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ANALYSIS AND OPTIMIZATION TOOL FOR ENGINEERING DESIGN

Master of Science Thesis

Examiner: Professor Asko Ellman
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ABSTRACT

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The main objective of this thesis is to assists the engineers with the early phases of an engineering design by providing them with the necessary tools to analyze and optimize the design. For this purpose a Design Analysis Tool, DA Tool, with various features has being developed. This DA Tool has been programmed in *Visual Basic for Applications,* VBA*,* on a Microsoft Office Excel environment.

Engineering deals with design of complex systems, thus analyses are so essential. With the analysis results this Tool provides, the designer will be able to shorten the lead-time for new products, lower the manufacturing cost, improve the reliability and quality of the products and efficiently satisfy the required functions.

The DA Tool primary features are: Analysis and Optimization. The analysis follows the *Sensitivity Analysis* method, an excellent approach to study the relationship between design parameters and system characteristics. This low-fidelity method could complement high-fidelity ones, such as Simulink/Matlab software, or even replace them on early-design phases since they would save an enormous quantity of time, consequently money, and its results are accurate enough. An algorithm making use of the *Solver* function of Excel has been developed for the optimization process. This iterative mechanism seeks the optimum value for the major design parameters, with regard to the system requirements criteria, from a set of available alternatives.

Two models have been analyzed with the DA Tool; an electric vehicle and a portable motion platform. The obtained results give a great overview of the design; showing the critical parts of the system, which need more attention as well as the range of magnitudes of the values for the different parameters.

For further development, it would be interesting the implementation of these functionalities in a more advance design software to complement it. Additionally, the study of the performance of this DA Tool in the design process of a new product, in a real company, measuring how much time and money does it save when compared to other more complex methods, would be something worth considering.

PREFACE

This Master of Science thesis was done in the Department of Mechanical Engineering and Industrial Systems (MEI) at the Tampere University of Technology (TUT). The supervisor of the thesis was Professor Asko Ellman.

I would like to thank Professor Asko Ellman for his interest, the suggestions and the advices he gave me during the thesis development process. I am also grateful to Niilo Latva-Pukkila for the work he made related to the topic of my thesis, which has been very helpful to understand and learn about VBA.

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TABLE OF CONTENTS

ABBREBIATIONS

DA	Design Analysis
VBA	Visual Basic for Applications is a programming language
EV	Electrical Vehicle
FR	Functional Requirement
DP	Design Parameter
DPP	Design Parameter Priority
SCP	System Characteristic Priority
SCC	System Characteristic Correlation
ASCC	Adjusted System Characteristic Correlation
SCD	System Characteristic Dependency
ASCD	Adjusted System Characteristic Dependency
GRG2	Generalized Reduced Gradient is an optimization algorithm
TUT	Tampere University of Technology
DOF	Degrees of freedom
M	Master Equation relating system characteristics functions.
T	Global target value
[A]	Matrix relating two vectors
{X}	Design parameters vector
{Y}	System characteristic vector
x	Design parameter
y	System characteristics
a	Element of a matrix
k	Element of a normalized matrix
s	Standard deviation in the sensitivities
n	Total number of design parameters
m	Total number of system characteristics
φ	Sign of a system characteristic
ϵ	Precision
R	Radius of the actuator joints in the motion platform
r	Radius of the actuator joints in the structure
h	Distance of the actuator joints in the vertical direction
a_y	Vertical acceleration
a_x	Horizontal acceleration
p	Pressure of the actuators
ω_max	Maximum inclination of the platform
V	Volume
m	Load (Platform + Driver)
F	Force of the actuator
Δp	Pressure increase in the actuators
CdA0	Drag area

1. INTRODUCTION

1.1 Design process

The engineering design process is a creative process seeking to solve a problem or facilitate certain activities. It can be considered as one of the four major areas of product development, which are; design engineering, manufacturing, product support and marketing. When developing a new product the design is one of the main steps, it can be defined as an interactive feedback process and graphically represented as in Figure 1.1. Given some performance specifications for a product, a model is created, the components are selected and the last step before the simulation is the optimization of the design parameters so that the model equations are able to fulfill the specifications. Finally the model is tested, from this process new specifications are obtained, which is new data to be used to improve the model.

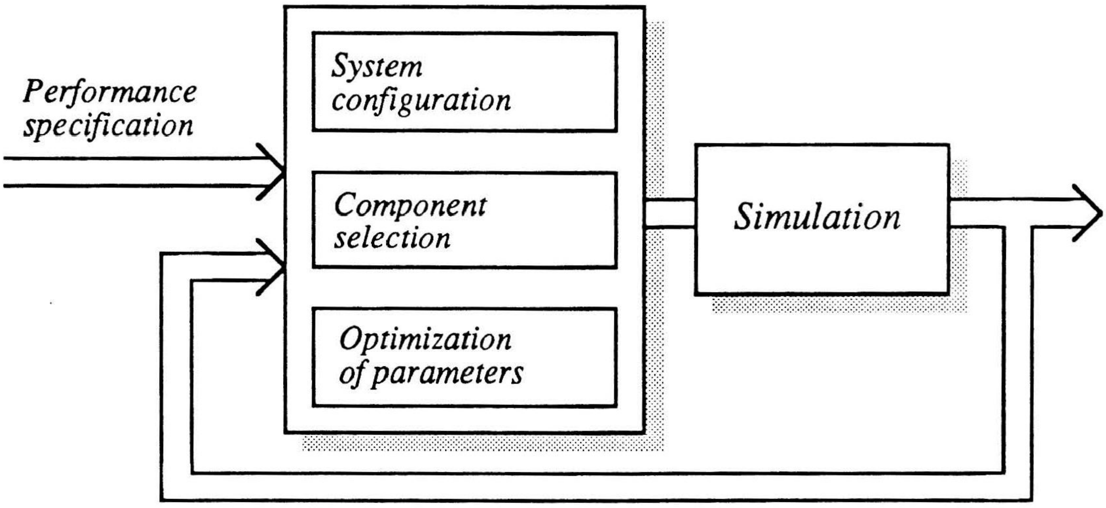


Figure 1.1 *Model-based design process flowchart (Figure from [1]).*

Treating design at a system level, this thesis will focus its attention in a quantitative model based perspective (design parameters and system characteristics) and will not study all the aspects of design. For that purpose some helpful design tools are used. In order to succeed in this process a thorough analysis of the design along with its optimization is needed. An adequate implementation of this process in engineering designs during early-phases will lead the designers to achieve a successful and profitable product.

1.2 Research methods

For this thesis an Excel DA Tool, based on *Visual basic for Applications (VBA),* has been developed. Microsoft Office Excel is very powerful software that combined with the possibility of programming VBA macros gives the user multitude of possibilities. The primary objective of this DA Tool is to analyze a design to understand how much each parameters affects the others and in which way, so that they can be modified and optimized to reach an accurate design. As an example this DA Tool has been used in two different engineering designs, a portable motion platform and an electric vehicle.

The DA Tool works within an Excel Workbook, divided in various worksheets. The application displays on the *MAIN* window all the *Design Parameters* along with the *System Characteristics* involved in the project. By using the control buttons also located in this window the user can easily obtain the analysis and the optimization results, which will be shown on different worksheets of the workbook. With these results the user will be able to understand better the design and the relationships between the different parameters.

The design analysis has been implemented following the method introduced by professor Petter Krus, in Linköping University at Sweden, describes in his handouts *Engineering Design Analysis and Synthesis* [2], which he has used in several of his works [3] [4] [5]. This Sensitivity Analysis method, involving both *System Characteristics* and *Design Parameters*, gives an instantaneous overview over what parameters of the design are of more importance for the desired behavior. It has been proven that this low-fidelity method is accurate enough, during the early design phases, in a research project at the Tampere University of technology [6] and much more faster that a high-fidelity analysis.

Afterwards, to reach the targeted values for the system characteristics the optimization of the design parameters is performed. This goal is achieved with an algorithm that makes use of the *Solver* function of Excel. Basically what this algorithm technique does is to optimize a set of non-linear equations with multivariable constraints.

The user, interpreting these results, both the sensitivity analyses and the optimization ones, can obtain a great overview of the design. He will be able to identify the critical parts of the system, which need more attention, how much the different parameters affect each other as well as the range of magnitudes of the values for the different parameters. Hence, take the correct decisions to improve the design and achieve a commercially profitable product.

1.3 Background

In engineering use, *design parameter*, notation used by Nam P. Suh [7], are measurable aspects that contribute to determining a system. These qualitative and quantitative factors are the functional and physical characteristics of a device, product, component or system, which are input to its design process.

Design parameters could be a considered as constants that affect all the other characteristics of the design by equations relating ones to each others, they determine cost and risk tradeoffs in the design of the system. Thus, these are the most significant parameters and the ones the DA Tool will optimize. The optimization of these parameters will guide the engineer on the design process during the early-phases.

The term *system characteristics* is used for all the parameters that describe the product, so these parameters as opposed to design parameters cannot be manipulated; they are determined by their corresponding formula and other variables. Actually, they are the principal equations that describe the mechanical model.

Fixed parameters and *calculated parameters* are minor variables or constants used in the model to build the *system characteristics* equations.

1.4 Thesis structure

Following the introduction chapter, four main parts can be identified; the first one, consist in one chapter that describes the user interface of the DA Tool. The second part, consisting in a theoretical chapters, covers the design analysis and the optimization processes. In 4th chapter 3 example models are presented and analyzed with the DA Tool. While the last one, is the thesis conclusion chapter.

Moreover, there is a short chapter discussing some technical details on how to prepare and use the DA Tool and how to create a new project.

2. USER INTERFACE

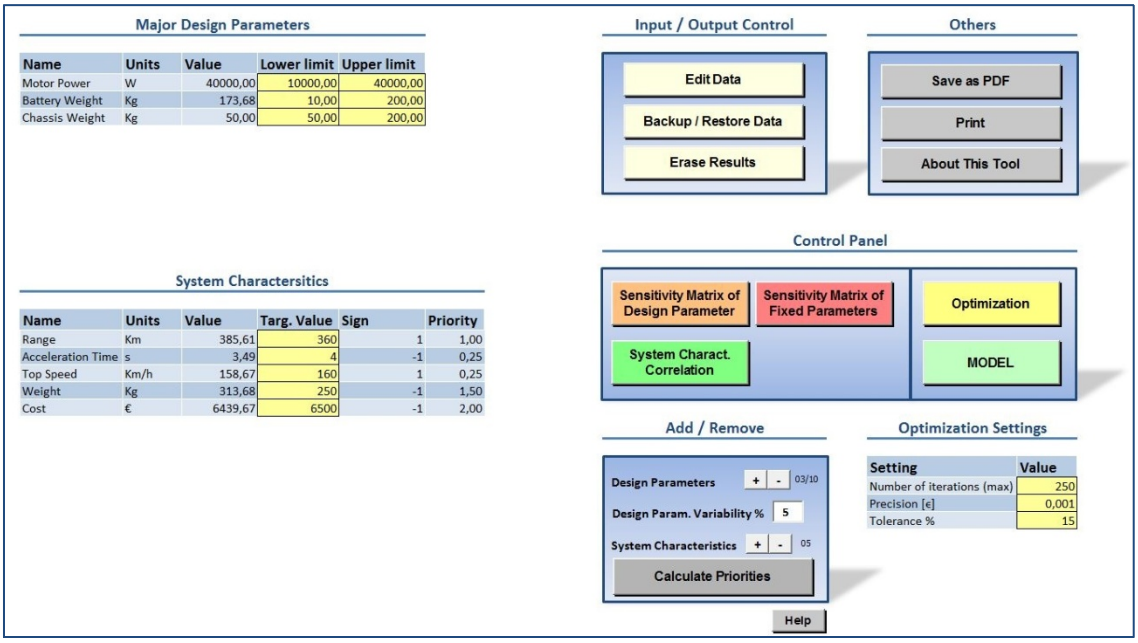
The DA Tool has been developed in a user-friendly way, where all the features are easy to use and understand. Users with basics knowledge on MS-Excel software once familiarized with the interface and the way to interpret the results will be able to work perfectly with this DA Tool.

Three core parts can be found within the DA Tool; the first one is the *MAIN* window, where the user will introduce all the input data involved on the design (*Design Parameters* and *System Characteristics*). In this window all the different buttons to performance the diverse features of the DA Tool can be found. On the second one, the *Equations* and the *Fixed Parameters* involved in the project along with some control buttons can be found. The last part consists on a set of worksheets, where obtained results of the analysis and optimization processes are shown.

2.1 Main Window

Once inside the DA Tool, the *MAIN* window or worksheet will be found. The *Major Design Parameters* and *System Characteristics* are located at the left side. At the right side there are several buttons; the ones to add and remove parameters and characteristics to the project, those dedicated to edit and backup these values, some settings for the optimization calculations, others to save or print the results and the most important ones the *Control Buttons,* to performance the different analyses features and the optimization of the model.

For instance, in Figure 2.1 it is shown the *MAIN* window the project of an Electric Vehicle (EV). This project consists on a five system characteristics model determined by three major design parameters.



Major Design Parameters

Name	Units	Value	Lower limit	Upper limit
Motor Power	W	40000,00	10000,00	40000,00
Battery Weight	Kg	173,68	10,00	200,00
Chassis Weight	Kg	50,00	50,00	200,00

System Charactersitics

Name	Units	Value	Targ. Value	Sign	Priority
Range	Km	385,61	360	1	1,00
Acceleration Time	s	3,49	4	-1	0,25
Top Speed	Km/h	158,67	160	1	0,25
Weight	Kg	313,68	250	-1	1,50
Cost	€	6439,67	6500	-1	2,00

Design Parameters 03/10
Design Param. Variability % 5
System Characteristics 05

Optimization Settings

Setting	Value
Number of iterations (max)	250
Precision [ϵ]	0,001
Tolerance %	15

Figure 2.1 *Main window interface.*

As it can be seen from the previous figure, the data of the major design parameters is represented in a table located in the upper-left corner of the *MAIN* worksheet; there is an example in Table 2.1. The user can enter there the name of the parameter, its units and actual value, along with some extra information that is used for the optimization process, which will be explained on further chapters.

Table 2.1 *Example of a major design parameters table.*

Major Design Parameters				
Name	**Units**	**Value**	**Lower limit**	**Upper limit**
Motor Power	W	22028,07	10000	40000
Battery Weight	Kg	97,18	10	200
Chassis Weight	Kg	50,00	50	200

In the table below an example of the system characteristics table can be seen.

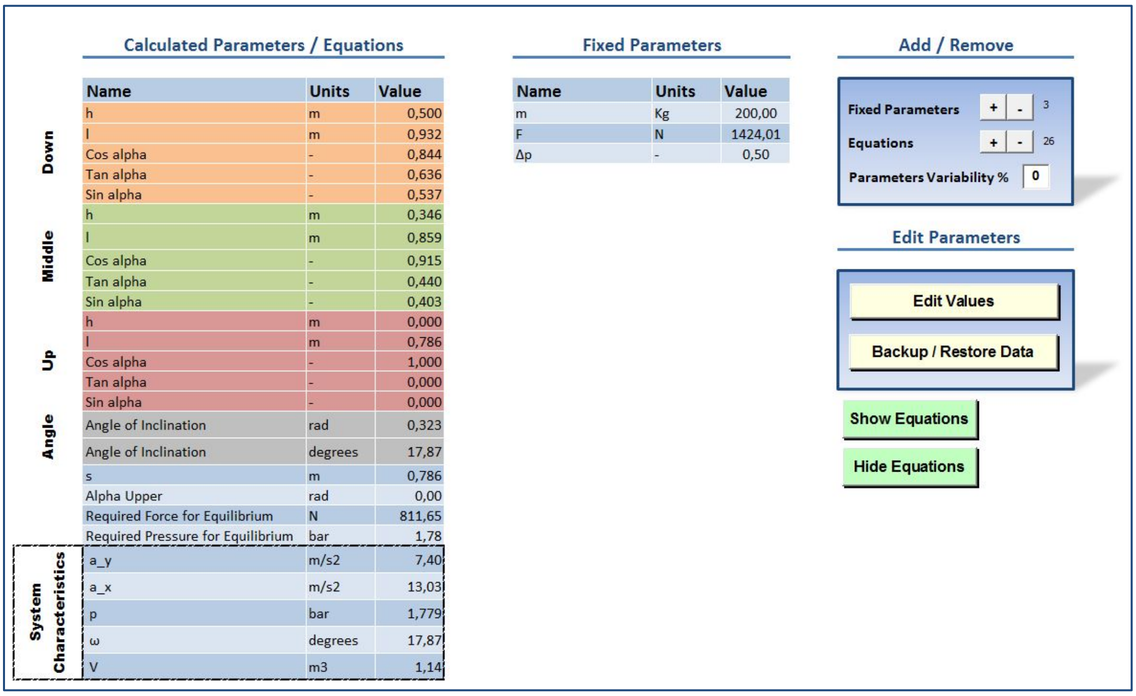
Table 2.2 *Example of a system characteristics table.*

System Characteristics					
Name	**Units**	**Value**	**Targ. Value**	**Sign**	**Priority**
Range	Km	290,43	320	1	1,00
Acceleration Time	s	4,59	5	-1	1,00
Top Speed	Km/h	143,60	150	1	1,00
Weight	Kg	219,21	220	-1	1,00
Cost	€	4009,06	3500	-1	1,00

System characteristics information is represented just beneath the table of the major design parameters. This table shows the name, units and value of the system parameters as well as the *Targeted Value,* which represents the value the system characteristic are desired to achieve, the adjacent cell, *Sign*, indicates if a higher value than the targeted one is aspire to or not, this data is used by the DA Tool in various calculations. In the last column it is represented the weight each characteristics has on the model, which are used for the optimization calculation.

2.2 Model window

On this worksheet, an example in Figure 2.2, all the necessary data and equations for further calculations is stored. There are also some control buttons.



