitting the parameters more robust and the parameters can be interpreted as physical properties of the battery cell.

6.2 Battery Model Fitting Results

The model from Tremblay is adopted in this paper to be used with dimensionless inputs. The input parameters are the State of Charge (SoC) and the C-rate. The model is also split in two parts, one equation for predicting the open-circuit cell voltage and one equation which takes the series resistance into account. The equations then become, with Q as the nominal cell capacity:

$$U_{OC,Tremblay}(SoD,C) = E_0 - k \cdot \frac{1}{1-SoD} \cdot Q \cdot (SoD + C) + a \cdot e^{\,b \cdot SoD \cdot Q},\ C \geq 0 \tag{1}$$

$$U_{Cell}(SoD,C) = U_{OC,Tremblay}(SoD,C) - R_i \cdot C \cdot Q,\ C \geq 0 \tag{2}$$

The C-rate C is assumed to be positive and to be a discharge rate. The model is only valid for discharging the cell and not for charging.
As discussed in the previous chapter, a good estimate of the coefficients for the model is achieved by fitting the model to the data captured at one individual C-rate of 1.0. This model can be used for discharge rates of up to $7C$ without loosing to much details. See Fig. 8 for the comparison of the fitted model to the measured data. The resulting fitted coefficients are shown in Table 1.

Table 1 – Baseline battery model coefficients for a *Sony VTC5* cell

Coefficient	Value	Unit
E_0	3.1109	V
R_i	13.0	$m\Omega$
k	0.011955	$\frac{V}{Ah}$
a	1.041113	V
b	1.277432	$\frac{1}{Ah}$
Q	2.6	Ah

Those coefficients are the baseline for the investigation of their influence on the wiring harness performance. Figure 9 shows the influence of each baseline coefficient on the open-circuit cell voltage. The discharge rate is fixed at $1\ C$. Each coefficient is varied separately in each subplot. As the model

