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Sensitivity analysis of CFD method with modeFRONTIER

Master's Thesis in the Fluid Dynamics

HAMED JAHROMI

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Division of Fluid Dynamics
CHALMERS UNIVERSITY OF TECHNOLOGY
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ABSTRACT

Prediction of physical phenomena is increasingly demanded by industry. Saving time and cost is the main goal of this approach. Empirical tests are costly and also time consuming; furthermore, rapidly rising costs severely limit freedom in design modification in empirical testing. At the Contamination and CFD section at Volvo cars, several numerical methods are carried out on a daily basis. There was a demand to investigate robustness of mentioned methods. Robustness in the sense that how much by applying new design factor such as boundary conditions, geometries or turbulence models, their specified response will be affected and in what manner. Variation of design factor could have a different effect on a response, so that having estimation about the result is valuable. Design of experiment and statistical analysis can be used as a systematic procedure to illustrate the uncertainty of method. In this thesis integration of ANSYS/FLUENT® as a main engineering simulation tool and modeFRONTIER® as a multi-objective and multi-disciplinary platform and MATLAB® as a high-level programing language is performed. The core knowledge of performing such a process is obtained, advantages and drawbacks of the procedure is studied. Such an integrated process is applicable in other disciplines as well.

Key Words: Design of experiment, modeFRONTIER, sensitivity analysis

Preface

This thesis has been done at Contamination and Core CFD department, CFD Climate attribute at Volvo Car Corporation in collaboration with fluid dynamic division at Applied Mechanics department and is the final part of Complex Adaptive Systems Master of Science program at Chalmers University of Technology.

First of all I would like to thank my supervisor, Frida Nordin, for giving me the opportunity to work on such an interesting and challenging project. I am very grateful for the support and guidance she has provided during this project. I am sincerely grateful to my examiner Lars Davidson, who introduced me to nice people at CFD Climate group and for his valuable feedback which helped greatly in improving the thesis.

Furthermore, I would like to extend my gratitude to Ahmed El-Bahrawy and Patrik Sondell for kindly sharing thier experience about modeFRONTIER and Christoffer Järpner at EnginSoft Nordic AB for his support and commitment.

I would like to thank Jonas Ask, Johan Levin, Dragos Moroianu, Carl Andersson and Anders Björtin at the CFD group for their hospitality and pleasant working environment. Also, I would like to thank my dear friend Shayan Rahat for his helpful feedback on my report. Lastly yet mostly, I am thankful to my wife Maryam for her love, kindness and support.

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1 Introduction

A robustness study of numerical methods which already serves as a verification tool in industry is demanded. Design of experiment (DOE) proposes a systematic approach to extract the maximum information within minimum of experiments, by conducting targeted experiments by smart arranging of design points in the domain; thereby a tool like modeFRONTIER can play an important role to achieve this idea by organizing statistical data from the experiments, reducing the redundant experiments and saving time and resources.

In the modern car the passenger climate comfort is increasingly crucial and visibility level through the windscreen as a result of proper functionality of HVAC system is of interest. There are some legal requirements that must be fulfilled by the car companies e.g. the time span that the windscreen takes to de-ice during winter at the maximum power of HVAC heating.

In order to reduce the development costs and save the time process, computational fluid dynamic (CFD) method is engaged; the de-icing simulation is applied on real size car compartment geometry. The employed CFD method for such a model consists of two main steps. Firstly creating a velocity field and pressure at steady state step by solving the momentum equation and then calculating the temperature over the windscreen in transient mode by solving the energy equation with consideration of boundary conditions. The turbulent model is the realisable $\kappa-\varepsilon$ model. A practical test was performed earlier to study the ice free area pattern. The required data for simulation of this physical phenomenon had been taken from the available HVAC system through physical testing. Specially, temperature of duct outlets were recorded for transient the part of the calculations. Comparison of simulation model and experimental test has been done and the results were satisfactory.

At the outset, methods were available for numerical simulations and experimental data gathering. During this thesis a procedure will be defined to analyze and study quantitatively and qualitatively the mentioned numerical method robustness. To do this, conjoint application of simulation and DOE has been utilized.

The experiment design of such a problem is of interest. For a new car design, the designer does not have any actual input data, and consequently prediction of system behavior (output data) without knowing detailed information is important to save time and resources. In particular, the relation between variations of the windscreen temperature distribution and duct outlet temperature distribution is of interest.