Calculated Parameters / Equations

	Name	Units	Value
Down	h	m	0,500
	l	m	0,932
	Cos alpha	-	0,844
	Tan alpha	-	0,636
	Sin alpha	-	0,537
Middle	h	m	0,346
	l	m	0,859
	Cos alpha	-	0,915
	Tan alpha	-	0,440
	Sin alpha	-	0,403
Up	h	m	0,000
	l	m	0,786
	Cos alpha	-	1,000
	Tan alpha	-	0,000
	Sin alpha	-	0,000
Angle	Angle of Inclination	rad	0,323
	Angle of Inclination	degrees	17,87
	s	m	0,786
	Alpha Upper	rad	0,00
	Required Force for Equilibrium	N	811,65
	Required Pressure for Equilibrium	bar	1,78
System Characteristics	a_y	m/s2	7,40
	a_x	m/s2	13,03
	p	bar	1,779
	ω	degrees	17,87
	V	m3	1,14

Fixed Parameters

Name	Units	Value
m	Kg	200,00
F	N	1424,01
Δp	-	0,50

Add / Remove

Fixed Parameters 3

Equations 26

Parameters Variability % 0

Figure 2.2 *MODEL window.*

On the left side the *Fixed Parameters,* constants of the model are stored. These parameters are used in the require equations to determine the model itself.

Moreover, on left side of the window the results of every equation of the model are shown. Notice that the system characteristics are calculated in this sheet and listed in the *Calculated Parameters / Equations* table. These values are passed into the *MAIN* window and displayed at their appropriate cell.

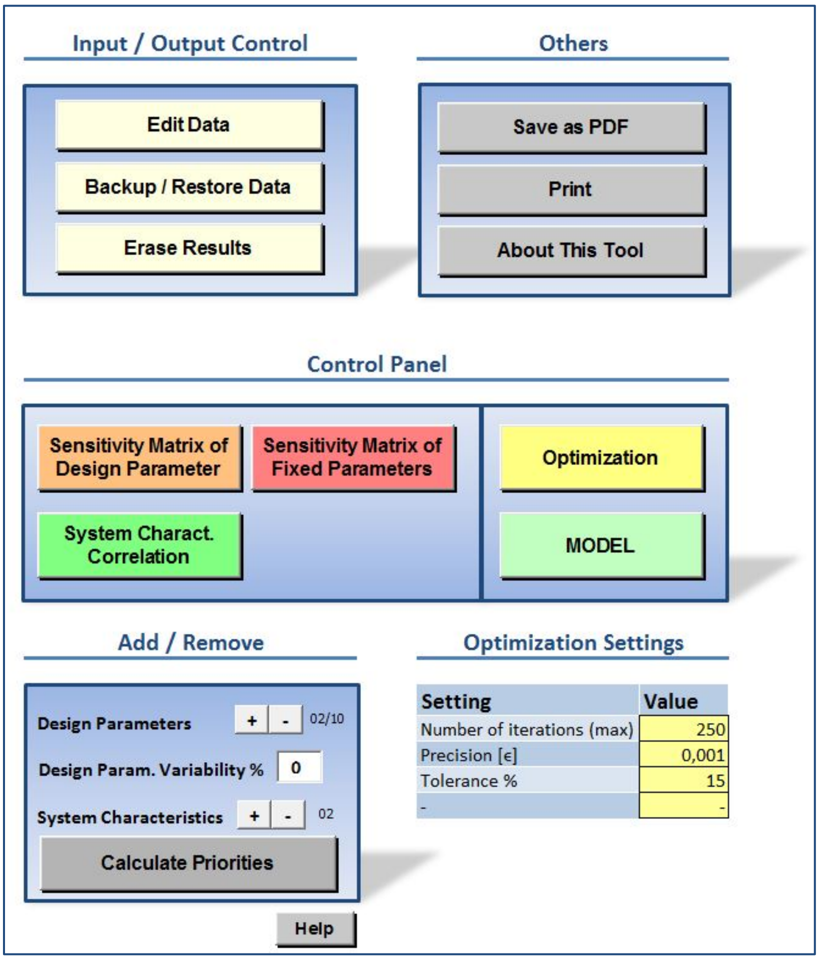
Table 2.3 *Two parameters equations.*

Name	Units	Value	Equations
Motor Weight	Kg	22,08	=Motor_Power/Motor_Specific_Power
Total Weight	Kg	170,20	=Chassis_Weight+Motor_Weight+Battery_Weight

On the other hand, if the user wishes to examine the equations of the model, the *Show Equations* control will display them. In Table 2.3 there is an example of the equations of two parameters involved on the design of an EV.

2.3 Using an existing model

Once model has been introduced into the DA Tool it will be ready to be analyzed. Beside the parameters tables of the model, at the *MAIN* window, the principal buttons and controls can be found, as shown more in detail in Figure 2.3. From there the user will be able to performance all the features of the DA Tool.



Design Parameters + - 02/10
Design Param. Variability % 0
System Characteristics + - 02

Setting	Value
Number of iterations (max)	250
Precision [ε]	0,001
Tolerance %	15
-	-

Figure 2.3 *Buttons and controls at Main window.*

2.3.1 How to edit the parameters

Starting from the table of design parameters at the *MAIN* worksheet, the column *Value* represents the actual values of the design variables. They can be freely changed; consequently the values of the rest of the parameters will vary instantaneously according to their respective equation. The columns beside this last one represent the limitations for the design parameters both the upper and the lower. These values will the constraints for the variables that will be used during the optimization process. They can be set freely but the upper limit must be always greater than the lower one.

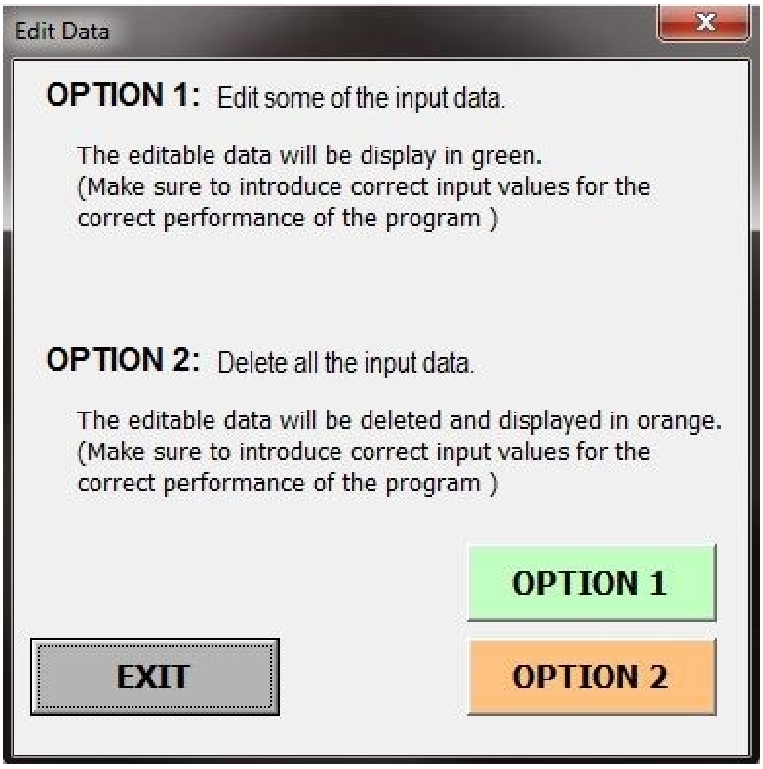
The *Value* column at the system characteristics table also displays the actual value of the different characteristics, although these values cannot be edited. They are the results of their respective equations, calculated at the *MODEL* worksheet. The values at the *Targ. Value* column indicate the desire value to be achieved by the system requirements. They are used for the optimization calculations and can be entered willingly. The *Sign* cell indicates whether the requirement value is desired to be greater than the targeted one or lower, "1" means a greater value is wanted while "-1" means the opposite. These values can be modified by the user. In the last column, *Priority,* it is represented the weight that has been assigned to each characteristic within the design. The priority values can be either calculated with the *Calculate Priorities* button situated at the *Add / Remove* module or entered manually.

On the other hand, at the *MODEL* window, the table in the left displays the results of all the equations of the model. Those values cannot be edited, although it would be possible editing the equations. At the table beside, the fixed parameters of the design are listed. These values are constants used for the equations to calculate further parameters; therefore, their value can be edited freely.

Additionally, there is a button to backup all the parameters of the model (*Backup / Restore Data*), which will show the pop-up window presented below. This functionality can be very useful, when the user wants to edit some parameters to study the changes in the design without losing the previous ones.

Figure 2.4 *Backup / Restore pop-up window.*

Moreover, under the title bar *Input / Output Control* it is possible to find the *Edit Input* button, which will display the window displayed below.



OPTION 1: Edit some of the input data.

The editable data will be display in green.
(Make sure to introduce correct input values for the correct performance of the program)

OPTION 2: Delete all the input data.

The editable data will be deleted and displayed in orange.
(Make sure to introduce correct input values for the correct performance of the program)

Figure 2.5 *Edit data pop-up window.*

Although this functionality is not really needed to edit the parameters, it could help a not very experienced user with this DA Tool, guiding him trough the editing process by coloring the cells of the editable parameters and showing an error message if invalid input is entered in any of the cells.

2.3.2 How to calculate the sensitivity and correlation matrixes

The buttons to performance the sensitivity analyses and correlation analysis can be found from *Control Panel* at the *MAIN* worksheet. The DA Tool will make use of all the required data, located in the tables of the design parameters and the system characteristics.

Sensitivity Matrix of Design Parameter button will performance the sensitivity analysis of the design parameters and display in another worksheet the results on two different matrixes; the *Normalized Sensitivity Matrix* and the *Relative Sensitivity Matrix*. These analyses are an exceptional approach to study relationships between design parameters and system characteristics.

The next button, *Sensitivity Matrix of Fixed Parameters*, conducts the same function as the previous one, but relating fixed parameters to system characteristics.

The last button, *System Charact. Correlation,* will provide the user a measure of dependency between the system characteristics involved in the project, the results will be displayed in a matrix in a different worksheet. Information about correlation is very useful when establishing the specifications for the design, since it can show the areas that can be improved without scarifying too much other, or to see the areas that might be worth sacrificing in order to improve others.

On the other hand, the button, *Erase Results*, will erase all the calculated results of the different worksheets of the workbook, so that new calculations with other values can be performed.

2.3.3 How to optimize a model

The *Optimization* button, colored in yellow, can also be found from the *Control Panel* module. Clicking this button the optimization process of the design parameters will be performed.

The optimization will modify the values of the design variables subjected to the constraints, situated at the design parameters table, so that the requirements of the design can be met. The priority values, at the system characteristics table, will affect the process to the extent that if a greater weight value is assigned to one requirement with respect the each others, the algorithm will try to optimize the design so that requirement is met insofar as possible leaving aside the importance of the others. The values at the tables that are only used for the optimization calculations are shown in yellow.

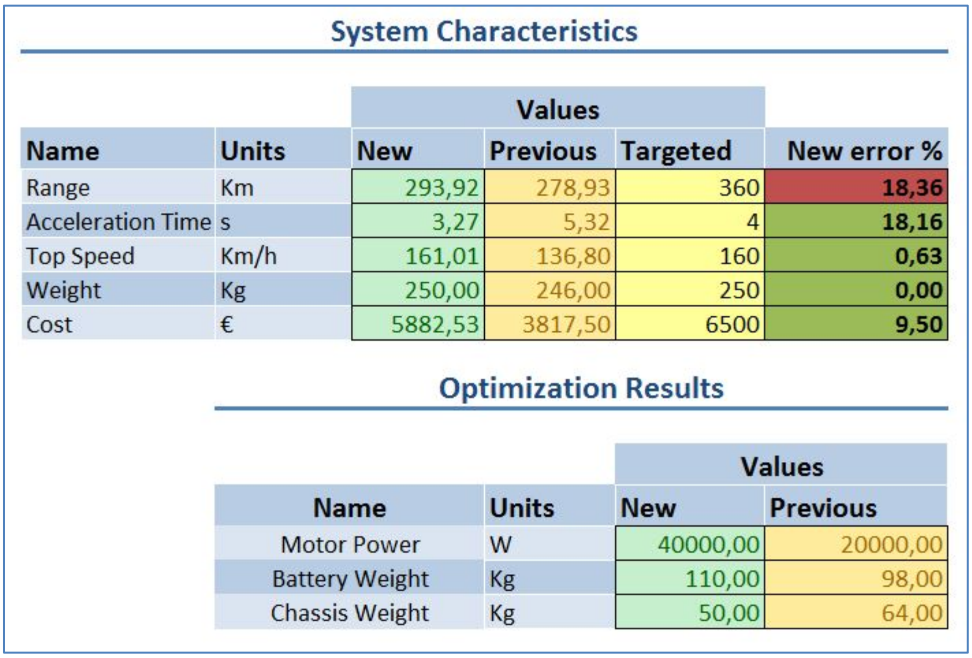
Furthermore, there are some setting options for the optimization process, shown below in Table 2.4. As default the recommended values are assigned, but the user will be able to change them freely within some restrictions.

Table 2.4 *Optimization settings controls.*

Optimization Settings	
Setting	**Value**
Number of iterations (max)	200
Precision [ϵ]	0,01
Tolerance %	10

The minimum number of iterations is 200, the precision must be between 0 and 1 and the tolerance range goes from 1% to 12%. If the data introduced by the user does not fulfill these limitations the DA Tool will change them to the default ones.

After having solved the optimization problem a new worksheet will be shown with two tables as represented below.



System Characteristics

		Values			
Name	**Units**	**New**	**Previous**	**Targeted**	**New error %**
Range	Km	293,92	278,93	360	**18,36**
Acceleration Time	s	3,27	5,32	4	**18,16**
Top Speed	Km/h	161,01	136,80	160	**0,63**
Weight	Kg	250,00	246,00	250	**0,00**
Cost	€	5882,53	3817,50	6500	**9,50**

Optimization Results

		Values	
Name	**Units**	**New**	**Previous**
Motor Power	W	40000,00	20000,00
Battery Weight	Kg	110,00	98,00
Chassis Weight	Kg	50,00	64,00

Figure 2.6 *Tables displaying the optimization results of a model.*

The first table will display the new design parameters values beside the previous ones. The second table shows the new system characteristics values driven by the optimized parameters. The last column of this table presents the error percentage of the value of the system characteristics in regard to the targeted one, if the new value of the characteristic is reached, 0% error, or exceeded in the desire direction the cell is colored in green, whereas if the targeted value is not achieved the cell is colored in red.

In addition, the user will be asked if he would rather proceed with the new values or return to the previous ones, if there is a positive answer the tool will return to the *MAIN* window and the new values will be copied into their appropriate cells, in the other case the tool will also take the user to the *MAIN* window but no changes will be performed on the major design parameters values.

3. DESIGN ANALYSIS FUNCTIONS

In this theoretical chapter, all the design analysis functions implemented in the DA Tool will described in detail. Starting from the normalized priority calculations for the system characteristics, following by the sensitivity analysis, the system characteristics analysis and finalizing with the optimization of the system parameters.

3.1 Introduction

The principal goal of design analysis is to gather information about the essence of the design solution, and how it can be modified in order to accomplish the desired specifications. For this propose diverse matrix methods are useful, considering they can be used to display, in a very visual way, the mapping of relationship between system characteristics and design parameters.

The relation between design parameters and system characteristics could also be seeing as a relationship between customer needs to system characteristics, input to output variables, etc. The relation between two input variables and two output variables can be represented as in equation (3.1):

$$\begin{pmatrix} y_1 \\ y_2 \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} \tag{3.1}$$

Where x_i are the input variables, y_i the output parameters and a_{ij} the different elements of matrix relating both of them. This can generalized as:

$$\{Y\} = [A]\{X\} \tag{3.2}$$

Where $[A]$ is the matrix relating vector $\{X\}$ of design parameters to vector $\{Y\}$ of system characteristics, assuming linear relationships.

In axiomatic design, the design matrix plays a central role [7] [8]. Using the nomenclature of axiomatic design, this matrix maps the relation amid design parameters, DP and functional requirements, FR.

More generally, the relationship between design parameters and system characteristics, can be expressed as:

$$\{FR\} = [A]\{DP\} \tag{3.3}$$

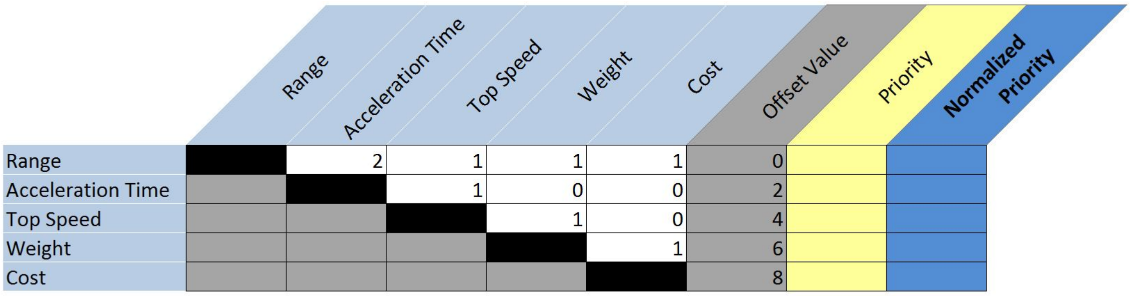
Being $[A]$ the design matrix. There are two axioms in axiomatic design. The first one is the independence axiom *“Maintain the independence of the functional requirements (FRs)”* Meaning that a design is better the more independent the functional requirements are one another. The second axiom “*Minimize the information content of the design”,* implying that a simpler design is mostly preferable over a complex one [7] [8].

3.2 Priority analysis

The priority or weight represents the importance that a certain parameter has in the model. Thus if a system characteristics is given a higher priority than another one means that within the model that characteristics is more significant than the other to achieve the desired goal. For this propose a functionality to help the user with choosing the priority value for each system characteristic has been implemented in the DA Tool. This functionality uses the parwise comparison method described by Krus in [2].

This method consist on comparing each characteristic to each other forming a priority table where the value for each one of them is calculated and normalized following some simple mathematical equations.

Thus, the first step is forming the table; due to symmetry it is only necessary filling half of the table. The table is filled with the values *2*, *1* or *0* indicating the relative importance between the two characteristics. In Figure 3.1 an example is shown, where the different requirements are put on both axis of the table for the calculations.



	Range	Acceleration Time	Top Speed	Weight	Cost	Offset Value	Priority	Normalized Priority
Range		2	1	1	1	0		
Acceleration Time			1	0	0	2		
Top Speed				1	0	4		
Weight					1	6		
Cost						8		

Figure 3.1 *Priorities calculation example.*

Number *2* is used to indicate that the requirement on the row is more important that the one on the column. The value 1 indicates that the requirements are equally important and *0* is used to indicate that the requirement on the row is less important than the one on the column.