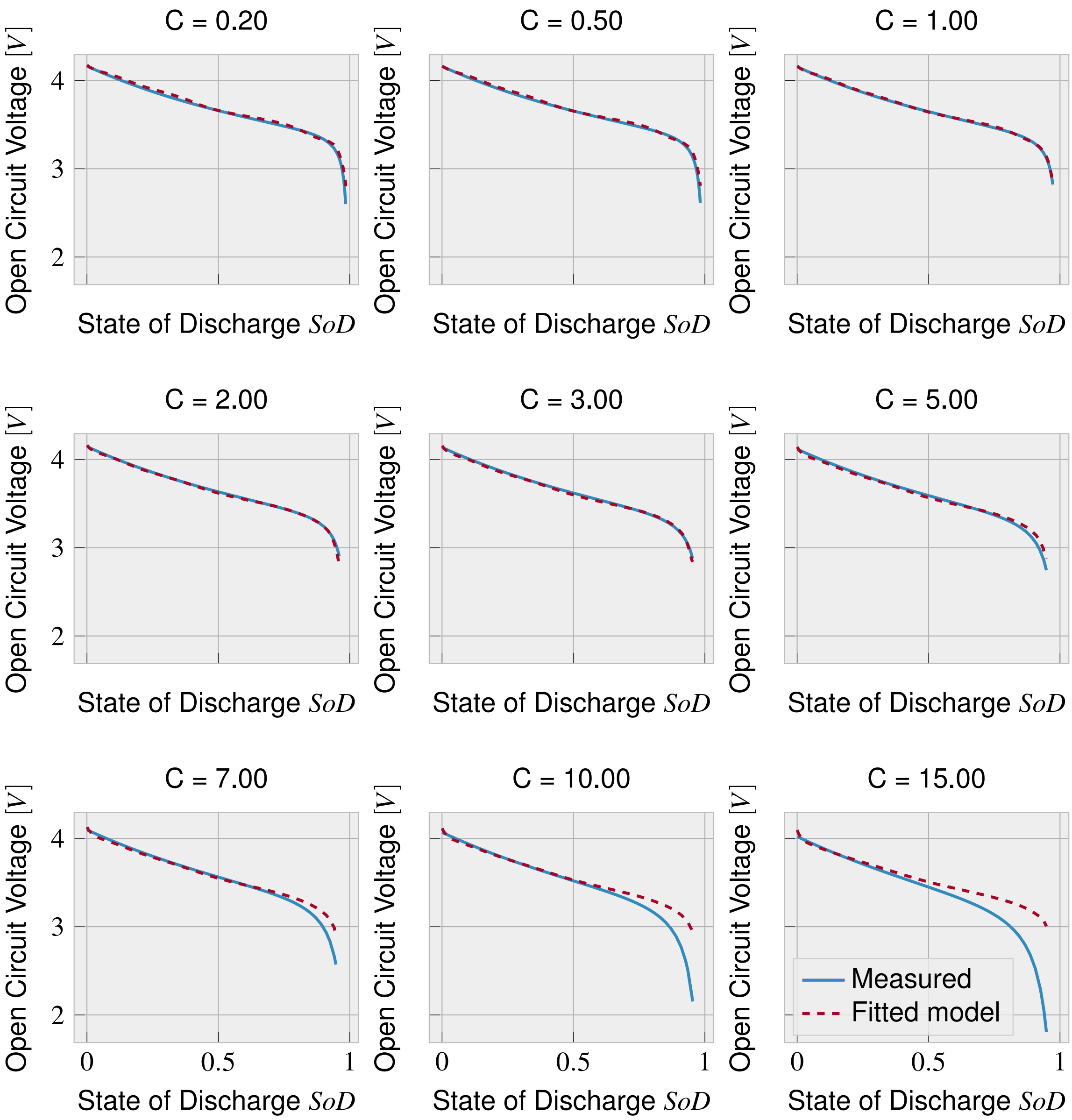


Figure 8 – Fitting results for different C-rates with the model from Tremblay

is a continuous analytical model, each coefficient influences the whole shape of the discharge curve, but for each coefficient you can identify one area where its influence is most significant.
The E_0 coefficient can be interpreted as the nominal cell voltage since it shifts the complete discharge curve when it is varied. The k coefficient determines the transition at the end of the discharge curve. When k is decreased, the voltage transition gets sharper. The a coefficient mainly sets the voltage at the beginning of the discharge curve. It can be interpreted as an indicator of the maximum charge voltage of the cell. The b coefficient influences the voltage level in the middle of the discharge curve. Each coefficient change directly impacts the energy content of the battery cell. This will directly influence the endurance performance of the investigated aircraft. The performance of the wiring harness is not influenced by the energy content, it is directly influenced by the applied voltage and current flow. For that reason, the energy content change is not compensated in the following optimizations.