This assessment will be performed with the help of two main software, ANSYS/FLUENT and modeFRONTIER. In modeFRONTIER different DOE methods are available where in this case study Latin hypercube and full factorial sampling are considered.

The location and the angle of attack of the defroster to the windshield are important factors, but are not considered in this thesis. The question that will be addressed in this thesis will be the effect of the affecting inputs in this special case and their qualitative effect on outputs. The proposed procedure is applicable to other simulation methods.

1.1 Requirements for defrosting duct system

There are some requirements for the automotive industry that should be met regarding the defrosting duct system: to secure the passenger safety that during the winter, the frozen and ice-covered surface of passenger cars windscreen should be cleaned in a specific area within a specified time span; to provide a sufficient visibility through the windscreen.

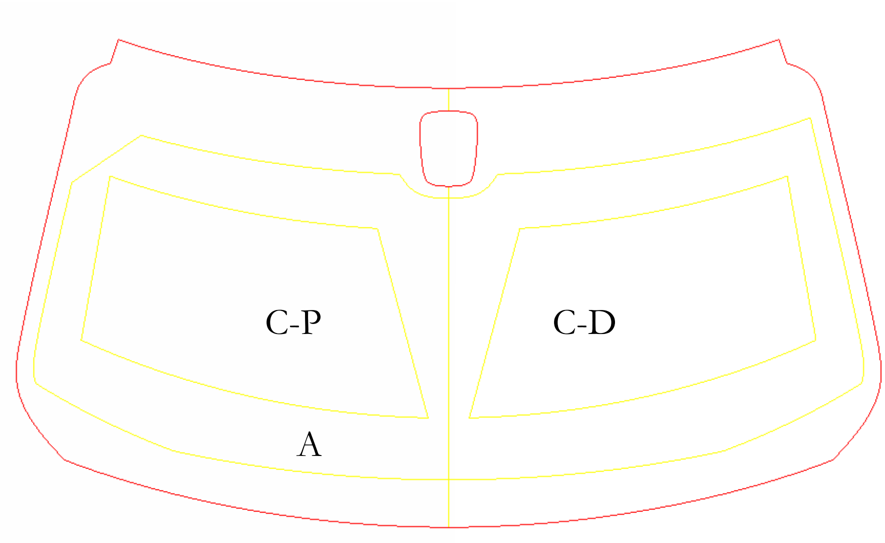


Figure 1-1 *Requirement areas over the windshield, C-D is a driver's field of vision, C-P is a passengers field of vision and A is general area of the windshield*

For instance, as shown in *Figure 1-1* the C-P, C-D and A areas should be ice free within a particular time span, after starting the HVAC system.

Within the duct system, energy in the form of hot air is delivered to the windshield area. The experience from the previous tests shows that the airflow coming through the duct system can be uneven. Furthermore, the jet of hot air does not cover the entire windscreen surface. This uneven airflow affects the temperature distribution over the windscreen.

Considering development costs, the design validations are crucial; specially with regards to meeting the aforementioned requirements. In fact one of the outcomes for this study could be increasing the capacity of windscreen defrost system to clean ice covered area over the windscreen within a specified time. [4,5]

The test for the windscreen de-icing experiment has been done in a cold chamber. Experimental tests are costly as well as time consuming. Furthermore, in case of new prototypes, the cold chamber testing could be infeasible.

1.2 Goals

At the CFD climate section, as a long term aim, investigation of variation of output due to variation of input is of interest. Establishing a general operational procedure for all existing methods is needed. Variation could be in boundary conditions, material properties, mesh density, geometry or numerical settings. Furthermore variation could be extended to sensitivity analysis of method, or component developed by a specific method.

In this thesis the suitability of using modeFRONTIER for sensitivity analysis has been investigated, meanwhile coupling with ANSYS/FLUENT as a main solver. As an example in the thesis, the semi-transient method has been used, from which the main output is the temperature distribution on the windscreen at different times. The input that varied in this case is the distribution of energy over the defroster duct outlet (with consistent total amount of energy delivered to the defroster duct). The output that was of interest is the temperature on the windscreen as a function of time, especially the temperature distribution in the small requirement areas (C-P & C-D). In this specific example it is the sensitivity of the component (defroster duct), when using our method for computing temperature, that is studied, not the method itself.