An offset value column is placed to the right of the matrix with the value *2i*, where *i* is the row number, to compensate the fact that values are distributed around one. The diagonal cells are filled with the column sum value with a negative sign as shown in Figure 3.2 and the row sum then becomes in the priority value. Finally, a common practice is to normalize the priorities values so that the average value is one.

	Range	Acceleration Time	Top Speed	Weight	Cost	Offset Value	Priority	Normalized Priority
Range	0	2	1	1	1	0	5	**1,25**
Acceleration Time		-2	1	0	0	2	1	**0,25**
Top Speed			-2	1	0	4	3	**0,75**
Weight				-2	1	6	5	**1,25**
Cost					-2	8	6	**1,5**

Figure 3.2 *Priorities calculation method.*

All this calculations are performed by pressing *Calculate* button, situated above the table. Then, the user will be asked whether he would like to copy these normalized values to the *MAIN* worksheet or whether he would like to maintain the previous ones.

Nevertheless, there could be a problem with this parwise comparison method, if the requirement that has the lowest ranks gets a weighting of zero. Not really appropriate since the fact that a parameter has been identified as a system characteristic means that it should have some weight.

3.3 Sensitivity analysis

Sensitivity analysis is an exceptional tool to examine the relation between design parameters and system characteristics; it can also give a quick outline over what parts of the design are interesting for the desired performance. Moreover, it is used to study the impact of uncertainties and disturbances in parameters and constants. So that is why, its implementation in this DA Tool is very convenient.

Sensitivity analysis is the primary tool for studying the degree of robustness in a system [2].

Assuming the system:

$$y = f(x) \tag{3.4}$$

Being f a nonlinear function. Nevertheless, linearizing around a nominal point, this can be written as:

$$y_0 + \Delta y = f(x_0) + \mathcal{J}\Delta x \tag{3.5}$$

Where $\mathcal{J}$ is the Jacobian;

$$\mathcal{J}_{ij} = \frac{\partial f_i(x)}{\partial x_j} \tag{3.6}$$

Thus,

$$\Delta y = \mathcal{J}\Delta x \tag{3.7}$$

This Jacobian $\mathcal{J}$ is identical to the sensitivity matrix *k,* whose elements can be expressed as follows:

$$k_{ij} = \frac{\partial y_i}{\partial x_j} \tag{3.8}$$

Where:

- k_{ij} Elements of the sensitivity matrix.
- y_i System characteristics of the model.
- x_j Design parameters of the model.

In Table 3.1 as an example a $(3\ x\ 3)$ sensitivity matrix is represented.

Table 3.1 *Sensitivity matrix.*

	x_1	x_2	x_3
y_1	K_{11}	K_{12}	K_{13}
y_2	K_{21}	K_{22}	K_{23}
y_3	K_{31}	K_{23}	K_{33}

Where x_i represent the parameters, y_j the system requirements and k_{ij} the elements of the matrix.

The following example shows the sensitivity matrix for a portable motion platform, a practical example that was used in a design project [6] [9] at Tampere University of Technology. Where this platform in Figure 3.3 was developed and built for a simulation vehicle.

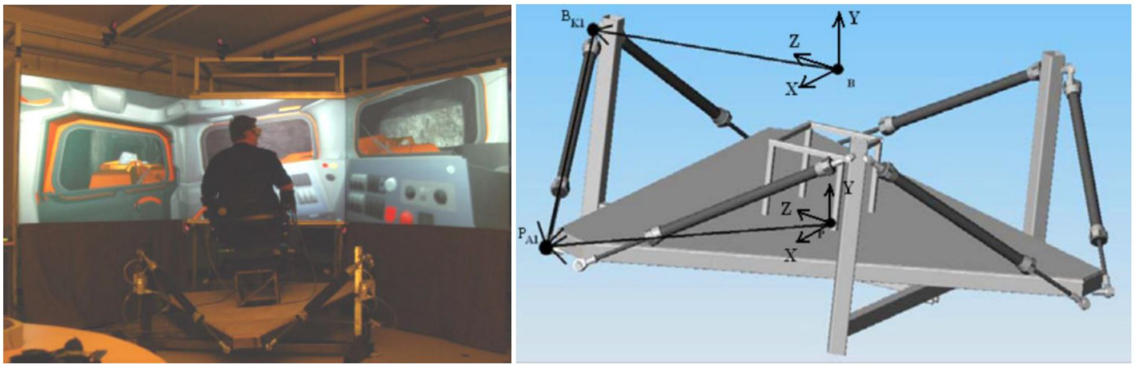
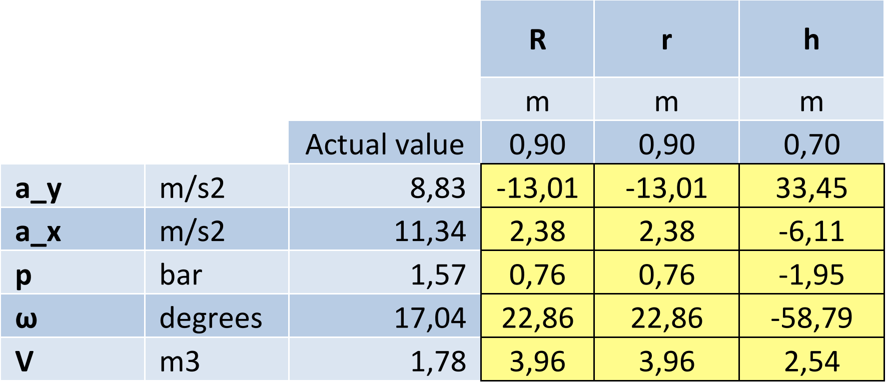


Figure 3.3 *Virtual environment for vehicle and construction of motion platform (Photo from: [10])*



			R	r	h
			m	m	m
		Actual value	0,90	0,90	0,70
a_y	m/s2	8,83	-13,01	-13,01	33,45
a_x	m/s2	11,34	2,38	2,38	-6,11
p	bar	1,57	0,76	0,76	-1,95
ω	degrees	17,04	22,86	22,86	-58,79
V	m3	1,78	3,96	3,96	2,54

Figure 3.4 *Sensitivity matrix of the design parameters for the motion platform.*

In the Figure 3.4 it can be seen the sensitivity matrix for the portable motion platform design. The three main preliminary design parameters are the radius of the actuator joints in the motion platform R , the radius of the actuator joints in the structure r and the distance of the actuator joints in the vertical direction h . While the system characteristics are: the vertical acceleration a_y , the horizontal acceleration a_x, the pressure of the actuators p, the maximum inclination ω_{max}, and the volume occupied by the platform V. This sensitivity matrix has been build making use of the DA Tool with the data provided by the user.

In the case that the number of design parameters and system characteristics were the same, it would be possible to invert the sensitivity matrix to analyze the influence on the design parameters with the variation of the system requirements.

Normalized sensitivities

With complex systems and a large sensitivity matrix, for the user it is quite complicated to get an overview of the system at hand due to the different magnitude of each parameter. That is why, a dimensional normalization is needed, and actually, the DA Tool will not show the sensitivity matrix results but the normalized sensitivity matrix. This normalization is build following this equation:

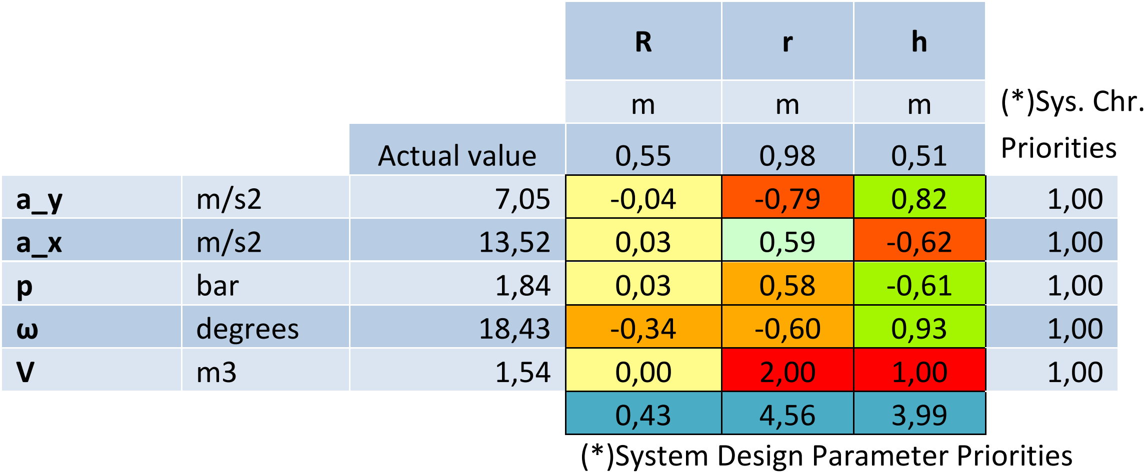
$$k_{ij}^{0} = \frac{x_j}{y_i}\frac{\partial y_i}{\partial x_j} \tag{3.9}$$

Where:

- k_{ij}^{0} Normalized elements of the normalized sensitivity matrix.
- y_i System characteristic of the model.
- x_j Design parameter of the model.

Hence, a non-dimensional value is obtained, indicating the percentage a specific system characteristic changes when a design parameter is changed in one percent. So that is much easier for the DA Tool user to determine the relative weigh of the different system parameters on the design.

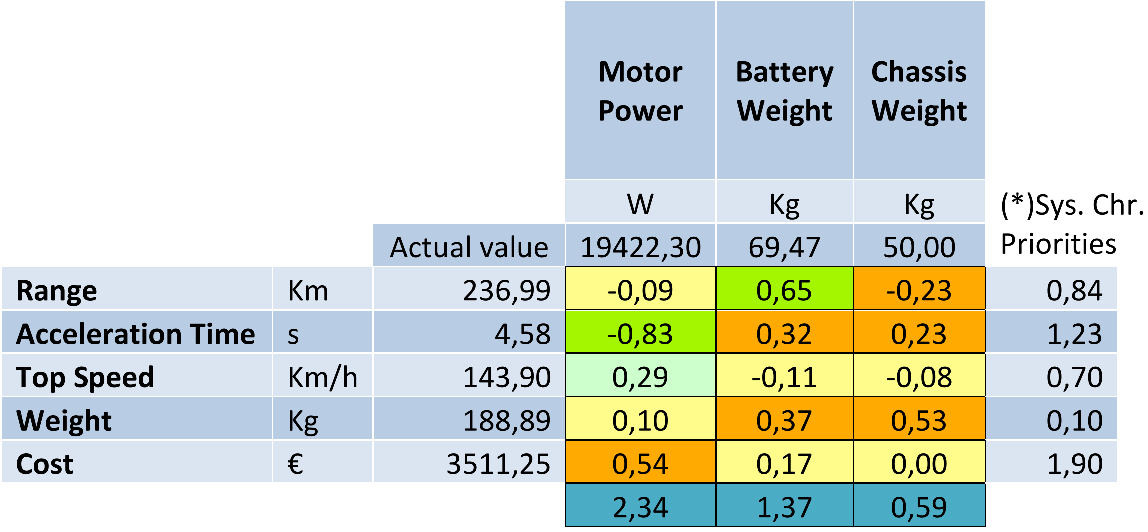
As previously discussed, the DA Tool will show these results on the *Sensitivity* worksheet after the user clicks the button *Sensitivity Matrix of Design Parameter,* as an example the normalized sensitivity matrices of the portable motion platform design, Figure 3.5, and the EV model, Figure 3.6, are shown here.



			R	r	h	
			m	m	m	(*)Sys. Chr. Priorities
		Actual value	0,55	0,98	0,51	
a_y	m/s2	7,05	-0,04	-0,79	0,82	1,00
a_x	m/s2	13,52	0,03	0,59	-0,62	1,00
p	bar	1,84	0,03	0,58	-0,61	1,00
ω	degrees	18,43	-0,34	-0,60	0,93	1,00
V	m3	1,54	0,00	2,00	1,00	1,00
			0,43	4,56	3,99	

(*)System Design Parameter Priorities

Figure 3.5 *Normalized sensitivity matrix for the motion platform.*



			Motor Power	Battery Weight	Chassis Weight	
			W	Kg	Kg	(*)Sys. Chr. Priorities
		Actual value	19422,30	69,47	50,00	
Range	Km	236,99	-0,09	0,65	-0,23	0,84
Acceleration Time	s	4,58	-0,83	0,32	0,23	1,23
Top Speed	Km/h	143,90	0,29	-0,11	-0,08	0,70
Weight	Kg	188,89	0,10	0,37	0,53	0,10
Cost	€	3511,25	0,54	0,17	0,00	1,90
			2,34	1,37	0,59	

(*)System Design Parameter Priorities

Figure 3.6 *Normalized sensitivity matrix for the EV model.*

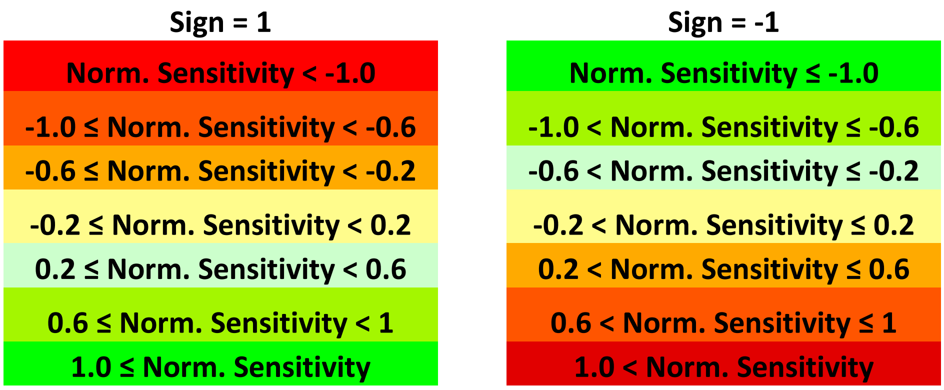
Notice that, a new row has been added to the matrix indicating the design parameters priorities, which can be calculated as:

$$DPP_j = \sum_{i=1}^{n} \left|k_{ij}^{0}\right| SCP_i \tag{3.10}$$

Where:

- DPP_j Priority value of each design parameters.
- k_{ij}^{0} Normalized elements of the normalized sensitivity matrix.
- SCP_i Priority value of each system characteristic.
- n Total amount of system characteristics.

To make it even easier for the user to understand the results, colors have been assigned to each value of the matrix following the legend in Figure 3.7, making the matrix more visual. So, from green to red, meaning that, if a value is colored in red that system characteristic change in a great amount and not in the desired direction with a small change on that design parameter, while if the color is green the requirement faces the opposite situation, a positive change on the value on the desired direction. Remember that, the sign indicates if the system characteristic at issue is desired to be high or low, "1" if a high value is desired and "-1" in the other situation.



Sign = 1	Sign = -1
Norm. Sensitivity < -1.0	Norm. Sensitivity ≤ -1.0
-1.0 ≤ Norm. Sensitivity < -0.6	-1.0 < Norm. Sensitivity ≤ -0.6
-0.6 ≤ Norm. Sensitivity < -0.2	-0.6 < Norm. Sensitivity ≤ -0.2
-0.2 ≤ Norm. Sensitivity < 0.2	-0.2 < Norm. Sensitivity ≤ 0.2
0.2 ≤ Norm. Sensitivity < 0.6	0.2 < Norm. Sensitivity ≤ 0.6
0.6 ≤ Norm. Sensitivity < 1	0.6 < Norm. Sensitivity ≤ 1
1.0 ≤ Norm. Sensitivity	1.0 < Norm. Sensitivity

Figure 3.7 *Color legend for the sensitivity matrices.*

With the information of this normalized sensitivity matrix the user will be able to conclude which are the most critical design parameters of a design and how much influence the modification of the parameters impact the system requirements.

Relative Sensitivities

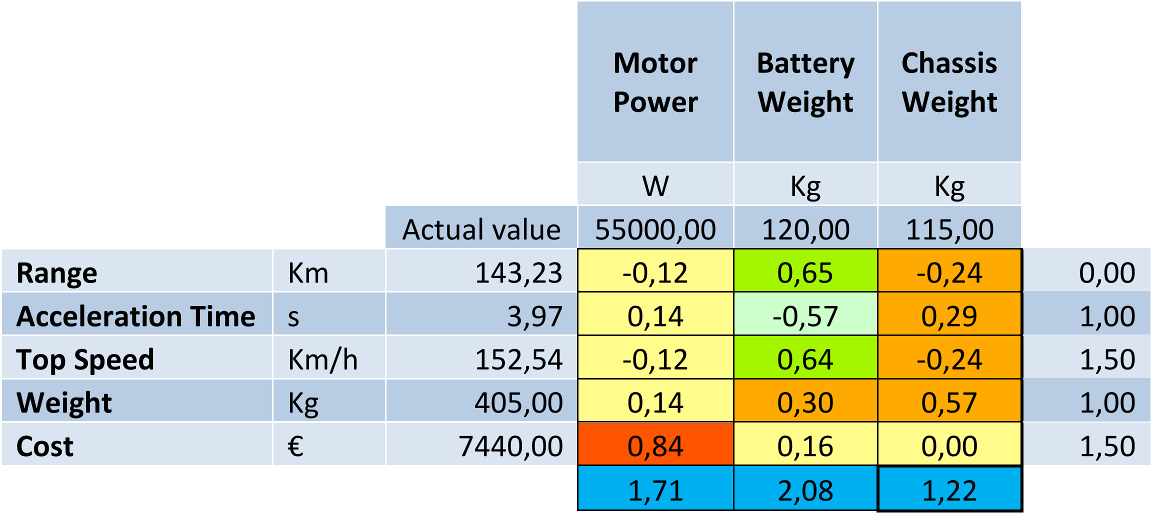
There is a different approach to obtain a better overview of the design rather than the sensitivity matrix. This can be achieved with the following formula:

$$K_{ij}^{0} = \frac{x_j \dfrac{\partial y_i}{\partial x_j}}{\sum_{l=1}^{N} \left| x_l \dfrac{\partial y_i}{\partial x_l} \right|} \tag{3.11}$$

Where:

- k_{ij}^{0} Normalized elements of the relative sensitivity matrix.
- y_i System characteristic of the model.
- x_j , x_l Design parameter of the model.
- N Total amount of design parameters.