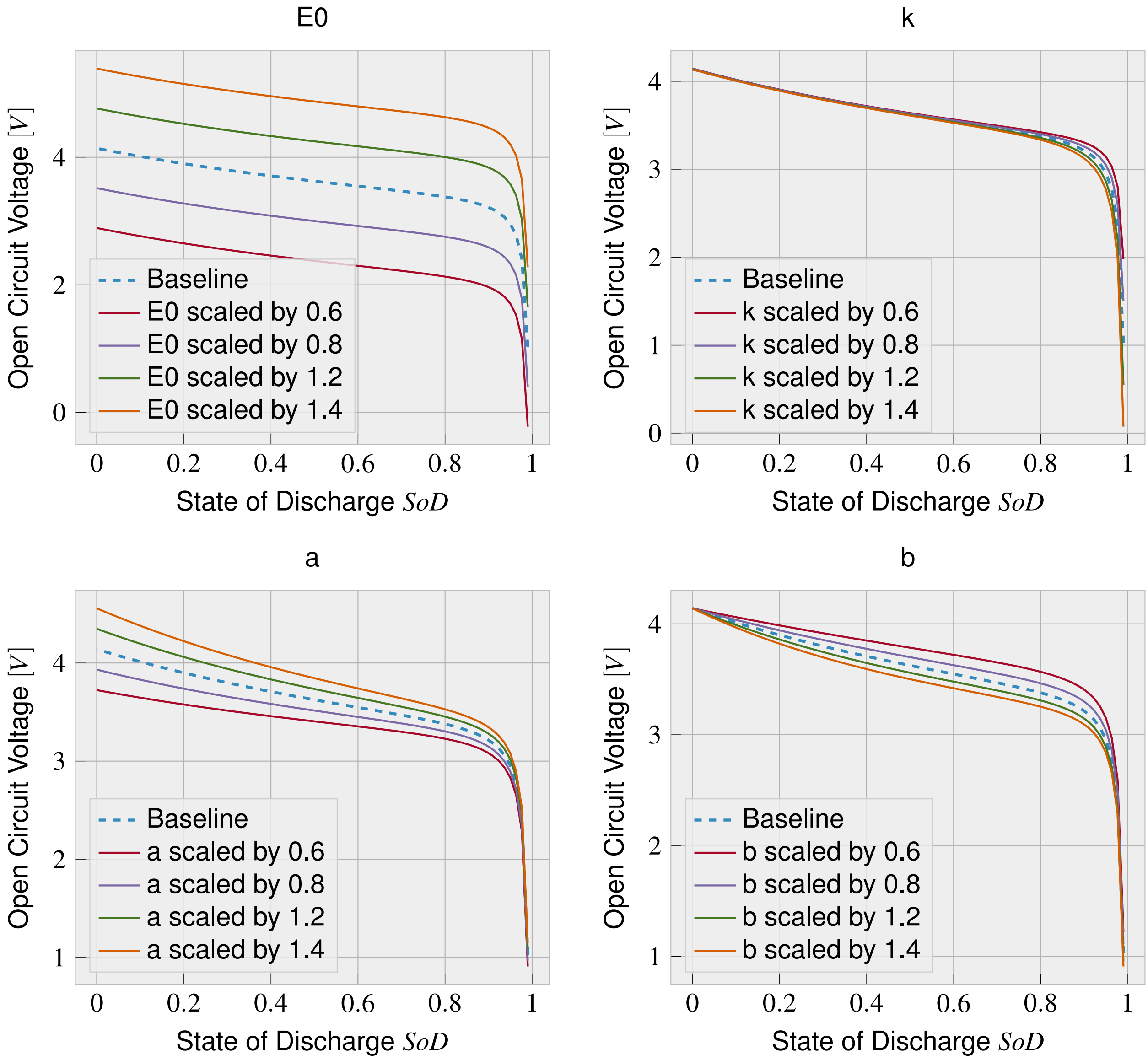


Figure 9 – Influence of model parameters on open-circuit cell voltage, $C = 1.0$

7. Results of the sensitivity study

The sensitivity of the wiring harness performance when varying the coefficients of the battery model is judged by the resulting mass of the wiring harness. Every coefficient of the battery model is varied separately and an optimal wiring harness is calculated for both discussed objective targets, minimizing the total harness mass and maximizing the endurance of the aircraft. The deviation of the resulting total harness mass to the baseline configuration is used for showing the sensitivity. The baseline configuration has the model coefficients as shown in Table 1. The resulting total harness masses of the baseline configurations are shown in Table 2. Note that the harness mass optimized for endurance is always higher than the harness mass for minimum harness mass.