In case of developing new defroster duct system prototype, the total energy that is delivered through the HVAC system is known, but not the energy distribution over the duct outlets. This lack of knowledge led to investigate the variation of energy distribution parameter over the duct outlet, considering uneven airflow distribution from the empirical test.

1.3 Delimitation

The scope of the thesis is to study the feasibility of using modeFRONTIER as multi-objective optimization software in Climate CFD attribute. Due to time limitation, there was no chance to compare the results with alternative software i.e. Design Exploration Toolbox of the ANSYS Workbench.

In some respects the presented study result would be limited to this special case study, and all conclusions are not generalized. Additionally, the obtained results during this thesis are affected by the assumptions that have been made. For instance the geometry could be assumed as an input parameter and produce substantially different results. Moreover, the DOE has been done for the first 6 minutes of de-icing process and only portions of the windscreen; C-Passenger is the considered area during the experiment. The complete period of de-icing process lasts 20 minutes.

1.4 Outline

In what follows, chapter 2 provides brief theory from physical viewpoint at CFD section. In the same chapter, there are explanations regarding basics of DOE and sampling methods. Afterwards, a brief introduction about statistical analysis tools such as scatter plot, student table and correlation matrix are given. Chapter 3 describes the methodology that is considered in detail as well as the blocks of procedure building in modeFRONTIER.

In chapter 4, results and conclusions are stated and in chapter 5, the graphical guide to implement the DOE method in modeFRONTIER is explained in detail.

2 Frame of Reference

This chapter consists of two main parts. The first part explains the numerical simulation properties of windscreen de-icing. In the second part some basic knowledge of the fundamentals of design of experiment and sampling methods will be given. This is followed by a short introduction regarding data analysis.

2.1 Numerical Simulation

To study the numerical solution of the windscreen de-icing process, a computational fluid dynamics (CFD) method has been used. In the numerical model, phase changes are neglected. It is assumed that when the outer surface of the windscreen reaches zero degrees centigrade, the ice is starting to melt. The result of numerical model shows reasonable agreement with experimental test. The study is conducted within the ANSYS/FLUENT framework.

The numerical model consists of a car compartment geometry, windscreen and duct systems, including their material properties. The aim of this numerical model is to predict the de-iced pattern area. The boundary conditions for the numerical method were obtained from the experimental test in transient step. The external area of the windscreen was not modeled, but considered as a boundary condition that is applied to the simulation.

The numerical model is using the Navier-Stokes equations to model the fluid motion by solving the governing equations. The equations consist of continuity, mass and energy equations. Next, the turbulence model needs to be determined. The characteristic of the flow decides the proper CFD model, which is the realisable $\kappa - \varepsilon$ model.

The numerical calculation involves two main steps, steady state and transient. In the steady state step, the velocity field was calculated. In the transient step, the air temperature is governed by a heat-up curve. The temperature increases by time according to time-temperature tabular data, which is extracted during the experiment in the cold chamber. The mentioned data were measured by registering the temperature versus time. The velocity field obtained from steady state step is used to solve the time-dependent temperature field, to find the melting process over the windscreen.

The boundary conditions, which are affecting the steady state step, are summarized in Table 2.1.1. The assumption here is isothermal flow and hence, energy sources and temperature gradient are neglected.

Table 2.1.1 Boundary conditions affected the steady state step

Air mass flow rate	0.1225 kg/s
Static pressure outlet	0 Pa

For the transient step, by using the results from the isothermal steady state step as an initial boundary condition, the velocity and pressure fields are known and initial temperature assumed -18 °C throughout the domain. In the thermal transient step the velocity and pressure fields are constant. The inlet boundary condition is the time-temperature tabular data at the duct outlet to the car compartment domain and the temperature distribution over the windscreen is calculated. See Table 2.1.2.

Table 2.1.2 Boundary conditions imposed on the thermal transient step

Temperature	Time dependent tabular data
Wall thermal B.C.	Convective heat transfer on the exterior of the windscreen and side windows. Adiabatic on the duct walls. Constant temperature of 255 °K on the rest of the walls

2.2 Design of Experiment-DOE

The aim of the DOE is to establish an experiment to study a process. The process could be interpreted as a physical test or numerical modeling. As a general approach, the mentioned processes are designed and conducted so that the planned and targeted variation applied to the input parameter(s) lead to extract desired information for analysis of output parameter(s). In this thesis DOE is used for robustness study of a component, defroster duct system.