Hence, in this new matrix, the sum of the elements of each row is one. So, with the relative sensitivity matrix, the user will have a better view of the relative importance of the system parameters. Although, the same conclusions are reached from this matrix as the ones obtained from the normalized one. This approach is very useful when the nominal value of one or more system characteristics is equal to zero, which will lead to a division with zero in the normalized sensitivity matrix calculation. In the following pictures Figure 3.8 and Figure 3.9 a couple of examples are shown.



			Motor Power	Battery Weight	Chassis Weight	
			W	Kg	Kg	
		Actual value	55000,00	120,00	115,00	
Range	Km	143,23	-0,12	0,65	-0,24	0,00
Acceleration Time	s	3,97	0,14	-0,57	0,29	1,00
Top Speed	Km/h	152,54	-0,12	0,64	-0,24	1,50
Weight	Kg	405,00	0,14	0,30	0,57	1,00
Cost	€	7440,00	0,84	0,16	0,00	1,50
			1,71	2,08	1,22	

Figure 3.8 *Relative sensitivity matrix of the design parameters for the EV design.*

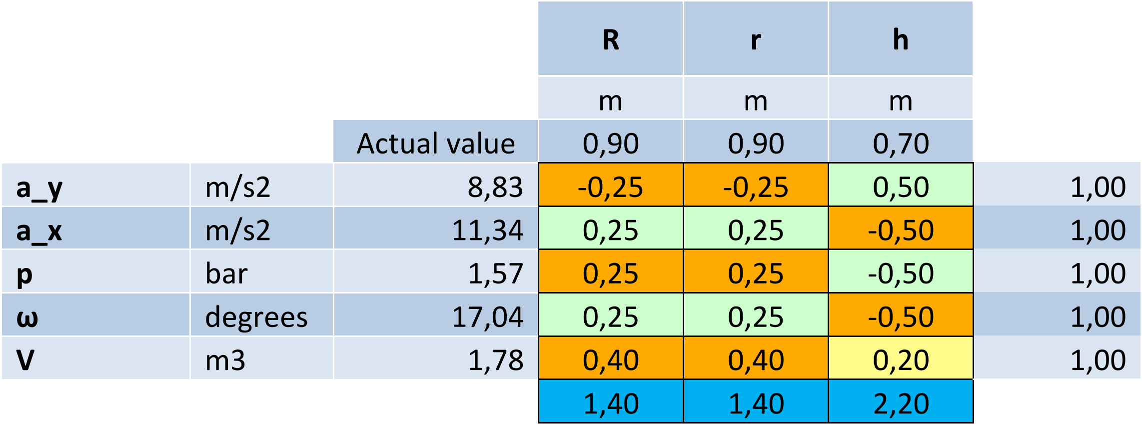
The design priorities are calculated with the following equation:

$$DPP_j = \sum_{i=1}^{n} \left|k_{ij}^{0}\right| SCP_i \tag{3.12}$$

Where:

- DPP_j Relative priority value of each design parameters.
- k_{ij}^{0} Normalized elements of the relative sensitivity matrix.
- SCP_i Priority value of each system characteristic.
- n Total amount of system characteristics.

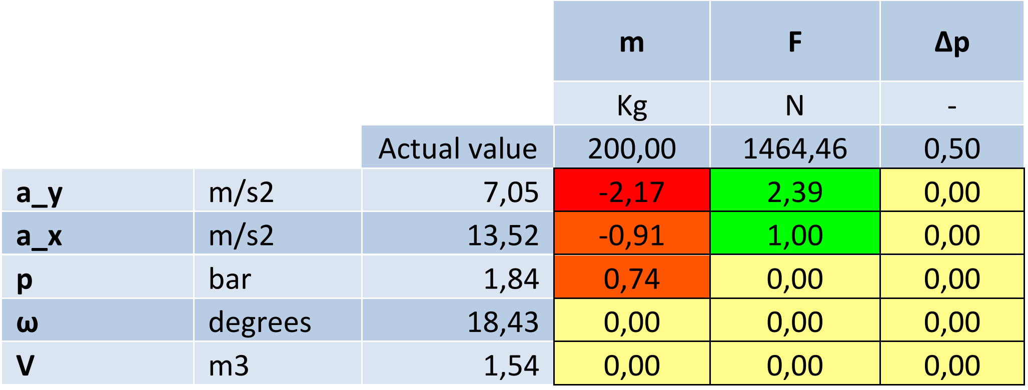
Notice that the same color rule, shown in Figure 3.7, applies. It is also acknowledgeable that the sum of the matrix row, in absolute values, is one.



			R	r	h	
			m	m	m	
		Actual value	0,90	0,90	0,70	
a_y	m/s2	8,83	-0,25	-0,25	0,50	1,00
a_x	m/s2	11,34	0,25	0,25	-0,50	1,00
p	bar	1,57	0,25	0,25	-0,50	1,00
ω	degrees	17,04	0,25	0,25	-0,50	1,00
V	m3	1,78	0,40	0,40	0,20	1,00
			1,40	1,40	2,20	

Figure 3.9 R*elative sensitivity matrix of the design parameters for the motion platform design.*

The sensitivity analysis can also be applied to the fixed parameters of the model design, also known as uncertainty parameters. In the next Figure 3.10 it is presented the normalized sensitivity matrix of fixed parameters for the motion platform design.



			m	**F**	**Δp**
			Kg	N	-
		Actual value	200,00	1464,46	0,50
a_y	m/s2	7,05	-2,17	2,39	0,00
a_x	m/s2	13,52	-0,91	1,00	0,00
p	bar	1,84	0,74	0,00	0,00
ω	degrees	18,43	0,00	0,00	0,00
V	m3	1,54	0,00	0,00	0,00

Figure 3.10 *Normalized sensitivity matrix of fixed parameters for the motion platform design.*

The same kind of conclusions can be acknowledged from the normalized sensitivity matrix as the ones reached with the matrix for the design parameters.

3.4 System characteristics correlation

A very common problem that engineers have to face when designing; is that some of the system characteristics may have a conflict of interest, in other words, when benefiting one of the characteristic you could be damaging one or more of the other characteristics. Thus, information on this matter is quite useful when arranging the system requirements, since it can shed light on the areas that could be improved without scarifying to much the others, or the other case around, which parameters might be worth sacrificing in order to improve the other areas.

Petter Krus describes two different methods to solve this problem [2]. The first one is the *System Characteristics Dependencies (SCD)*, which uses the following equation:

$$SCD_{ik} = \sum_{j=1}^{m} k_{ij}^{0} k_{kj}^{0} \tag{3.13}$$

Where:

- SCD_{ik} Elements of the system characteristic dependencies matrix.
- k_{ij}^{0} , k_{kj}^{0} Normalized elements of the sensitivity matrix.
- m Total amount of system characteristics.

However, the alternative quantification method might do the data interpretation for the user more straightforward. Thus, the SCD feature has been left out of the DA Tool and the *System Characteristics Correlation (SCC)* has been used instead.

The SCC matrix can be assembled with equation (3.14), resulting on a symmetric matrix.

$$SCC_{ik} = \frac{\frac{1}{n}\sum_{j=1}^{n} k_{ij}^{0} k_{kj}^{0}}{s_i s_k} \tag{3.14}$$

Where:

- SCC_{ik} Elements of the system characteristic correlation matrix.
- k_{ij}^{0} , k_{kj}^{0} Normalized elements of the sensitivity matrix.
- n Total amount of system characteristics.
- s_i , s_k Standard deviation in the sensitivities.

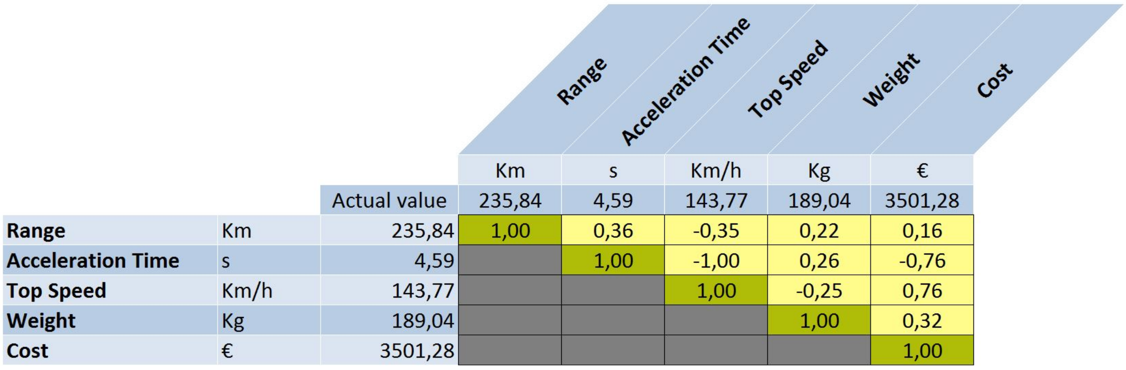
Where s is calculable as:

$$s_i = \sqrt{\frac{1}{n}\sum_{j=1}^{n}(k_{ij}^{0})^2} \tag{3.15}$$

Where:

- k_{ij}^{0} Normalized elements of the sensitivity matrix.
- n Total amount of system characteristics.
- s_i Standard deviation in the sensitivities.

The values of the matrix SCC_{ik} are limited to the $(-1, 1)$ interval. Thus, in this case there is no information regarding the dominant direction of dependency. The correlation measures the angle (cosine) between two row vectors of the sensitivity matrix. Hence, if the correlation is minus one, the vectors are pointing different directions. If it is zero they are orthogonal and if it is one, they are aligned. An example of the *SCC* matrix is shown in the following Figure 3.11.



			Range	Acceleration Time	Top Speed	Weight	Cost
			Km	s	Km/h	Kg	€
		Actual value	235,84	4,59	143,77	189,04	3501,28
Range	Km	235,84	1,00	0,36	-0,35	0,22	0,16
Acceleration Time	s	4,59		1,00	-1,00	0,26	-0,76
Top Speed	Km/h	143,77			1,00	-0,25	0,76
Weight	Kg	189,04				1,00	0,32
Cost	€	3501,28					1,00

Figure 3.11 *SCC matrix example.*

Nonetheless, the DA Tool will make use of the *Adjusted System Characteristics Correlation (ASCC).* With the *ASCC* matrix would be possible for the user to quickly judge how much the system characteristics impact each other. This matrix can be build with the equation below.

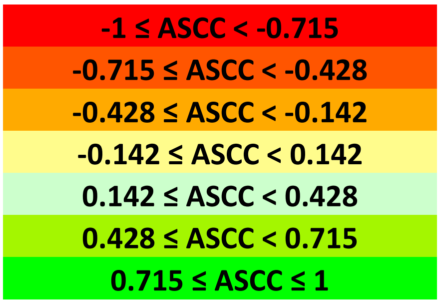
$$ASCC_{ik} = \varphi_i \varphi_k \frac{\frac{1}{n}\sum_{j=1}^{n} k_{ij}^{0} k_{kj}^{0}}{s_i s_k} \tag{3.16}$$

Where:

- $ASCC_{ik}$ Elements of the adjusted system characteristic correlation matrix.
- k_{ij}^{0} , k_{kj}^{0} Normalized elements of the sensitivity matrix.
- n Total amount of system characteristics.
- s_i , s_k Standard deviation in the sensitivities.
- φ_i , φ_k Sign of each system characteristic.

Where s, the standard deviation in the sensitivities, is calculable as mentioned in equation (3.15) and φ is the sign that represents the desire direction of dependency for each of the system characteristic, $\varphi = 1$ if a large value is required and $\varphi = -1$ if a small value is desired.

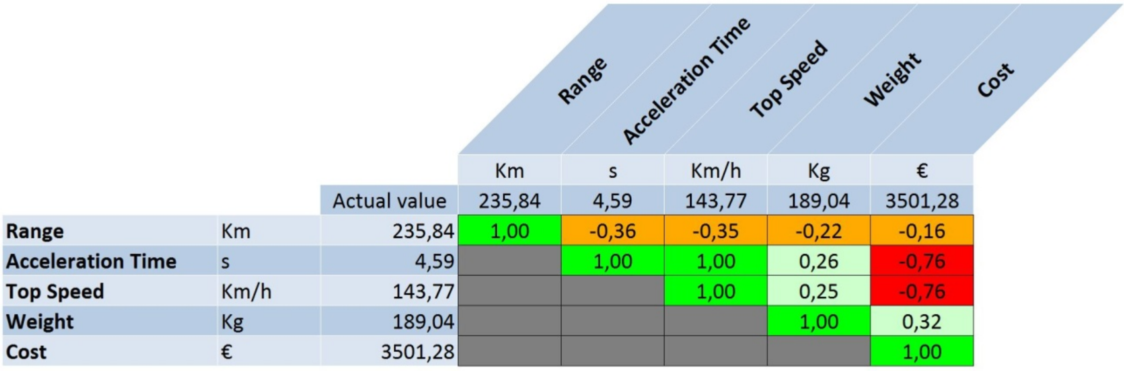
In this case also a symmetric matrix is obtained. Thus, only the upper triangle will be represented in the result worksheet. Additionally, to improve the matrix display colors are assigned following the legend in Figure 3.12, red meaning an unfavorable interaction between the system characteristics, while green means a highly beneficial interaction between them. With the information obtained from the ASCC matrix the DA Tool user should be able to decide which parameters of the model should be changed to achieve the desired goal.



-1 ≤ ASCC < -0.715
-0.715 ≤ ASCC < -0.428
-0.428 ≤ ASCC < -0.142
-0.142 ≤ ASCC < 0.142
0.142 ≤ ASCC < 0.428
0.428 ≤ ASCC < 0.715
0.715 ≤ ASCC ≤ 1

Figure 3.12 *Color legend for the ASCC matrix.*

For instance, pressing the button *System Charact. Correlation* at the *MAIN* worksheet in the EV model, for the given data, will show the results in Figure 3.13.



			Range	Acceleration Time	Top Speed	Weight	Cost
			Km	s	Km/h	Kg	€
		Actual value	235,84	4,59	143,77	189,04	3501,28
Range	Km	235,84	1,00	-0,36	-0,35	-0,22	-0,16
Acceleration Time	s	4,59		1,00	1,00	0,26	-0,76
Top Speed	Km/h	143,77			1,00	0,25	-0,76
Weight	Kg	189,04				1,00	0,32
Cost	€	3501,28					1,00

Figure 3.13 *Adjusted system characteristics correlation matrix example.*

The interpretation of these results is done looking to the matrix row by row. From this analysis it can be concluded which characteristics are in conflict and in which way does the change on one of the requirements affect the other characteristics of the design.

3.5 Optimization

The design process, of any engineering project, is an interactive feedback process where its performance is compared to the given specifications. This used to be a manual process where the design engineer made a prototype which was tested and modified until reaching an adequate performance.

However, this changed with the introduction of the optimization methods helped by powerful computers. Once the system layout is established, it is possible to use an optimization strategy and a simulation model of the system to achieve this goal. Generally, the number of parameters in a system is too large to be handled successfully using a numerical optimization. That is why the performance parameters that uniquely define the system have to be identified. This set of performance parameters is what it has been called the major design parameters [7]. They are a few compared to the total number of parameters in the design project. Thus, the optimization process is reduced to a more realistic proportions and the optimization of a rather complex system can be achieved.

Basically, optimization methods, used in the engineering field, can be classified into two different families. The gradient method is widely used and suitable for problems where the gradient of the functions can be calculated explicitly at each point. These are the unconstrained problems with linear functions. For instance, they can be found in many structure optimization applications, the most well known is the *Simplex* method by Spendley [10] and J. A. Nelder & R. Mead [11].

Moreover, the other group is formed by the non-gradient methods, direct-search methods, since gradient information may not be available, consequently of a more general use. These methods are extremely effective when solving non-linear functions of several variables within a constrained region, which usually is the kind of problem an engineer has to face, when modelling a new product. Therefore, the optimization feature of this DA Tool makes use of one of this method for multivariable non-linear equations.

In first instance it was considered the implementation of the *Complex* optimization method, a modification of *Simplex*, developed by M. J. Box [12] in 1965, which is the one Petter Krus has used in many of his works, such as the optimization of hydraulic systems [1] and the optimization of systems designs [13]. Actually, it is a wildly spread method in many engineering areas [14] [15] [16]. Nonetheless, the obtained results were not as satisfactory as expected. Therefore it was decided the implementation of another method.

Considering that the DA Tool was been developed on an Excel environment it was decided to make use of one of the advance built-in features this software provides, the *Solver* tool. The Microsoft Excel *Solver* tool uses the Generalized Reduced Gradient, GRG2, non-linear optimization code developed in 1975 by Leon Lasdon, University of Texas at Austin, and Allan Waren, Cleveland State University, [17]. Thus, with the assistant of this feature an algorithm suitable for the optimization problems this DA Tool faces was developed.

3.5.1 Optimization algorithm

The optimization algorithm has been implemented in the code of the DA Tool, via VBA procedure, so that the user will only have to click one button at the *MAIN* worksheet and the computer will perform the require amount of operations obtaining the optimum major design parameters values as an output in order the system characteristics to fulfil the system requirements.

This optimization process can be defined as a multivariable constrained optimization problem. Thus, the problem is to maximize the system characteristics functions of the form:

$$f_j(x_1, x_2, \dots x_n)\,, \qquad j = 1,2 \dots m \tag{3.17}$$

Where m is the amount of system requirements involved in the model. Subjected to $2n$ constraints, where n is the amount of design parameters of the model, of the form:

$$g_i \leq x_i \leq h_i\,, \qquad i = 1,2, \dots n \tag{3.18}$$

Where the implicit variables, $x_{n+1}, \dots x_m$ are dependent functions of $x_1, x_2, \dots x_n$. For, design, $x_1, x_2, \dots x_n$ are the design parameters X_{DP} and the dependent functions $x_{n+1}, \dots x_m$ are a subset of the vector of the system characteristics Y_{SC}. The lower and upper constraints g_i and h_i are either constants or functions of $x_1, x_2, \dots x_n$.

Thus, the objective is to simultaneously find the values $x_1, x_2, \dots x_n$ of the design parameters that satisfying the constrains $g_i \leq x_i \leq h_i$ $(i = 1,2, \dots n)$, called upper and lower limit at the DA Tool, accomplish the system characteristics equations $f(x_1, x_2, \dots x_n)$ to reach the targeted values y_j, but taking into consideration the weight w_j that it has been assigned to each system characteristic $f(x_1, x_2, \dots x_n)$.