Table 2 – Total harness of baseline configurations for different objectives

Configuration	Minimize Harness Mass	Maximize Endurance
eCRM001	9.3 kg	12.1 kg
eCRM002	10.9 kg	16.1 kg
eCRM003	12.1 kg	14.5 kg

The following chapters always use the deviation to the baseline harness mass to compare the optimization results of each configuration among each other. There are only results included where the optimization showed a clear convergence. For some coefficients, especially at the boundary of the sensitivity study, the optimization boundaries of some wire gauges are not sufficient or the overall mission simulation does not produce valid results, because the problem gets to "stiff" for the ODE solver. Those results are not included in the following discussion.
The optimization uses only discrete wire gauges as defined by the standards. This leads to discrete results where one input parameter changes but the resulting total harness mass does not change, because the next bigger or smaller wire gauge does not yet satisfy the objective target. The following discussion does not explicitly mention this effect when discussing the results of the sensitivity study.

7.1 Results Coefficient "E_0"

The coefficient E_0 which sets the nominal voltage level of the cell is varied from $2.49\ V$ to $3.73\ V$. The results are shown in Fig. 10. The figure shows the deviation of the resulting optimal harness mass to the baseline mass for both of the investigated objectives and each of the investigated aircraft configurations.

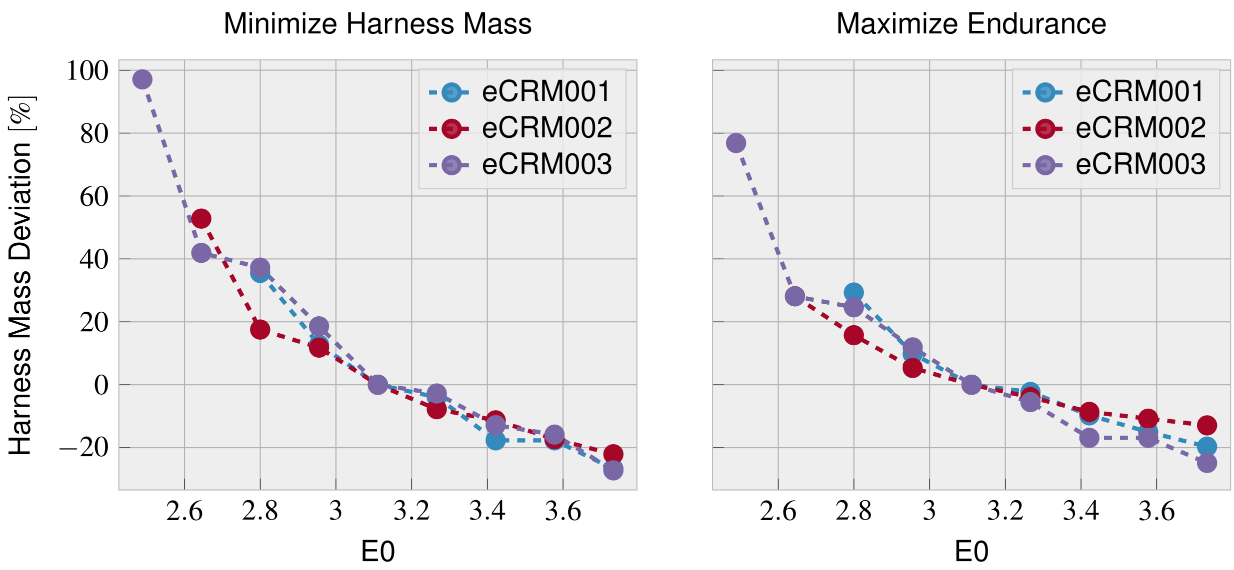


Figure 10 – Harness mass deviation for the coefficient E_0, with different optimization objectives.

The coefficient E_0 impacts all aircraft and objectives in a similar way. When the coefficient is decreased the resulting voltage of the battery pack is also decreased. This results in an increase in battery current since the power demand stays constant. For the wiring harness to handle this increase in wire current, the wire gauge of some harness links has to be increased which increases the total harness mass. This effect applies to both objectives. This coefficient also has the highest impact on the total harness mass compared to the other coefficients of the battery model. It can double the required harness mass compared to the baseline mass.