There are two main aspects that should be considered in this area, the design of experiment and the statistical analysis of the data. The stated aspects are inherently intertwined, as will be further explained in the following subsections.

The main principles of DOE are randomization, replication and blocking. These three principles act in a supportive manner. They complete each other to increase the precision of the experiment. Precision of experiment is threatened by either extraneous errors or systematic error due to nature of the experiment.

By randomization, in fact one tries to be sure that the entire input parameter domain is surveyed. The goal of randomization is to guarantee that the entire domain has the same chance of being examined.

By replication, one tries to be sure that the entire possible scenario between all input parameters is covered. In other words, repeating the experiment with planed decision and controlled condition. Replication with randomization allows the experimenter to predict the error variance. Without randomization, a large number of replication to predict the error variance would be useless. More replication leads to more precise results from the experiment. Blocking means treatment of all desired input parameters by excluding undesired parameters (noises). [1]

It’s worth mentioning that since this thesis deals with a computer experiment, there would be no random error, which is very common in physical experiments. Hereupon the cited DOE principle, *blocking* is useless. [8]

Since one expect to draw a meaningful conclusion from the results, having a proper statistical approach is necessary. Answers to questions such as what is to be studied, how the data are to be collected, how these data are to be analyzed, are essential.

By considering what came before, to establish a DOE with the proper statistical approach, the following guideline is required.

Recognition of the problem. The Experimenter needs to consider all aspect of the experiment as well as goals and possible ideas, which could arise during the experiment. Another aspect is interaction of experiment with other departments, which is considerable, simultaneously.

All possible problems or studies that can be addressed by the experiment should be reflected. Possible problems or studies are about stability and robustness, finding unknown areas of problem, verifying if the system has a similar performance under varied circumstances, optimization and factor screening.

Selection of input parameters (Factors) ranges and levels. Experimenter needs to identify the important input parameters, which has an influence on response parameters. The input identification leads to selection of factors that planned to be varied during the experiment. Design factors are selected, to be studied during the experiment and Constant factors are example of typical classification of parameters.

Hereafter, *factor(s)* identifies the input parameters, over which the experimenter can exercise control and intends to change. It’s notable that since one deals with simulation experiments, all the factors are controllable and so noise factors are negligible.

The next step would be selecting the range of the factors. This range should be selected according to specification of the variable. Also the number of levels that each factor can take to vary needs to be determined. The range and the levels comes from process knowledge. Process knowledge is a combination of awareness regarding theory and the previous practical experience.

Selection of proper design (sampling method). In this step, experimenter decides on sample size (number of experiments) and also selection of proper run order. Also in this step randomization and blocking will be applied on the run methods, if be required. Generally, the sampling method determines how the design points spread out through the domain. Since the sampling method defines the possible combination of input parameters which can occur, it would affect both quality of results and the required time for DOE.

Conduction of the experiment. It’s recommended to perform some small pre-runs to be sure about consistency of experimental condition, errors and monitoring the experiment.

Statistical analysis. Statistical analysis methods are crucial to interpret the data. Furthermore, statistical analysis is used to ascertain the reliability and validity of results.

Drawing conclusion. In this step, assuming the correct design method has been chosen, valid and valuable conclusions can be drawn from the results.

2.2.1 Robust design

The main characteristics of a robust design can be listed as: 1- To ensure that the mean of the output parameter is at anticipated vicinity. And also 2- variation in the vicinity of mentioned mean is as small as possible. To be more clear, in a robust design, the output parameter is as insensitive to variation of input parameter(s) as possible. [1] After performing DOE, it's possible to predict whether the manufactured product design (in this case defroster duct system) is robust or not.