The *Solver* function is only capable of optimizing one multivariable function subjected to a large number of constraints following the GRG2 method, which uses quadratic estimations. Therefore, since the mechanical models analyzed by the DA Tool have several equations, the developed optimization algorithm has to form a master equation involving all the system characteristics equations and their corresponding weight. This can be accomplishing with the following equation:

$$M(f_j) = \sum_{j=1}^{m} f_j(x_1, x_2, \dots x_n) w_j \tag{3.19}$$

Where:

- $M(f_j)$ Master equation relating all the system characteristics functions.
- $f_j(x_1, x_2, \dots x_n)$ Function of the system characteristics.
- w_j Weight of the system characteristic within the design.
- m Total amount of system characteristics j.

Thus, the equation (3.19) is the one *Solver* function will optimize making it as equally possible to a global target value T that can be calculated as:

$$T = \sum_{j=1}^{m} y_j w_j \tag{3.20}$$

Where:

- T Global target value for *Solver* to achieve.
- y_j Target value for the system characteristics.
- w_j Weight of the system characteristic within the design.
- m Total amount of system characteristics.

There are also the constraints determined by assigned *Sign* φ_j to each system characteristic $f_j(x_1, x_2, \dots x_n)$. Thus:

$$\begin{cases} f_j(x_1, x_2, \dots x_n) \leq y_j \,, & if \;\; \varphi_j = -1 \\ f_j(x_1, x_2, \dots x_n) \geq y_j \,, & if \;\; \varphi_j = +1 \end{cases}; \;\; j = 1,2 \dots m \tag{3.21}$$

Where:

- $f_j(x_1, x_2, \dots x_n)$ Function of the system characteristics.
- y_j Targeted value for each system characteristic.
- φ_j Sign assigned to each system characteristic.
- m Total amount of system characteristics.

Finally, the optimization problem the *Solver* function will solve is:

$$M(f_j) = T \tag{3.22}$$

Subjected to the constraints:

$$g_i \leq x_i \leq h_i \,, \qquad i = 1,2, \dots n \tag{3.23}$$

$$\begin{cases} f_j(x_1, x_2, \dots x_n) \leq y_j \,, & if \;\; \varphi_j = -1 \\ f_j(x_1, x_2, \dots x_n) \geq y_j \,, & if \;\; \varphi_j = +1 \end{cases}; \;\; j = 1,2 \dots m \tag{3.24}$$

The optimization function *Solver* has several configuration options from which three could be considered the most important ones; maximum number of iterations, precision and tolerance %. In fact, these are the options the user will be able to set at the *MAIN* worksheet. The first one, maximum number of iterations, represents the limit of times the problem would be solve, the default value is set to 200, which should be enough for medium size problems. The second one is a number between 0 and 1 that specifies the degree of precision to be used in solving the problem, the default precision is set to 0.01. The closer the number is to cero the higher the precision. Generally, the higher the degree of precision specified the more time *Solver* will take to reach solutions. The last option, tolerance %, applies to the defined constraints on the problem. Represents the percentage of error allowed in the optimal solution when a constraint is used on any element of the problem. A higher degree of tolerance would speed up the solution process. This value should be between 1% and 12%, and it is set by default to 10%.

The optimization process is almost instantaneous; it does not usually take more than two seconds. This measurement has been performance with an Intel Core 2 Duo CPU @ 3,00GHz with Excel's screen-updating feature disabled. Of course it will vary depending in the complexity of the problem and the amount of equations.

4. PRACTICAL CASES

In this chapter three example models are going to be presented. They will be analyze and optimize with the developed DA Tool, the result will be discussed in detail. First of all, as an introduction to how to interpret the results a very simple model is going to be analyzed, a parabolic shot. The second example to be analyzed will be the portable motion platform built in TUT. After, it will be the turn of the electric vehicle model.

The first step, given the system requirements, is to build a model, determine its equations. A model could be considered as a large set of equations, variables and constants that define a product or device. Once identified all the involved parameters, they should be classified in system characteristics, fixed parameters and major design parameters, being these last the most significant variables. Building low-fidelity models for a small to medium size project takes around one day, a significant reduction when compared to high-fidelity approaches.

The next step is the introduction of all the data (parameters, characteristics, programmed equations…) into a new project in the DA Tool, this process could take around 15-20 minutes. Finally everything is ready for the analysis and the optimization process to begin.

4.1 Parabolic shot

A parabolic shot is a simple example whose model has few equations, therefore a very interesting approach on how to use the DA Tool and interpret the results.

Model

In this problem, represented in Figure 4.1, an object is shot from origin of the Cartesians axes with an initial velocity of V_0 and a certain angle θ. Subjected only to the gravitational force g. The model variables and equations are shown below.

System characteristics:

- Range
- Maximum Height

Design parameters, variables;

- Initial velocity V_o (m/s)
- Shot angle θ $(degrees)$

Fixed parameters:

- Gravity $g = 9{,}81\ m/s^2$

Equations:

- $Range = \frac{V_o{}^2 \sin(\theta)}{g}\ (m)$
- $Maximum\ Height = \frac{V_o{}^2 \sin(\theta)^2}{2g}\ (m)$

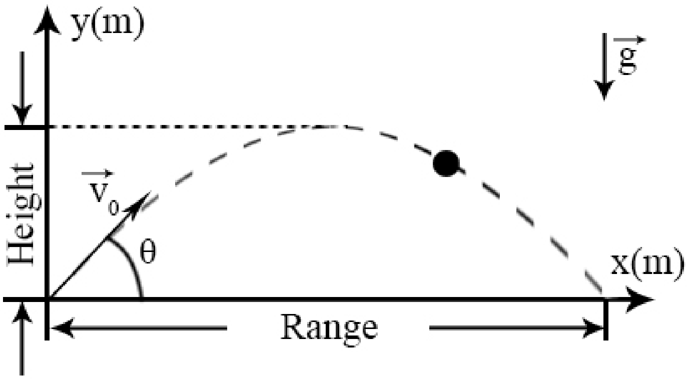


Figure 4.1 *Parabolic shot.*

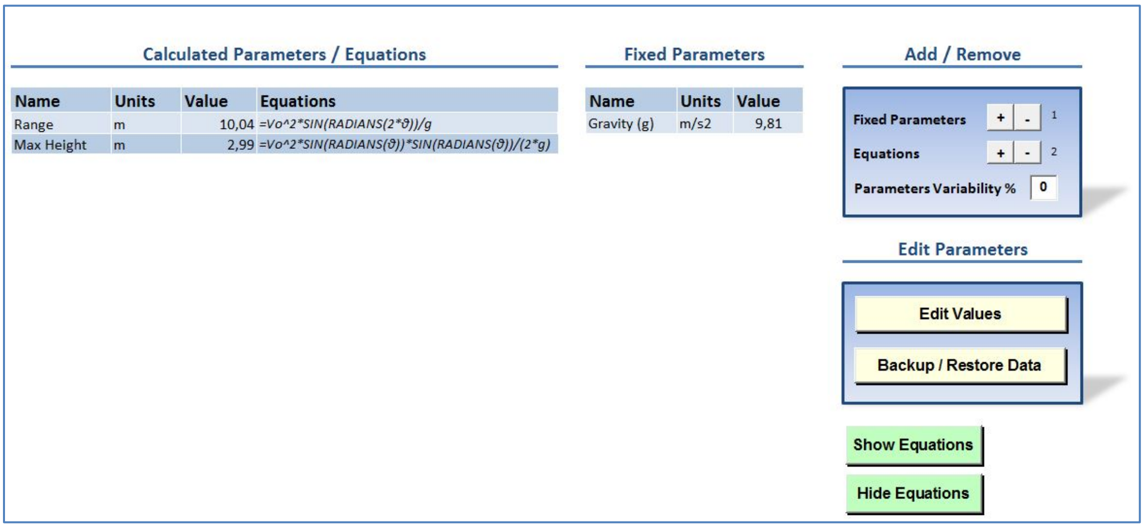
The constraints for this problem are:

- $0 \leq V_o \leq 50$
- $0 \leq \theta \leq 90$

While the targeted values for the system requirements are:

- $Range \geq 100\ m$
- $Max\ Height \geq 15\ m$

Thus, this model is imported into the DA Tool. Below in Figure 4.2 and Figure 4.3 are shown two screenshots of the *MODEL* worksheet and *MAIN* window.

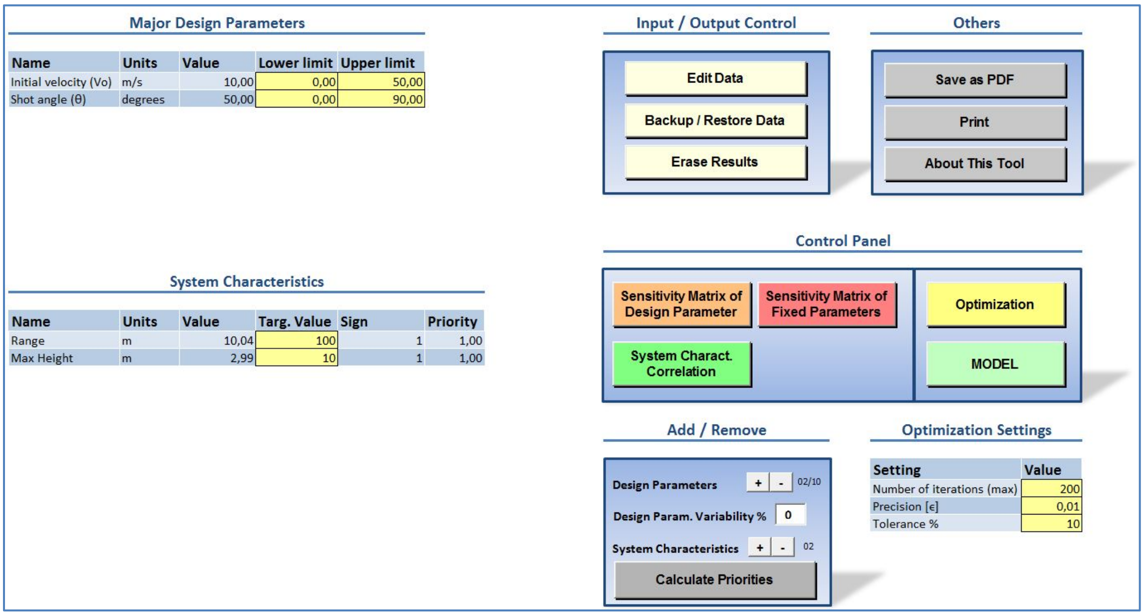


Name	Units	Value	Equations
Range	m	10,04	*=Vo^2*SIN(RADIANS(2*ϑ))/g*
Max Height	m	2,99	*=Vo^2*SIN(RADIANS(ϑ))*SIN(RADIANS(ϑ))/(2*g)*

Name	Units	Value
Gravity (g)	m/s2	9,81

Fixed Parameters 1
Equations 2
Parameters Variability % 0

Figure 4.2 *MODEL worksheet for the parabolic shot problem.*



Name	Units	Value	Lower limit	Upper limit
Initial velocity (Vo)	m/s	10,00	0,00	50,00
Shot angle (θ)	degrees	50,00	0,00	90,00

Name	Units	Value	Targ. Value	Sign	Priority
Range	m	10,04	100	1	1,00
Max Height	m	2,99	10	1	1,00

Design Parameters 02/10
Design Param. Variability % 0
System Characteristics 02

Setting	Value
Number of iterations (max)	200
Precision [ϵ]	0,01
Tolerance %	10

Figure 4.3 *MAIN worksheet for the parabolic shot problem.*

Analysis and optimization

Thus the tables of the major design parameters and system characteristics will look like in Table 4.1 and Table 4.2.

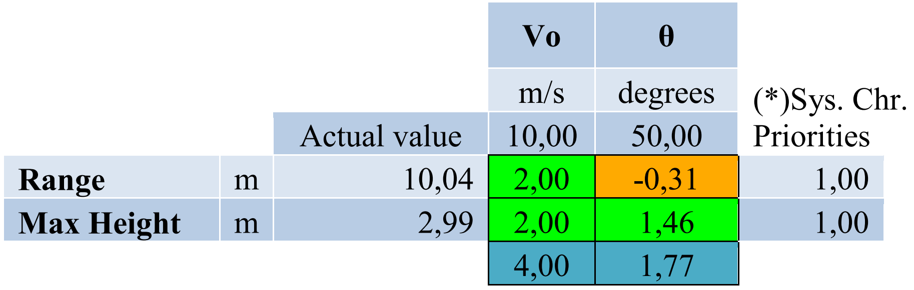
Table 4.1 *Variables of the parabolic shot problem.*

Major Design Parameters				
Name	**Units**	**Value**	**Lower limit**	**Upper limit**
Initial velocity (Vo)	m/s	10,00	0,00	50,00
Shot angle (θ)	degrees	50,00	0,00	90,00

Table 4.2 *Characteristics of the parabolic shot problem.*

System Characteristics					
Name	**Units**	**Value**	**Targ. Value**	**Sign**	**Priority**
Range	m	100,00	100	1	1,00
Max Height	m	15,00	15	1	1,00

The results for the sensitivity analysis for this situation are shown in the figure below.

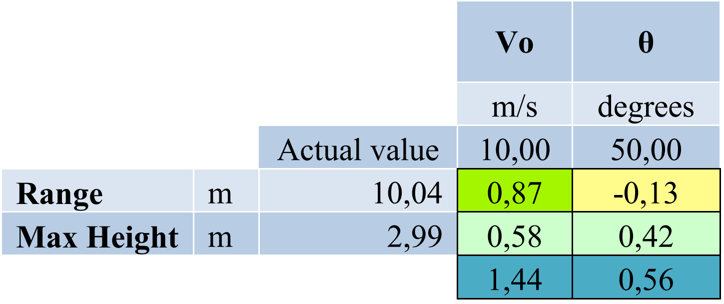


			Vo	**θ**	
			m/s	degrees	(*)Sys. Chr. Priorities
		Actual value	10,00	50,00	
Range	m	10,04	2,00	-0,31	1,00
Max Height	m	2,99	2,00	1,46	1,00
			4,00	1,77	

(*)System Design Parameter Priorities

Figure 4.4 *Normalized sensitivity matrix of the variables for the parabolic shot problem.*

As explained before in chapter 3.3 these tables show how much the system characteristics change when the design parameters are modified in one percent. Taking into consideration the signs and the colors of the values (color legend in Figure 3.7) it is acknowledgeable if these values vary in the interest of the model or not. Both the normalized sensitivity matrix and the relative one, in Figure 4.5, express the same information, although the second one gives a better overview, since the sum of the elements of each row is one, giving a better view of the relative importance of each system parameter. Analyzing these results it can be concluded which of variables of the problem affects to a greater degree to each of the system requirements.



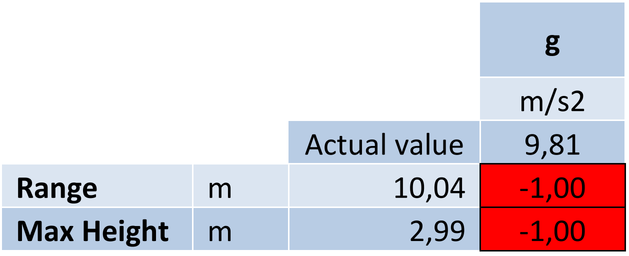
			Vo	**θ**
			m/s	degrees
		Actual value	10,00	50,00
Range	m	10,04	0,87	-0,13
Max Height	m	2,99	0,58	0,42
			1,44	0,56

(*)System Design Parameter Priorities

Figure 4.5 *Relative sensitivity matrix of the variables for the parabolic shot problem.*

Thus, in the case of the shot angle θ it can be seen that increasing it would have a negative impact on the range. From the normalized sensitivity table it is known that a 1% increase in θ will lead to a 0,31% decrease on the range, making the objective of reaching the 100 m more difficult. It is obvious that for a given shot velocity if the angle of the shot is increased the range will be shorter. On the other hand, this increase on the angle θ will have an extremely positive impact on the maximum height, a 1,46% per 1% increase, as expected. The second variable V_o has a good impact over both of the requirements, a 2%. Meaning that increasing the variable value in 1% both requirements would increase a 2% towards the targeted value. Examining the last row of both matrixes it can be concluded that the initial velocity is a more critical parameter than the shot angle (4,00 to 1,77). Considering the relative sensitivity matrix row by row it can be concluded that for the range the initial velocity has a greater influence than the shot angle, whereas in from the second row it can be seen that both variables affect more or less to the same extent.

The results for the sensitivity analysis of the fixed parameters do not have much interest in this problem since there is only one. The results interpretation would follow the same technique that the one with the previous matrixes of design parameters. Anyway it is shown in the figure below.

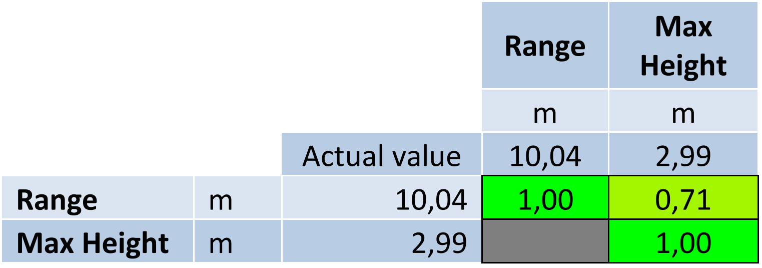


			g
			m/s2
		Actual value	9,81
Range	m	10,04	-1,00
Max Height	m	2,99	-1,00

Figure 4.6 *Normalized sensitivity matrix of the fixed parameters for the parabolic shot problem.*

As expected an increase on the gravitational force would lead to shorter range and lower shots.

Furthermore, the results for the characteristics correlation analysis are presented in the figure below.



			Range	Max Height
			m	m
		Actual value	10,04	2,99
Range	m	10,04	1,00	0,71
Max Height	m	2,99		1,00

Figure 4.7 *Adjusted system characteristics correlation matrix for the parabolic shot problem.*

This symmetric matrix should be examined row by row to acknowledge how much influence each requirements has over the others. In this concrete situation of the parabolic shot problem, the gain in any of the two characteristics will result in a gain of almost the same quantity in the other.