7.2 Results Coefficient "R_i"

The internal resistance R_i of the battery cells is varied from $7.79\ m\Omega$ to $20.8\ m\Omega$. The results for this are show on Fig. 11.

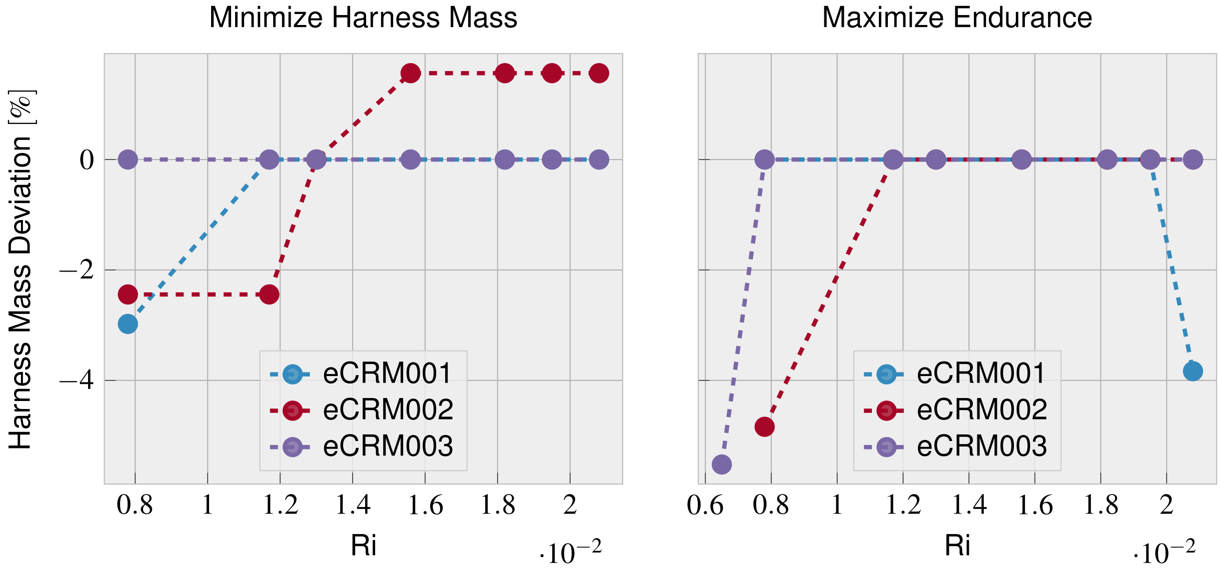


Figure 11 – Harness mass deviation for the coefficient R_i, with different optimization objectives.

The sensitivity study for this coefficient is rather cumbersome, because low resistances further increase the stiffness of the underlying ODE. For this reason, the results of Fig. 11 are uncertain and not coherent. A possibly visible trend is, that a lower internal resistance can decrease the required harness mass. A lower internal resistance results a lower voltage drop at the battery terminals under load which effectively yields a higher battery voltage under load. The higher voltage reduces the overall load current due to the constant power demand. This again leads to the reduced harness mass. But since there are some outliers in the results and the overall shape seems not to be consistent among the different aircraft configuration, this effect is more speculative than observable.

7.3 Results Coefficient "k"

The k coefficient which determines the shape of the battery discharge curve at low SoCs is varied from $0.48\ \frac{V}{Ah}$ to $1.91\ \frac{V}{Ah}$. The influence of this coefficient on the total harness mass is plotted in Fig. 12.