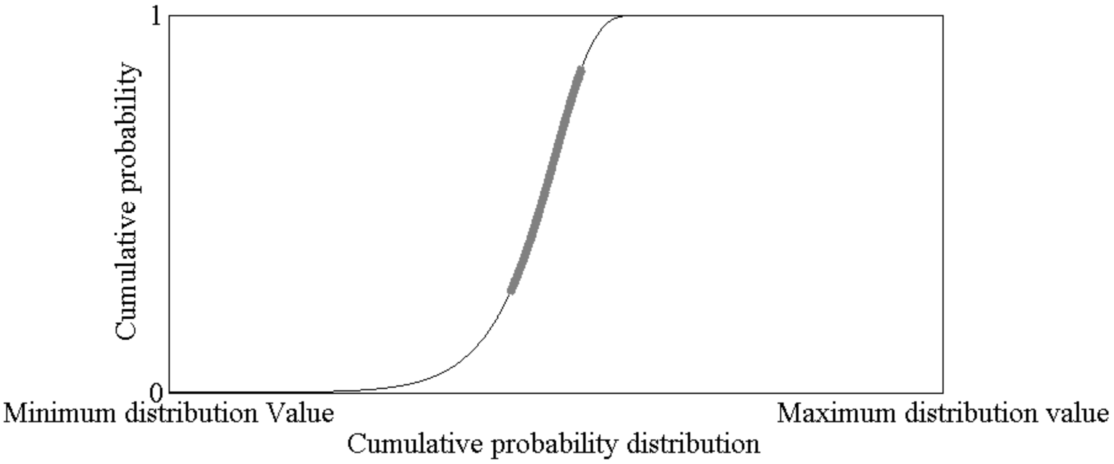
In this thesis the statement of the problem consist of two main parts; *Screening analysis* which investigates the leverage of each input parameter and *statistical analysis* which examines the main effect of input parameters variation over the output parameters. This sequential approach helps us to divide the problem (process) to smaller parts, in order to reduce time and effort.

2.2.2 Screening Analysis Step, Latin Hypercube Design

At the screening analysis step, the proper approach is to keep the number of levels as small as possible. Concurrently, the range of factors should be relatively large. With the insight gained regarding significance of factors and their regions, one can narrow the mentioned ranges and levels for the succeeding step.

It is assumed that there is limited initial knowledge about available factors and their ranges. The thesis deals with the deterministic simulation model, which means output response values are taken to be related to the factors through a deterministic mathematical model. The desired sampling method is space filling design that has been suggested for such deterministic computer models due to almost even or uniform distribution of designs based on measures of distance between points. [8]

Considering cumulative probability distribution, the Y axis is scaled from 0 to 1 and represents the cumulative probability to the correspond value in the X axis. The 0 to 1 scale of the cumulative curve is the range of possible random numbers generated during the sampling. A value is assigned to the selected random number according to the cumulative curve. The steep area in the cumulative curve means strong probability to be the chosen value. For instance in *Figure 2-1* upper graph, the thick area in the cumulative curve reveals more likely to be sampled area. In the graph below, the corresponding probability distribution function is illustrated.



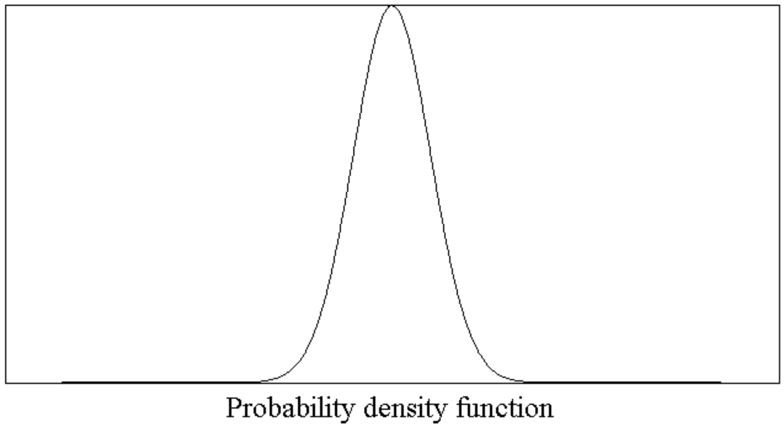


Figure 2-1 Cumulative probability distribution and (up) its corresponding probability distribution function (down)