At this point, it is have a great overview for the model concerned. The initial velocity has been identified as the critical parameter and it has been seen that both requirements have a very close and reciprocal behavior.

It would be time now to check if this model can fulfill the targeted requirements making use of the optimization feature of the DA Tool. Thus the optimization algorithm is run with the default settings resulting in the following solutions.

Table 4.3 *Optimized variables in the problem of the parabolic shot.*

		Values	
Name	**Units**	**New**	**Previous**
Vo	m/s	37,72	10,00
θ	degrees	21,80	50,00

Table 4.4 *New values for the system characteristics consequence of the optimized variables in the problem of the parabolic shot.*

		Values			
Name	**Units**	**New**	**Previous**	**Targeted**	**error %**
Range	m	100,00	10,04	100	0,00
Max Height	m	10,00	2,99	10	0,00

From the Table 4.4 it is seen that the new values for the variables V_o and θ displayed in Table 4.3 make possible the fulfillment of the targeted requirements with a 0% error.

Anyway, a 0% error optimization with complex models is not usually possible to be achieved. In these situations, when a perfect optimization is not reached, the values of the requirements will vary from the targeted ones in the beneficial direction for the design, indicated by the sign stored at the table of system characteristics. In the situation that the requirements are not met, the values of the characteristics will be as closer as the equations let them to the targeted ones.

4.2 Portable motion platform design

Detailed below are the analysis and the optimization results of a low-fidelity model of the portable motion platform that was build at Tampere University of Technology (TUT), previously shown in Figure 3.3. This portable motion platform was designed to be used in Virtual Environment, since this kind of devices could be really useful when training operators on how to handle complex industrial mobile machines [9].

Model

This 6 degrees of freedom (DOF) motion platform, driven by pneumatic actuators, principal requirements according to [6] where:

- the platform needs to be portable so that at least two men can move and transport it
- the platform needs to be low that it does not limit visibility in the simulator
- the platform needs to small enough to fit inside the Virtual Environment
- the platform needs to perform certain acceleration in the vertical (Y) direction
- the platform needs to perform certain acceleration in the horizontal (X) direction
- the platform needs to perform certain inclination

Therefore a low-fidelity model was developed within 7 hours [6]. The model consists of five system requirements:

- a_y vertical acceleration (m/s^2)
- a_x horizontal acceleration (m/s^2)
- p pressure of the actuators (bar)
- ω inclination of the platform ($degrees$)
- V volume occupied by the platform (m^3)

Which are determined by three major design parameters:

- R radius of the actuators joints in the motion platform (m)
- r radius of the actuators joints in the structure (m)
- h distance of the actuators joints in the vertical direction (m)

The model was built with 26 equations including the five equations that determine the system characteristics values [6]. These equations are listed in the table below.

Table 4.5 *Equations for the EV model.*

Parameter	Equation
h	=h_Lower
l	=SQRT(h_Lower^2+s_Small^2)
Cos alpha	=s_Small/l_Lower
Tan alpha	=h_Lower/s_Small
Sin alpha	=h_Lower/l_Lower
h	=SQRT(l_Medium^2-s_Small^2)
l	=0.5*(l_Lower+l_Upper)
Cos alpha	=s_Small/l_Medium
Tan alpha	=h_Medium/s_Small
Sin alpha	=h_Medium/l_Medium
h	=SQRT(l_Upper^2-s_Small^2)
l	=MAX(0.8*l_Lower,s_Small)
cos alpha	=s_Small/l_Upper
tan alpha	=h_Upper/s_Small
Sin alpha	=h_Upper/l_Upper
Angle of Inclination (Rad)	=(h_Lower-(SinAlpha_Upper*l_Upper))/(R_Big+r_Small)
Angle of Inclination	=ATAN(TanGamma_rad)*(180/PI())
s	*=SQRT(r_Small^2+R_Big^2-2*r_Small*R_Big*COS(PI()/3))*
Alpha Upper	=ACOS(CosAlpha_Upper)
Required Force for Equilibrium	*=((m_Small*9.81)/6)/SinAlpha_Medium*
Required Pressure for Equilibrium	=(f_Initial+300)/625
a_y	=((6*F_Big*SinAlpha_Medium)-(m_Small*9,81))/m_Small
a_x	=((2*F_Big*CosAlpha_Medium))/m_Small
p	=p_initial
ω	=TanGamma
V	=PI()*(MAX(R_Big; r_Small))^2*h_Lower

Three fixed parameters were needed for the equation; platform weight m, force of the actuators F and pressure increase in the actuators Δp.

Listed below in Table 4.6 and Table 4.7 are the values used and calculated in the analysis of this model.

Table 4.6 *Equations for the portable motion platform design.*

Calculated Parameters / Equations			
Name	**Units**	**Value**	
h	m	0,700	**Down**
l	m	1,140	
Cos alpha	-	0,789	
Tan alpha	-	0,778	
Sin alpha	-	0,614	
h	m	0,493	**Middle**
l	m	1,026	
Cos alpha	-	0,877	
Tan alpha	-	0,548	
Sin alpha	-	0,480	
h	m	0,148	**Up**
l	m	0,912	
cos alpha	-	0,987	
tan alpha	-	0,165	
sin alpha	-	0,163	
Angle of Inclination	Rad	0,306	**Angle**
Angle of Inclination	Degrees	17,04	
s	m	0,900	
Alpha Upper	Rad	0,163	
Required Force for Equilibrium	N	680,70	
Required Pressure for Equilibrium	bar	1,57	

Table 4.7 *Fixed parameters for the portable motion platform design.*

Fixed Parameters		
Name	**Units**	**Value**
m	Kg	200,00
F	N	1293,20
Δp	-	0,50

The major design parameters were subjected to the following constraints:

- $0{,}50 \leq R \leq 1{,}30\ (m)$
- $0{,}50 \leq r \leq 1{,}30\ (m)$
- $0{,}50 \leq h \leq 0{,}90\ (m)$

While the targeted values for the system characteristics were:

- $a_y \geq 7\ m/s^2$
- $a_x \geq 13\ m/s^2$
- $p \leq 2\ bar$
- $\omega \geq 17\ degrees$
- $V \leq 2\ m^3$

For the calculations a 0% variability was set for both the design parameters and fixed parameters. The same priority has been assigned to all the system characteristics, since it was decided that they are all equally important in this model.

Analysis and optimization

Introducing the model information into the DA Tool the table of design parameters will look like the one below, while one for the system characteristics is presented Table 4.9

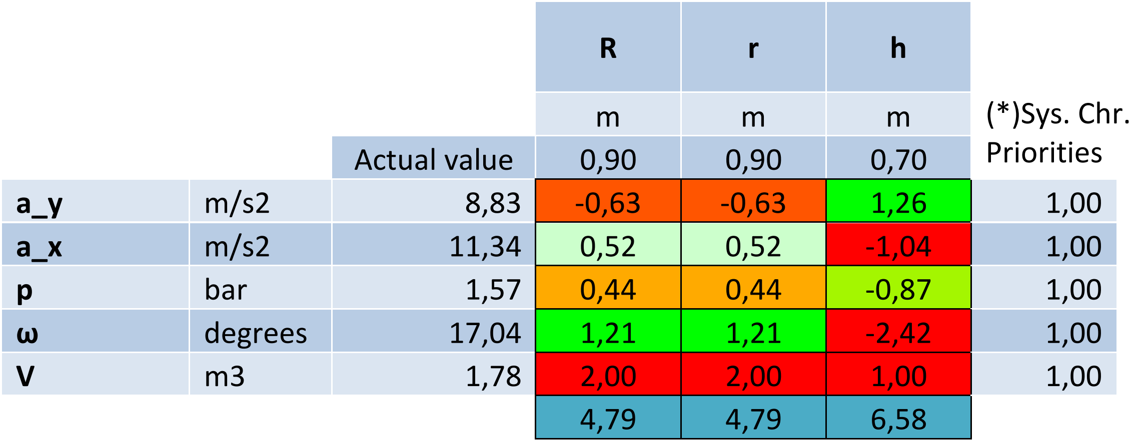
Table 4.8 *Design parameters of the portable motion platform design.*

Major Design Parameters				
Name	**Units**	**Value**	**Lower limit**	**Upper limit**
R	m	0,90	0,50	1,30
r	m	0,90	0,50	1,30
h	m	0,70	0,50	0,90

Table 4.9 *System characteristics of the portable motion platform design.*

System Characteristics					
Name	**Units**	**Value**	**Targ. Value**	**Sign**	**Priority**
a_y	m/s2	8,83	7	1	1,00
a_x	m/s2	11,34	17	1	1,00
p	bar	1,57	3	-1	1,00
ω	degrees	17,04	10	1	1,00
V	m3	1,78	2	-1	1,00

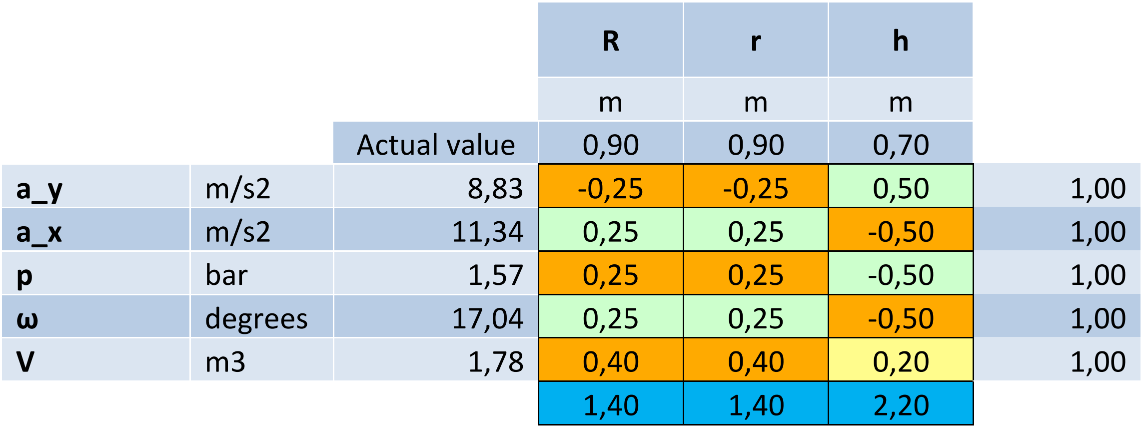
In Figure 4.8 and Figure 4.9 the result for sensitivity analysis of the design parameters results are displayed.



			R	r	h	
			m	m	m	(*)Sys. Chr. Priorities
		Actual value	0,90	0,90	0,70	
a_y	m/s2	8,83	-0,63	-0,63	1,26	1,00
a_x	m/s2	11,34	0,52	0,52	-1,04	1,00
p	bar	1,57	0,44	0,44	-0,87	1,00
ω	degrees	17,04	1,21	1,21	-2,42	1,00
V	m3	1,78	2,00	2,00	1,00	1,00
			4,79	4,79	6,58	

(*)System Design Parameter Priorities

Figure 4.8 *Normalized sensitivity matrix of the design parameters for the portable motion platform design.*



			R	r	h	
			m	m	m	
		Actual value	0,90	0,90	0,70	
a_y	m/s2	8,83	-0,25	-0,25	0,50	1,00
a_x	m/s2	11,34	0,25	0,25	-0,50	1,00
p	bar	1,57	0,25	0,25	-0,50	1,00
ω	degrees	17,04	0,25	0,25	-0,50	1,00
V	m3	1,78	0,40	0,40	0,20	1,00
			1,40	1,40	2,20	

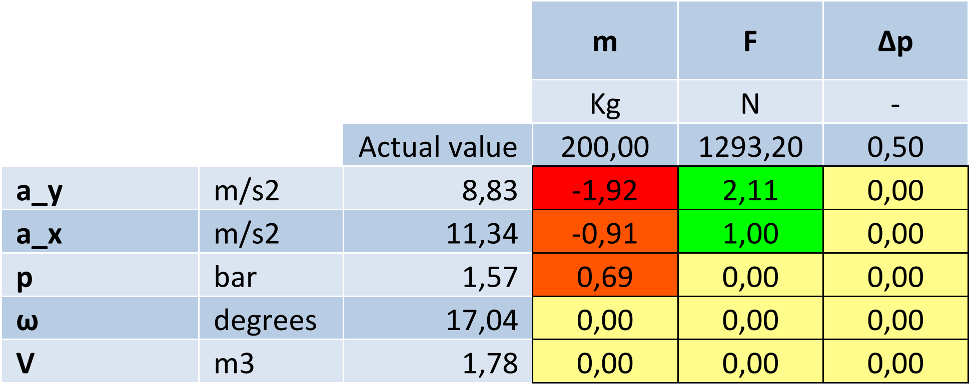
Figure 4.9 *Relative sensitivity matrix of the design parameters for the motion platform design.*

From the last row of the normalized sensitivity matrix it is concluded that h, distance of the actuator joints in the vertical direction, is the most critical parameter, while R and r are equally important, both of them with a priority of 4,79. In fact, it is noticeable that the modification of these two parameters impacts in the same amount the system characteristics.

The increase of the radiuses R and r is beneficial for the characteristics; horizontal acceleration a_x and the maximum inclination ω, making them grow a 0,52% and 1,21% respectively per 1% increase of the design parameter. On the other hand, there are three characteristics that are harmed by these modifications; vertical acceleration a_y decreases in 0,63%, the pressure of the actuator increases in 0,44%, while there is a drastic 2% increase of occupied volume *V*. So it can be stated that the increase of these two parameters does more harm than good. In the case of the design parameter *h* it is also clear that the model faces the same situation, the growth of the parameter damages the design.

Thus, from the sensitivity analysis of the design parameters can be concluded that decreasing the value of all three design parameters variables would be in the benefit of the design, improving the portable motion platform performance.

In the case of the fixed parameters the results are displayed in the following Figure 4.10.



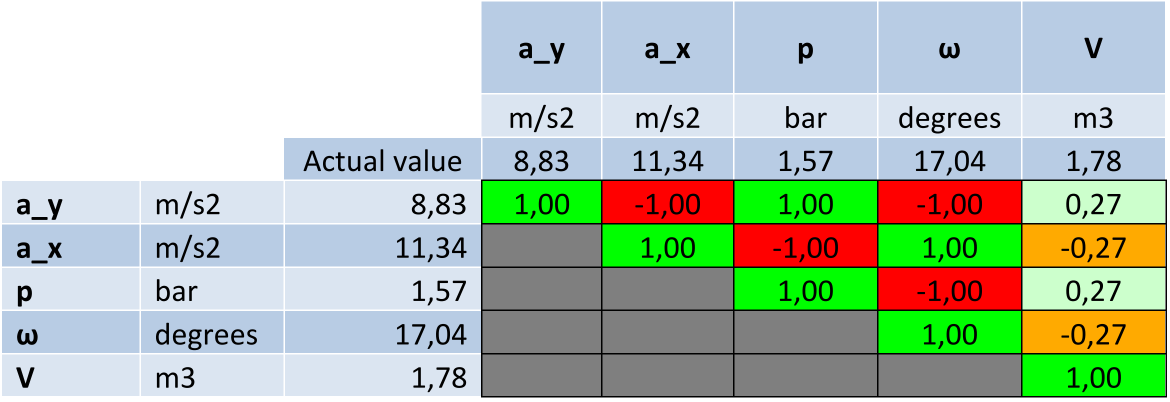
			m	**F**	**Δp**
			Kg	N	-
		Actual value	200,00	1293,20	0,50
a_y	m/s2	8,83	-1,92	2,11	0,00
a_x	m/s2	11,34	-0,91	1,00	0,00
p	bar	1,57	0,69	0,00	0,00
ω	degrees	17,04	0,00	0,00	0,00
V	m3	1,78	0,00	0,00	0,00

Figure 4.10 *Normalized sensitivity matrix of the fixed parameters for the portable motion platform design.*

The pressure increase *Δp*, does not affect any of the system characteristics. The gain of force *F* has a favorable impact over both accelerations, the vertical and horizontal one. However, the mass m is critical parameter since its increase significantly impairs three of the system characteristics, the vertical acceleration a_y above all.

Therefore, the ideal modifications for the fixed parameters would be the reduction of the platform weight m, for instance using lighter materials, and the increase of the actuators force, using more powerful ones if there were room in our budget.

From the following Figure 4.11, it can be seen the ASCC matrix for the motion platform design, it is possible to deduce the impact each system characteristics has over the others.



			a_y	a_x	p	ω	V
			m/s2	m/s2	bar	degrees	m3
		Actual value	8,83	11,34	1,57	17,04	1,78
a_y	m/s2	8,83	1,00	-1,00	1,00	-1,00	0,27
a_x	m/s2	11,34		1,00	-1,00	1,00	-0,27
p	bar	1,57			1,00	-1,00	0,27
ω	degrees	17,04				1,00	-0,27
V	m3	1,78					1,00

Figure 4.11 *ASCC matrix of the motion platform design.*

This information of this matrix states that the volume V is the less critical characteristic, while among the others there is almost equilibrium. For instance, a beneficial modification of the vertical acceleration a_y will have a positive impact on the pressure p, but it would have a negative impact of the same amount on the horizontal acceleration a_x as well as on ω. Taking into consideration V, the impact of the modification slightly benefits the design.

Briefly, in the interest of the design would be finding a balance between the increase of vertical acceleration, pressure and volume while decreasing horizontal acceleration and the inclination characteristic.

With all the gathered information from the previously analysis is the moment for optimization process to check whether is possible to improve the design of the platform. The results of this process are shown in Table 4.10. For these calculations the default settings were used.

Table 4.10 *Optimization results for the platform model.*

		Values	
Name	**Units**	**New**	**Previous**
R	m	0,66	0,90
r	m	0,66	0,90
h	m	0,50	0,70

As previously deduce after the optimization the value of all the design parameters has been reduced. Following, in Table 4.11 the new system characteristics values are presented.

Table 4.11 *New values for the system characteristics consequence of the optimized variables in the portable motion platform design.*

		Values			
Name	**Units**	**New**	**Previous**	**Targeted**	**error %**
a_y	m/s2	8,08	8,83	7	15,40
a_x	m/s2	11,48	11,34	13	11,73
p	bar	1,61	1,57	2	19,26
ω	degrees	19,16	17,04	17	12,69
V	m3	0,67	1,78	2	66,34

Although, the horizontal acceleration a_x differs from the targeted value in 11,73%, all the other requirements are satisfied and the targeted values exceeded in benefit of the design, as it can be seen from the table above.