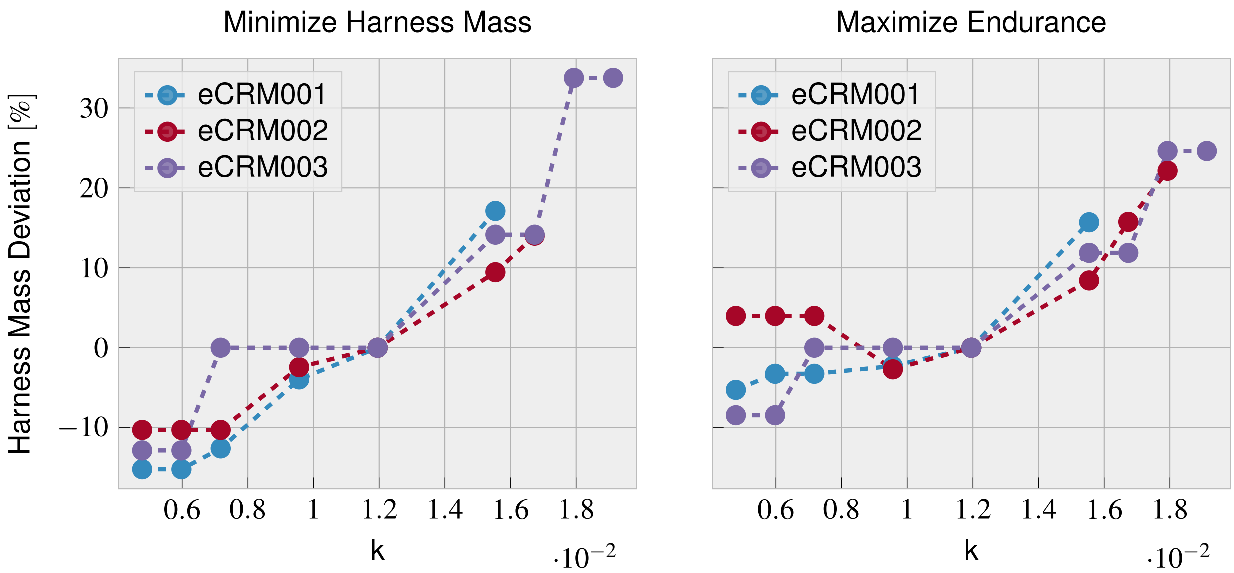


Figure 12 – Harness mass deviation for the coefficient k, with different optimization objectives.

Compared to the other coefficient, the k coefficient does not change the shape of the discharge as much, see Fig. 9, but its influence on the harness mass cannot be neglected. The voltage transition at the end of the battery discharge curve directly influences the sizing of the wires. The rapid decrease of the voltage leads to high load currents which demand increased wire gauge sizes. The hover flight phase at the end of the mission profile begins in that region of the discharge curve which is influenced the most by the k coefficient. The hover flight phase has the biggest overall power demand and also involves all wires of the harness. By a small change of the voltage resulting by the change of the k coefficient, the current increases in this flight phase. For minimizing the total harness mass, this is the critical flight phase which effectively sizes the wires of the harness. Therefore, the k coefficient influences the harness mass more for this objective target than for the objective of maximizing endurance.
For maximizing the endurance, the power loss within the wires during cruise flight gains more importance. This already results in larger sized wires compared to the first objective target. Hence, the influence of the k coefficient is reduced but still present.

7.4 Results Coefficient "a"

The coefficient a mainly sets the voltage level at the beginning of the discharge curve and coupled to that is the voltage level and slope during the main part of the discharge curve. It is varied from $0.42\ V$ to $1.67\ V$.