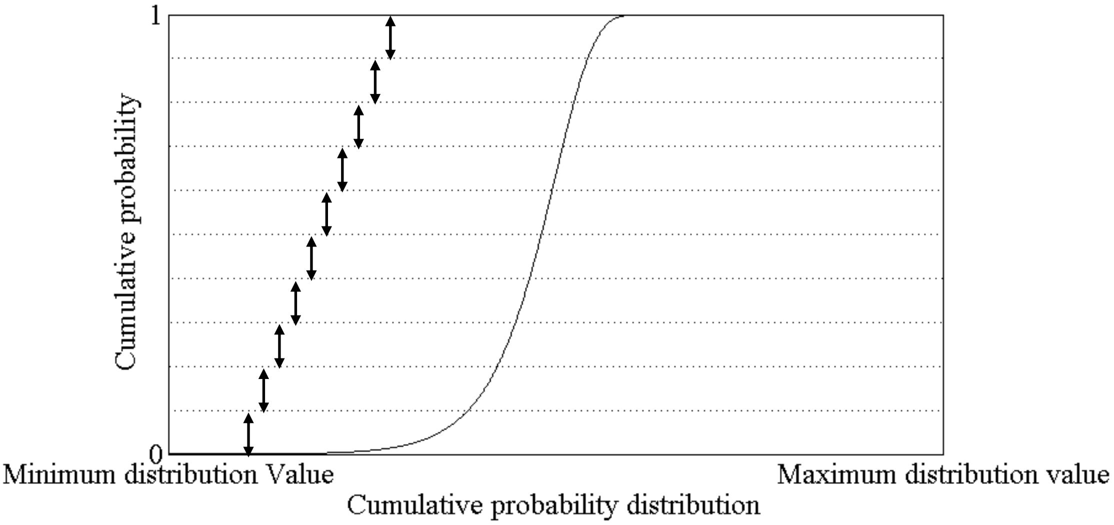


Figure 2-2 10 equal intervals for above cumulative curve

In Latin hypercube sampling, the arrangement of input probability distributions determines the sampling. This arrangement divides cumulative curves into equal intervals. Next the sample is chosen randomly from mentioned intervals of input distribution. Selection from every interval is mandatory. In *Figure 2-2* i.e. the cumulative curve is divided into 10 intervals.

In other words in the Latin hypercube sampling method m points (values) in n dimensions (variables) are created as $m \times n$ matrix. This matrix is constructed in a way that each of n dimensions is divided into m levels so that only one point resides in each level. The following *Figure 2-3* is an example of Latin hypercube design in two factors for 10-run in range 0 to 10.

When the number of factors increases this method only shows the main effect (effect on the response variable).

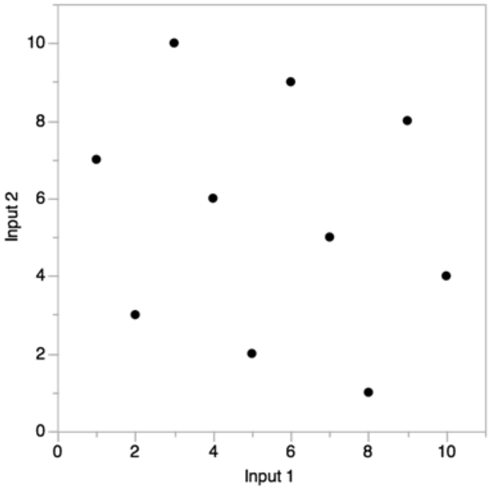


Figure 2-3 A 10 run Latin hypercube design sample

2.2.3 Statistical analysis step, full factorial design

For the statistical part full factorial method is chosen. Due to straightforward approach and simplicity of the full factorial design, the experimenter will be able to study interaction among factors as well as the main effect(s) over response variables. In this method all the possible combination between all designs points at all levels are orthogonally and simultaneously investigated.

For m points in n dimensions n^m runs is created. Full factorial delivers an excellent sampling of factors and provides ample information regarding effect of factor over response variables.

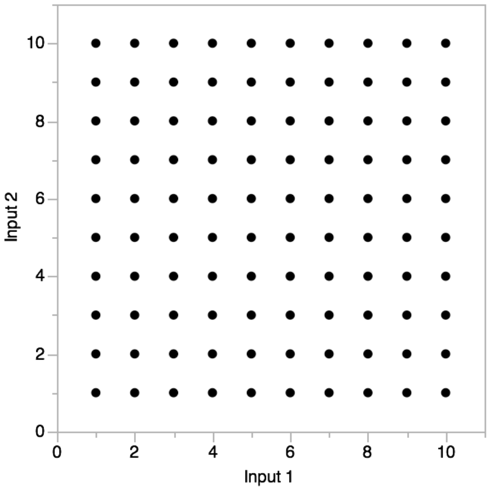


Figure 2-4 A full factorial sampling for 2 factors and 10 levels

The full factorial method needs a huge amount of time and resources, especially in case of calculation of complicated series of experiments, which is considered a drawback. Particularly, when the number of input parameters (factors) increases, the expense of calculation will increase dramatically. *Figure 2-4* shows 2 factors for 10 so that, 10^2 combinations are available. Within modeFRONTIER the limitation of number of designs is 256000.