From the analyses results can be concluded that new design is quite accurate and satisfactory. Although, it would be possible to improve it, for instance varying some parameter of the design, which could be deduced from another sensitivity analysis, or just by giving a greater weight to the a_x characteristic.

4.3 Electric vehicle design

In this chapter a low-fidelity model of an electric vehicle prototype is going to analyze and modify according to the obtained results to meet some given requirements.

Model

This simple EV model, consisting in only 19 equations, focuses the attention into the performance of the batteries and their impact in the design. Thus, from the model the following five parameters were identified as system requirements:

- $Range\ (Km)$
- $Acceleration\ time\ (s)$
- $Top\ speed\ (Km/h)$
- $Weight\ (kg)$
- $Cost\ (€)$

On the other hand, it was concluded that the most representative variables of the EV model that determine more accurately the design, are the following three design parameters:

- $Motor\ power\ (W)$
- $Battery\ weight\ (kg)$
- $Chassis\ weight\ (kg)$

Listed below and following the Excel's notation, the 19 equations, including the 5 system requirement formulas, can be consulted.

- Motor Weight = Motor_Power/Motor_Specific_Power
- Total Weight = Chassis_Weight+Motor_Weight+Battery_Weight
- Total Weight (Driver) = Total_Weight+Driver_Weight
- Cruise Speed = 1000/3600*Cruise_Speed
- Motor Cost = 0.07*Motor_Power*1.4
- CdA = CdA0*(Total_Weight/180)^(0.67)
- Power Required Cruise = (CdA*1.25*(Cruise_Speed_ms)^3)/(2*Motor_Efficiency*Battery _Efficiency)
- Battery Capacity = Battery_Energy_Density*Battery_Weight
- Battery Power = Battery_Power_Density*Battery_Weight
- Available Power = MIN(Battery_Power,(Motor_Power*Motor_Efficiency))
- Battery Cost = Battery_Capacity*Battery_Spec_Cost
- Energy Running Cost = (Energy_Cost*Power_Required_Cruise)/(3600*Cruise_Speed_ms)
- Battery Running Cost = (1000*Power_Required_Cruise)/(3600*Cruise_Speed_ms)*(Battery_Spec_Cost /Battery_no_of_Cycles)
- Running Cost = Energy_Running_Cost+Battery_Running_Cost

- Range = 3,6*Cruise_Speed*Battery_Capacity/Power_Required_Cruise
- Acceleration Time = Total_Weight_Driver_Incl*(100/3,6)^2/(2*Available_Power)
- Top Speed = 3,6*1,25992*(Available_Power/(CdA*1,25))^(1/3)
- Weight = Chassis_Weight+Total_Weight
- Cost = Battery_Cost+Motor_Cost+Chassis_Cost

For the calculations the following 14 fixed parameters were used; Motor Specific Power, Motor Efficiency, Max Safety Weight, Battery Spec. Cost, Battery Energy Density, Battery Power Density, Battery Efficiency, Battery no of Cycles, CdA0, Target Handling Weight, Driver Weight, Cruise Speed, Energy Cost, Chassis Cost.

Below are presented the values used for the analysis of this example. The major design parameters were subjected to the following constraints:

- $10 \leq Motor\ power \leq 60\ (kW)$
- $50 \leq Battery\ weight \leq 150\ (Kg)$
- $70 \leq Chassis\ weight \leq 200\ (kg)$

While the targeted values for the system requirements were:

- $Range \geq 200\ km$
- $Acceleration\ time \leq 4\ s$
- $Top\ speed \geq 170\ km/h$
- $Weight \leq 400\ kg$
- $Cost \leq 7000$ €

Listed below are the fixed parameters values used for the analysis.

Table 4.12 *Used fixed parameters values.*

Fixed Parameters		
Name	**Units**	**Value**
Motor Specific Power	W/kg	1000
Motor Efficiency	-	0,90
Max Safety Weight	Kg	20
Battery Spec. Cost	€/Wh	0,25
Battery Energy Density	Wh/Kg	35
Battery Power Density	W/kg	300,00
Battery Efficiency	-	0,86
Battery no of Cycles	-	1000
CdA0	m2	0,55
Target Handling Weight	Kg	180
Driver Weight	Kg	80
Cruise Speed	Km/h	90
Energy Cost	€/Wh	0,10
Chassis Cost	€	1000

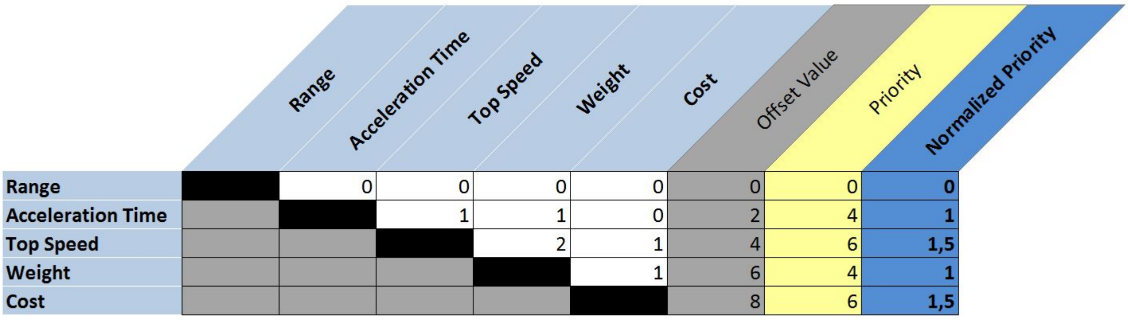
Driven by the equations the values for the other characteristics are the ones presented in Table 4.13.

Table 4.13 *Calculated parameters values.*

Calculated Parameters / Equations		
Name	**Units**	**Value**
Motor Weight	Kg	55,00
Total Weight	Kg	290,00
Total Weight (Driver Incl.)	Kg	370,00
Cruise Speed	m/s	25,00
Motor Cost	€	5390,00
CdA	-	0,76
Power Required Cruise	-	9500,81
§Battery Capacity	Wh	4200,00
Battery Power	Wh	36000,00
Available Power	Wh	36000,00
Battery Cost	€	1050,00
Energy Running Cost	€/Km	0,01056
Battery Running Cost	€/Km	0,02639
Running Cost	€/km	0,03695

Analysis and optimization

The EV model is imported into the DA Tool and the priorities assigned to each characteristic, taking into account the constraints of the problem, making use of the DA Tool feature. In the figure below it is shown the priorities calculation process.



	Range	Acceleration Time	Top Speed	Weight	Cost	Offset Value	Priority	Normalized Priority
Range	■	0	0	0	0	0	0	**0**
Acceleration Time		■	1	1	0	2	4	**1**
Top Speed			■	2	1	4	6	**1,5**
Weight				■	1	6	4	**1**
Cost					■	8	6	**1,5**

Figure 4.12 *Priorities calculation.*

This information will result in the following two tables, Table 4.14 and Table 4.15.

Table 4.14 *Major design parameters table.*

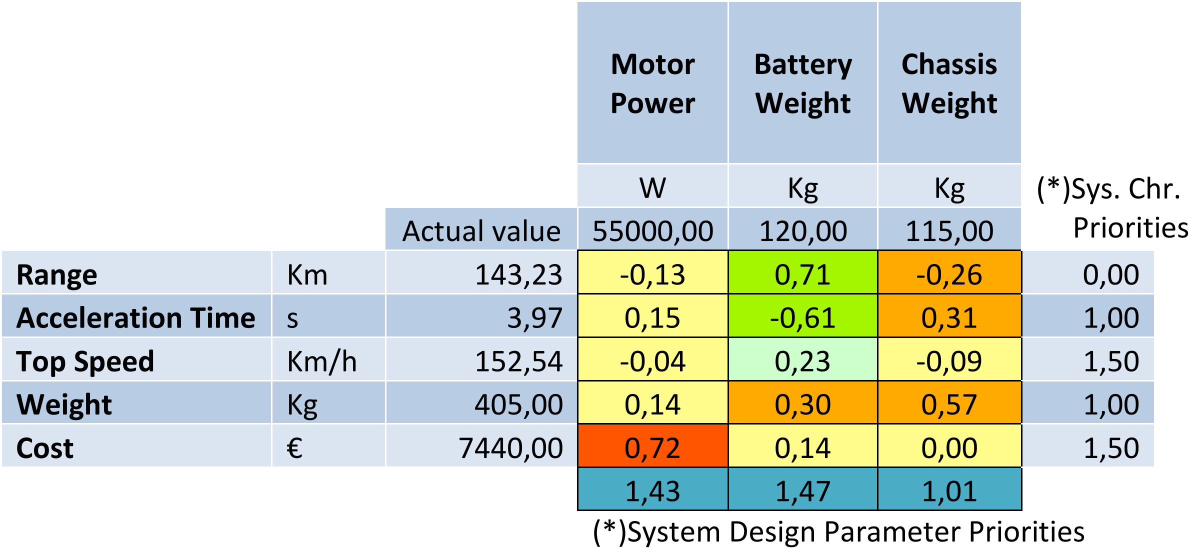
Major Design Parameters				
Name	**Units**	**Value**	**Lower limit**	**Upper limit**
Motor Power	W	55000	10000	60000
Battery Weight	Kg	120	50	150
Chassis Weight	Kg	115	70	200

Table 4.15 *System characteristics table.*

System Characteristics					
Name	**Units**	**Value**	**Targ. Value**	**Sign**	**Priority**
Range	Km	143,26	200	1	0,00
Acceleration Time	s	3,97	4	-1	1,00
Top Speed	Km/h	152,54	170	1	1,50
Weight	Kg	405,00	400	-1	1,00
Cost	€	7440,00	7000	-1	1,50

It can be seen from the table above that the requirements are not being met. Thus, making use of the DA Tool it will be tried to improve the mechanical design.

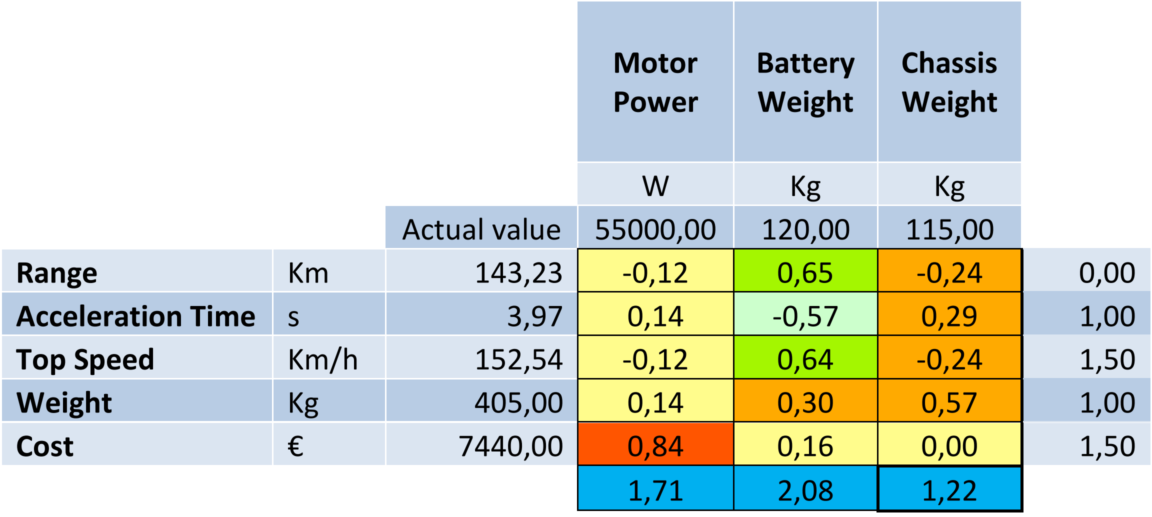
The obtained results for the sensitivity analysis of the design parameters are displayed in Figure 4.13 and Figure 4.14.



			Motor Power	**Battery Weight**	**Chassis Weight**	(*)Sys. Chr. Priorities
			W	Kg	Kg	
		Actual value	55000,00	120,00	115,00	
Range	Km	143,23	-0,13	0,71	-0,26	0,00
Acceleration Time	s	3,97	0,15	-0,61	0,31	1,00
Top Speed	Km/h	152,54	-0,04	0,23	-0,09	1,50
Weight	Kg	405,00	0,14	0,30	0,57	1,00
Cost	€	7440,00	0,72	0,14	0,00	1,50
			1,43	1,47	1,01	

(*)System Design Parameter Priorities

Figure 4.13 *Normalized sensitivity matrix of the design parameters.*



			Motor Power	Battery Weight	Chassis Weight	
			W	Kg	Kg	
		Actual value	55000,00	120,00	115,00	
Range	Km	143,23	-0,12	0,65	-0,24	0,00
Acceleration Time	s	3,97	0,14	-0,57	0,29	1,00
Top Speed	Km/h	152,54	-0,12	0,64	-0,24	1,50
Weight	Kg	405,00	0,14	0,30	0,57	1,00
Cost	€	7440,00	0,84	0,16	0,00	1,50
			1,71	2,08	1,22	

Figure 4.14 *Relative sensitivity matrix of the design parameters.*

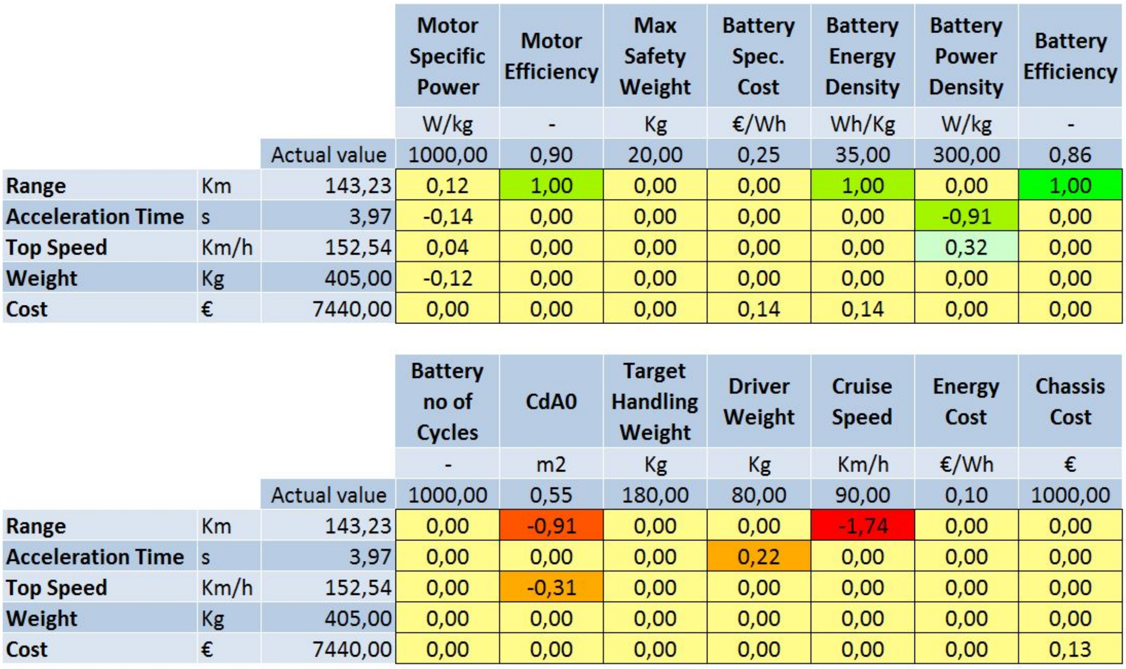
From the analyses results, in the case of the battery weight parameter it is seen that it mostly affects the range, acceleration time and top speed in a positive way. Whereas, the chassis weight has a negative impact in all of the characteristics except from the cost. On the other hand, the motor power parameter mostly affects the cost, although it may seem surprising that increasing the motor power would not increase the acceleration time, in fact there is a slightly reduction in this parameter. This is consequence of the equations of the model, since increasing the motor power will directly affect the weight of the design among other parameters. Thus, there is a certain point when the increase of the motor power starts being in contrast with the acceleration time, it can be seen that now that point has been exceeded.

Hence, with the interpretation done in the previous paragraph it is deduced that the chassis weight is the less critical design parameter, since it is the one that affects to a lesser way the system characteristics, while the chassis cost and the motor power do it to a greater rate. These conclusions are also stated in the last row of the normalized sensitivity matrix (Figure 4.13). Where it is clearly seen that the priority for the chassis weight is 1,01; whereas the priorities for the battery weight and motor power are almost the same: 1,47 and 1,43 respectively.

Thus in this occasion, it can be stated that increasing the chassis weight would be unfavorable for the design; actually, the most advantageous situation for the design would be reducing it as much as possible. The range is benefited by the choice of a more powerful battery, which implies an increase in its weight. Although, the increase of the battery weight would not work in the favor of the other four system parameters. Considering the motor power parameter, its increase will not lead to any significant improvement, whereas the cost of the design is drastically raised.

Finally, is time to ponder the obtained results, analyze them, take a look at the available budget and make decisions to improve the design insofar as possible. In conclusion, in this situation it should be tried to reduce the chassis weight and the motor power parameters and increasing as much as possible the battery weight.

The obtained results for the *Sensitivity Analysis* of the fixed parameters are displayed in Figure 4.15.