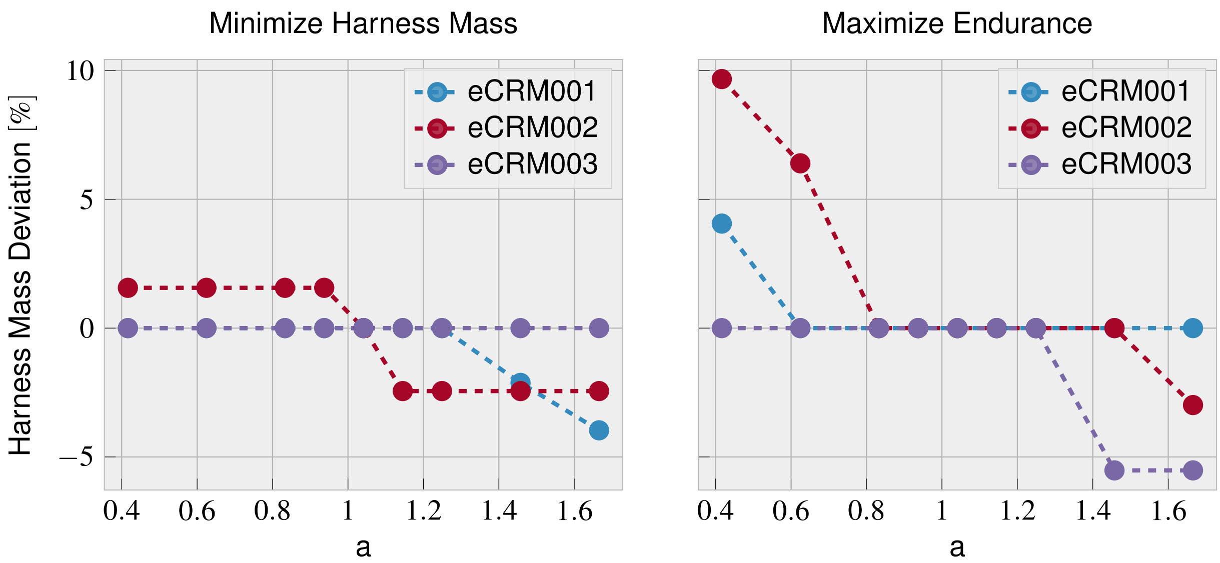


Figure 13 – Harness mass deviation for the coefficient a, with different optimization objectives.

The voltage level in the middle part of the discharge curve affects the endurance objective more than the objective for minimizing the total harness mass. As mentioned previously, this part of the discharge curve is the sizing case for maximizing the endurance. A decreased voltage level in this part leads to increased I^2R losses within the wires. This loss is compensated by increasing the gauge of the affected wires. The *eCRM002* configuration has a more interconnected wiring harness which has a higher number of wires involved during cruise flight. That is why this configuration is affected more by decreasing the a coefficient compared to the other configurations.

7.5 Results Coefficient "b"

The coefficient b which determines the voltage level of the cell during the middle of discharge curve is varied from $0.51\ \frac{1}{Ah}$ to $2.04\ \frac{1}{Ah}$.
Decreasing the b coefficient increases the voltage level. Since the shape of the transition of the voltage at the end of the discharge curve is also influenced by the b coefficient, both objective targets are influenced by a change of this coefficient. With the increased voltage level, the wire current gets lower and therefore the total harness mass can be reduced for both objective targets. When