2.2.4 Exploratory Data Analysis

In two following subsections, examples of the exploratory data analysis (EDA) techniques are presented.[7] The aim of EDA techniques is to obtain intuition regarding a data set. The main approach could be considered as a graphical one. Through the EDA method, the following questions, which are relevant to our problem, are answered:

- Does the input parameter(s) have an effect on output parameter(s)?
- What are the most important factors?
- What is the best function for relating a response variable to a set of factor variable?

2.2.4.1 Scatter plot

A scatter plot discloses relation or association between two variables. This relation is declared in the plot, where two sets of data variables are plotted versus each other. A vertical axis Y is usually the output parameter and horizontal axis X is the input parameter. One can find out whether variables X and Y are related and how they are related, linearly or non-linearly, positive or negative. Quadric, exponential, sinusoidal relation or outlier are possible condition. The following scatter plot is an example of positive linear relation between two variables.

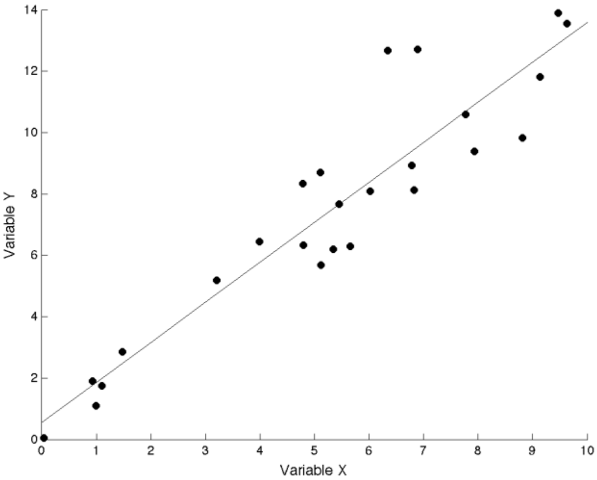


Figure 2-5 scatter plot showing positive linear correlation

2.2.4.2 Correlation matrix and *t*-student analysis

Correlation matrix is the advantageous classical statistical tool, which evaluates the correlation coefficient between a pair of variables. The range of correlation is from +1 to -1, which reveals the strength of correlation. Zero value means lack of correlation.

t-student analysis is a statistical method which uses *t*-distribution. The aim of *t*-student analysis is to identify whether the two sets of data differ significantly or not. The method assumes that result follows the normal distribution if the null hypothesis is true. Another caution is the two sets of data should be independent to obtain proper results. If the data sets distribution was not normal and e.g. was skewed, a larger data set is needed.

3 Research Method

This chapter will describe the research method considered for this thesis, which consist of two main parts. The first part presents the research strategy, thereafter followed by an explanation of the data collection methodology.

3.1 Research strategy

The following time line was followed to obtain the aim of thesis. See *Figure 3-1*. After determining the aim of the first step, literature study has been done to cover the most relevant concept i.e. numerical simulation of de-icing over the windscreen and basics of design of experiment and its application in automotive industry. Another important subject was a feasibility study of coupling modeFRONTIER and ANSYS/FLUENT to establish a general procedure. Finally the obtained results have been analyzed and recommendations regarding practicality of applying such a procedure are discussed.