			Motor Specific Power	Motor Efficiency	Max Safety Weight	Battery Spec. Cost	Battery Energy Density	Battery Power Density	Battery Efficiency
			W/kg	-	Kg	€/Wh	Wh/Kg	W/kg	-
		Actual value	1000,00	0,90	20,00	0,25	35,00	300,00	0,86
Range	Km	143,23	0,12	1,00	0,00	0,00	1,00	0,00	1,00
Acceleration Time	s	3,97	-0,14	0,00	0,00	0,00	0,00	-0,91	0,00
Top Speed	Km/h	152,54	0,04	0,00	0,00	0,00	0,00	0,32	0,00
Weight	Kg	405,00	-0,12	0,00	0,00	0,00	0,00	0,00	0,00
Cost	€	7440,00	0,00	0,00	0,00	0,14	0,14	0,00	0,00

			Battery no of Cycles	CdA0	Target Handling Weight	Driver Weight	Cruise Speed	Energy Cost	Chassis Cost
			-	m2	Kg	Kg	Km/h	€/Wh	€
		Actual value	1000,00	0,55	180,00	80,00	90,00	0,10	1000,00
Range	Km	143,23	0,00	-0,91	0,00	0,00	-1,74	0,00	0,00
Acceleration Time	s	3,97	0,00	0,00	0,00	0,22	0,00	0,00	0,00
Top Speed	Km/h	152,54	0,00	-0,31	0,00	0,00	0,00	0,00	0,00
Weight	Kg	405,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Cost	€	7440,00	0,00	0,00	0,00	0,00	0,00	0,00	0,13

Figure 4.15 *Normalized sensitivity matrix of the fixed parameters.*

Here it is noticeable that most of the values of the matrix are zero, meaning that the variation of most of the fixed parameters does not affect the system characteristics. The most noteworthy is the cruise speed, which growth reduces drastically the range of the EV. The Cda0 increase is unfavorable for the range and top speed. On the other hand, an increase in the battery power density would lead to a great improve on top speed and acceleration time. The range can be benefited increasing the motor efficiency and both the energy density and efficiency of the battery.

Utilizing better quality components it would be possible the introduce of some changes in the fixed parameters values, to improve the design. These changes are shown in Table 4.16 and their impact in the system characteristics in Table 4.17.

Table 4.16 *Improvement of some of the fixed parameters.*

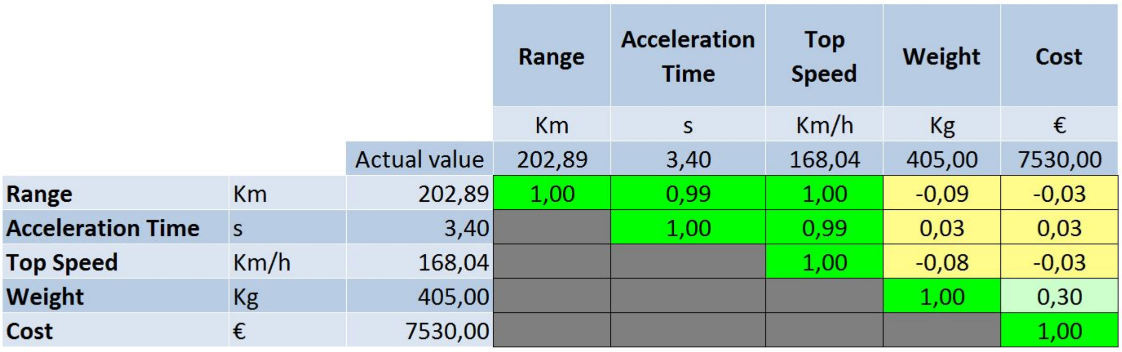
		New	Old
Motor Efficiency	-	0,92	0,90
Battery Energy Density	Wh/Kg	38	35
Battery Power Density	W/kg	350	300
Battery Efficiency	-	0,90	0,86
CdA0	m2	0,48	0,55
Cruise Speed	Km/h	87	90

Table 4.17 *Impact of the improvement of the fixed parameters on the system characteristics.*

		New	Old	Targ. Value
Range	Km	202,89	143,23	200
Acceleration Time	s	3,40	3,97	4
Top Speed	Km/h	168	153	170
Weight	Kg	405	405	400
Cost	€	7530	7440	7000

Now the range restriction is met, the top speed has been increased and the acceleration time reduced. On the other hand, the weight and cost characteristics need to be improved.

Performing the characteristics correlation analysis the ASCC matrix will be shown and it will be easier understanding how the system characteristics impact each other.



			Range	Acceleration Time	Top Speed	Weight	Cost
			Km	s	Km/h	Kg	€
		Actual value	202,89	3,40	168,04	405,00	7530,00
Range	Km	202,89	1,00	0,99	1,00	-0,09	-0,03
Acceleration Time	s	3,40		1,00	0,99	0,03	0,03
Top Speed	Km/h	168,04			1,00	-0,08	-0,03
Weight	Kg	405,00				1,00	0,30
Cost	€	7530,00					1,00

Figure 4.16 *Adjusted system characteristics correlation table (ASCC).*

With a quick glance to the matrix in Figure 4.16 (color legend in Figure 3.12) it can be stated that the project cost has a negative impact over range, acceleration time and top speed. For instance, to increase the top speed and reduce the acceleration time, a more powerful motor is needed, which implies a greater monetary inversion.

Examining the matrix row by row, it can be affirmed that all the system characteristics are in conflict with the weight and the cost to a greater or lesser extent. The acceleration time is clearly benefited by the increase of the top speed and to a lesser extent by the reduction of the EV weight. The reduction of weight has a favorable impact over the cost.

At this time, the designer would have a great overview of the design; the critical parameters have been identified, as well as the fixed parameters to take into consideration and the impact each system characteristics has over the others.
The results of the optimization process are shown in Table 4.18. The optimization has been performance with the default settings.

Table 4.18 *Optimization results for the EV design.*

		Values	
Name	**Units**	**New**	**Previous**
Motor Power	W	49020,99	55000,00
Battery Weight	Kg	125,83	120,00
Chassis Weight	Kg	112,57	115,00

Therefore, these are the values the design parameters should have so that the design can achieve the system requirements. In the table below it can see how these new values affect the system characteristics.

Table 4.19 *New values for the system characteristics consequence of the optimized variables in the EV design.*

		Values			
Name	**Units**	**New**	**Previous**	**Targeted**	**error %**
Range	Km	214,03	202,89	200	7,01
Acceleration Time	s	3,22	3,40	4	19,53
Top Speed	Km/h	171,06	168,04	170	0,62
Weight	Kg	400,00	405,00	400	0,00
Cost	€	6999,46	7530,00	7000	0,01

It is noticeable that all the restrictions have been met, with a very narrow error %. Thus, the desire design has been achieved with the help of this DA Tool, proving that the analyses are really useful and the optimization algorithm has an outstanding performance.

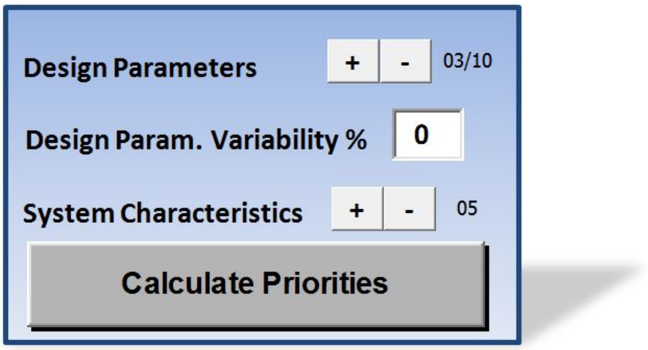
5. FINAL CONSIDERATIONS

5.1 Creating a new project

When the user starts the DA Tool, the file named *New Project.xlsm,* for the first time, a pop-up window will appear asking for a name for the new project. After the user has entered the desired name, the DA Tool will save the new project at the directory indicated by the user with the previously selected name. From now on, he will continue working in his project from the new file, whereas the original *New Project.xlsm*, remains blank, being possible the development of further projects.

For instance, imagine the user wants to design and electric motorcycle. He would open the DA Tool and enter *Electric_Motorcycle* as name, save it at his desktop and start working on it. In this situation, he will have the file *Electric_Motorcycle.xlsm* at this directory *C:\Users\UserName\Desktop*, while the file *New Project.xlsm* remains blank.

Once the file has been created, the user shall proceed introducing the equations, design parameters, system characteristics and constants into their corresponding tables at the *MODEL* and *MAIN* worksheets, with the help of the keys at the *Add /Remove* control boxes, the control box at the *MAIN* window is shown in Figure 5.1. It is possible to add up to 10 rows to the major design parameters table, whereas there is no limitation in the other ones.



Design Parameters 03/10

Design Param. Variability % 0

System Characteristics 05

Figure 5.1 *Add / Remove controls.*

The introduced equations make use of several parameters situated along the entire workbook. Therefore all the cells containing parameters, variables, constants or formulas should be assigned a name. For example, in the EV model case shown before the total *Cost* parameter will be function of the *Chassis Cost*, the *Battery Cost* and the *Motor Cost* as shown in the following equation.

$$Cost = Battery\ Cost + Motor\ Cost + Chassis\ Cost \tag{5.1}$$

Thus, according to the defined variables for that case and notation of Excel, the user will have to type on the cell for the *Cost* value the following formula:

$$= Battery\_Cost + Motor\_Cost + Chassis\_Cost \tag{5.2}$$

Afterwards, the data missing at the tables (constraints, priorities, sign...) is filled. The priorities can be either introduced freely or making use of the built in feature. The variability for the sensitivity and correlation calculations can also be set.

Moreover, there is a *Help* button under the *Add / Remove* module, which will display a pop-up window showing some brief to guide the user during this process.

5.2 Other considerations

As it can be deduced from the previous paragraphs apart from the *MAIN* and *MODEL* worksheets there are other windows where the results for each function are presented. These worksheets are named:

- Sensitivity_Design
- Sensitivity_Fixed
- Chr_Correlation
- Optim_Results

The last one, *Optim_Results,* is hidden and the user will only be able to reach it when performing the optimization process of a model. The user can navigate through these different worksheets using tabs, shown in Figure 5.2, which are situated at the bottom of the Excel window. A different colour has been assigned to each one of them to make the navigation easier, these colours correspond with the ones the control buttons have.

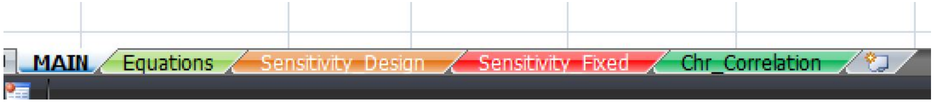


Figure 5.2 *Tabs to navigate through worksheets.*

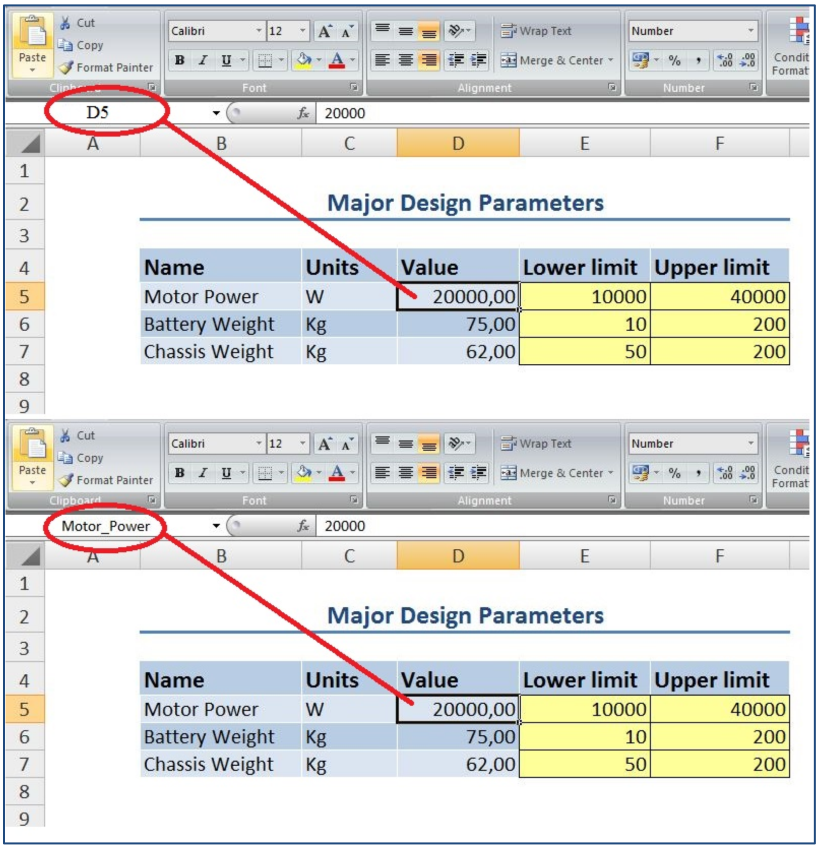
Additionally, there is another hidden worksheet, *Priorities,* which is an intermediate window for the user to assign the corresponding weight to the system characteristics, there a help button, which will guide the user through this process, can be found.

In all of these windows there is a blue button, Figure 5.3, in the top left corner to go back to the *MAIN* worksheet after seeing the results, to performance new calculations or modifications in some of the system parameters.

Figure 5.3 *Back to Main worksheet button.*

On the other hand, the *MODEL* button at the *Control Panel* will switch to the worksheet with the model equations and fixed parameters information.

Renaming the cells can be easily done by selecting the desired cell, introducing the new name in the *Name box* and pressing enter. The *Name Box* is situated in upper-left side of the display, as shown in the following Figure 5.4.



D5 20000

Major Design Parameters

Name	Units	Value	Lower limit	Upper limit
Motor Power	W	20000,00	10000	40000
Battery Weight	Kg	75,00	10	200
Chassis Weight	Kg	62,00	50	200

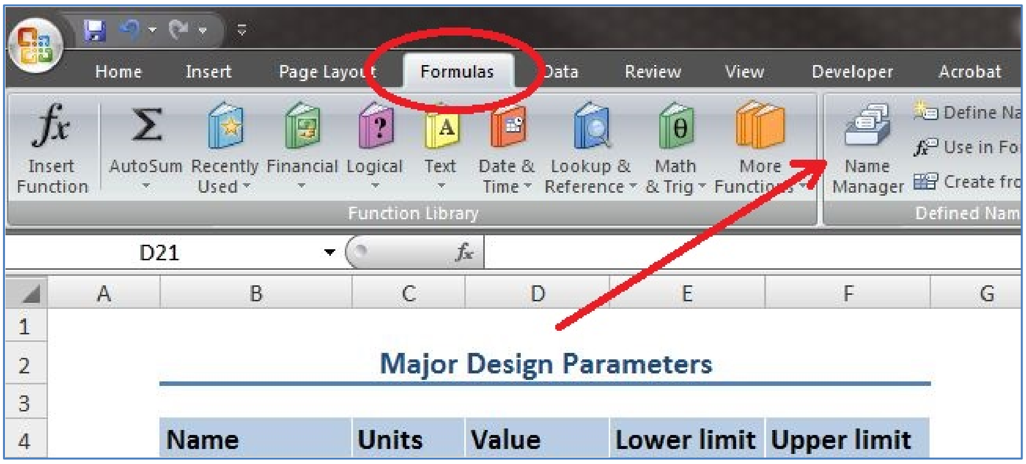
Motor_Power 20000

Major Design Parameters

Name	Units	Value	Lower limit	Upper limit
Motor Power	W	20000,00	10000	40000
Battery Weight	Kg	75,00	10	200
Chassis Weight	Kg	62,00	50	200

Figure 5.4 *Naming a cell.*

Henceforth, when introducing a formula into a cell the user will be able to reference the involved parameters typing the previously assigned name. However, if the user wishes to edit or delete the names of any cell, he should head to the *Name Manager* label in the *Formulas* tab, as it can be seen in the figure below.



Major Design Parameters

Name	Units	Value	Lower limit	Upper limit

Figure 5.5 *Name Manager location.*

Additionally, at the *Others* module, the user is provided with some basic controls; save the obtained results in PDF format, send them to a printer machine and a button that shows some brief information about this DA Tool.

The DA Tool has been developed in a high definition monitor, with a resolution of $1680x1050\ pixels$. Therefore, in screens with lower resolution the user experience may not be as satisfying.

On the other hand, the DA Tool makes use of macros, VBA procedures for Excel, thus for an appropriate performance of the DA Tool the user should enable all macros when asked. As mentioned before the Excel command *Solver* it is also used. However, usually it is not installed. This add-in can be installed selecting the *Solver Add-Ins* check box at *Menu › Excel Options › Add-Ins › Go...*

6. CONCLUSIONS

In this thesis a DA Tool for low-fidelity modelling approach has been developed and used in two practical design cases; a portable motion platform and an electric vehicle (EV). This DA Tool makes use of a range of linked analysis mechanisms, useful for the design process of any engineering device, this range encompass from sensitivity analysis up to design optimization.

Particularly, the normalized sensitivity matrix is an exceptional tool to illustrate design dependencies in sophisticated engineering designs, enabling the accountability between top level design parameters down to system characteristics, meaning that there is an evident relation between system requirements and design parameters. The system characteristics correlation matrix is also a very powerful mechanism when arranging the system requirements. Furthermore, it has been proven that it is possible to instantaneously and satisfactorily optimize, using the developed optimization algorithm, the model-design, solving a multivariable system of non-linear equations problem subjected to several constraints.

In first place the portable motion platform model was analyzed. The equations of the low-fidelity EV model along with the design parameters, system characteristics and fixed parameters were introduced into the DA Tool. In this occasion the system requirements were not prioritized over each others. The imported data from the model was analyzed with the DA Tool. From the result it was possible to get a great overview of the EV model as well as the identification of the critical parameters. The optimization process was implemented attempting to approximate the values of the system characteristics to the targeted ones. Finally, a satisfactory result was accomplished and the critical parameters of the design identified.

In the electric vehicle low-fidelity model case a similar process was followed. Some design limitations were set, in order to try to improve the design to meet them. After an active analysis, modifying some of the parameters, and the optimization process it was possible to fulfil all the limitations reaching quite an accurate design.

The overall results from both cases, evidence that an accurate approach can be achieved with a modest number of equations, the identification of the major design parameters and system characteristics. The relative error following this method is reasonable and admissible for an early design process. This powerful DA Tool does not require high-level modeling skills and it is suitable to assist the designer in the early design phases, proving this DA Tool very useful.

On the other hand, it can be said that for a proper performance of the DA Tool, an adequate acknowledges of all the involved parameters and characteristic is needed, as well as a careful selection of the target values for the system characteristics in conjunction with the limits for the design parameters. Additionally a precise prioritization of the system characteristics is vital for a proper optimization process and the sensitivity analysis.

It has been seen that the DA Tool can also be used to solve simple problems such as, the parabolic shot. Therefore, it can be concluded that this DA Tool can encompass a wide field of knowledge and not only the mechanical engineering. For instance, this DA Tool could be use in the schools by teachers to present physics or mathematical problems.

For further development and research, taking into account that the most important design decisions are made in early design phases, it would a wise idea for the companies to embrace these analysis methods in these phases to complement the existing ones, which would help saving time and giving a quick overview of the system.

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