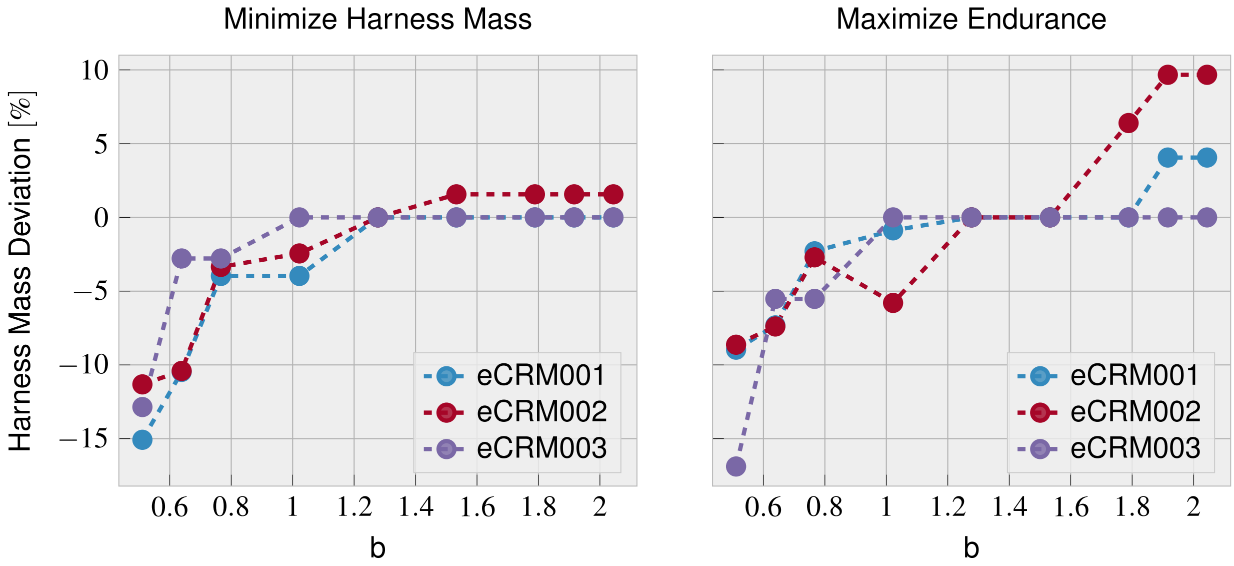


Figure 14 – Harness mass deviation for the coefficient b, with different optimization objectives.

increasing the b coefficient or decreasing the voltage level, the endurance objective shows a higher penalty compared to the objective to minimize the harness mass.

8. Conclusion

Simulations using the constant voltage model are a good first approach to quickly estimate preliminary aircraft performance and range values, but they are not suited to perform optimizations with the goal to maximize the performance of a mission and they are not suited to size the wires of a wiring harness for every corner case. The steep voltage drop of the discharge curve of LiIon battery cells severely influences the sizing of the wires towards the end of a mission when the cell gets depleted beyond a SoC of approx. 0.3.

The discussed battery voltage as presented in [5] is fitted against measured data of a modern LiIon cell. The resulting battery model shows a good agreement with the measured data for C-rates below 7.0. For higher C-rates the model assumptions are no longer valid and the prediction error of the model increases. For the scope of the investigation of the influence of the model coefficients, this limitation does not affect the results.

The paper sizes two different wiring harnesses for each of the investigated aircraft configurations. One harness which minimizes the total harness mass and one harness which maximizes the total endurance of aircraft.

The nominal cell voltage has the highest influence on both objective targets. The higher the cell voltage is, the lower the wire currents get. This enables the reduction of wire gauges, which makes the wiring harness lighter and increases the efficiency of the energy transmission within the wires.

The other coefficients of the battery model affect the two objective targets in different ways. The objective to minimize the total harness mass is more affected by the model coefficients which determine the shape of the discharge curve towards lower SoCs. The steep voltage drop of the battery cells is the main design driver here. The higher the voltage is towards the end of the discharge curve, the lower the maximum wire current becomes and with that, the harness mass can directly be decreased. The endurance objective is not influenced as much by these coefficients.

The endurance objective gets more affected by the model coefficients which determine the voltage level in the middle of the discharge curve, where the main part of the cruise flight segment is located. Since the cruise flight is the longest flight segment in the mission which solely determines the endurance, optimizing the energy loss in this segment has the most impact on the mission performance. The model coefficients which increase the voltage during this flight phase have therefore a positive effect on the wiring harness performance for this objective.

From the results you can argue that a switching power supply could make sense, which compensates the voltage drop when the battery cell is nearly depleted and therefore increases the efficiency of the

wiring harness. This approach is already discussed in [1] and it did not achieve a higher overall efficiency in this study, as the additional weight of the DC-DC converters diminishes the efficiency gain of the power transmission.
As a closing remark, it has to be mentioned, that redundancy is not part of the optimization and there are no requirements implemented to accommodate for that. Including requirements for redundancy may change the outcome of the absolute harness mass, but the relative effects should not change.

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10. Copyright Statement

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