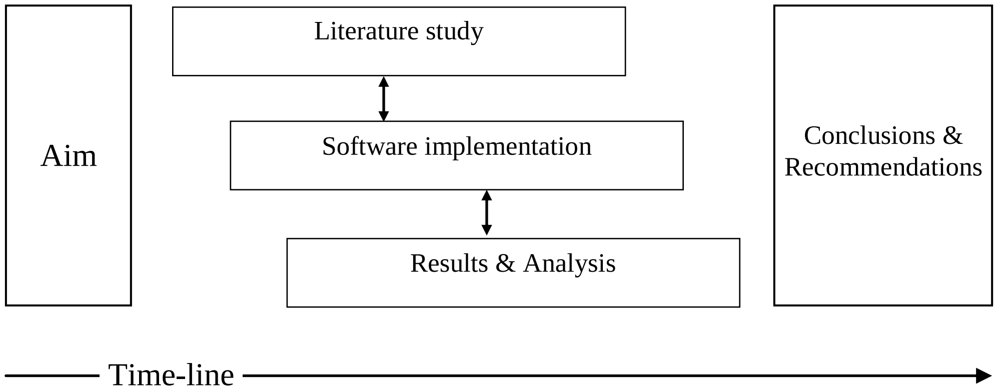


Figure 3-1 Research strategy

3.1.1 Literature study

The outcome of the literature study is reflected in chapter 2. The result of the literature study was to obtain the core knowledge of de-icing simulation over the windscreen. Also how one can apply the DOE methods to increase the productivity of a system by scrutinizing all possible boundary condition, which can be applied only over one component of the integrated system.

3.1.2 Software implementation

ModeFRONTIER consists of some built-in CAE software inherently, but does not include ANSYS/FLUENT. A major step in the project was the preparation of simulation data for further processing in modeFRONTIER. Due to the specialized nature of the work, significant effort was required to interface the two software packages.

3.1.2.1 Results and Analysis

MATLAB was the main pre-post processing auxiliary software in this process. Physical conditions were verified for each design at pre-processing step by MATLAB. Result analysis was performed at each step by the means of statistical analysis tools available in modeFRONTIER.

3.2 Validity and reliability

Validity and reliability are important factors when one performs such a study. *Validity*, describes how correct and accurate the study is conducted. To make it more reliable, adequate time was spent and similar experience in the literature was considered during the thesis.

Reliability, expressed whether this procedure is applicable for the other application at the department or parallel attribute. Since the essential element of DOE is implemented, one can apply the presented procedure to other simulation, with some modification in the software setup part.

4 Empirical study

While the aim of the thesis is to establish a general method to apply DOE to all procedures, which is utilized at Climate CFD department, one of the widely used numerical methods is employed for this study, de-icing of windscreen. Therefore, the experiment in this thesis is numerical simulation model of de-icing of passenger car windscreen.

A platform is required to perform all cited physical simulations and statistical analysis i.e. a network of data transferring. This network should have some specification. The most necessary of them is that, all these activities such as a simulation and mathematical calculation process can be implemented concurrently, as well as a data transferring and interacting between events.

The modeFRONTIER provides user with all the necessary elements to establish a DOE method, including events such as physical simulation and pre-post processing point and input and output parameters. The following *Figure 4-1* depicts very simple diagram, which shows all elementary requirements to establish a DOE method. Within this chapter all required steps to build such a workflow are explained.

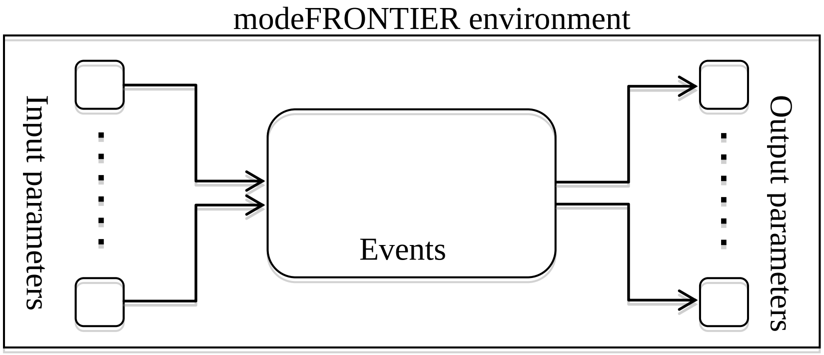


Figure 4-1 modeFRONTIER workflow

4.1 Design environment

The secondary objective is to verify the robustness of the duct system. The duct system serves as crucial part of the deicing process, which delivers air, either cold or hot, from HVAC system to car compartment. For the secondary objective, robustness means how the energy variation through the duct outlet influences the de-icing result over the windscreen. It is notable that the total amount of energy delivered to the duct is constant.

To reduce the calculation cost, a repetitive approach to gaining knowledge is encouraged, typically involving these consecutive steps. This approach consists of screening analysis and statistical analysis steps. Firstly screening analysis narrows the field of variables under assessment that is followed by statistical analysis, which clarify the main effect of factors. According to type of design, DOE method determines the sampling method.

In the modeFRONTIER environment one needs to make a workflow. The workflow will connect input parameters to the solver tool and consequently output parameter in a most simple situation. At intermediate steps, pre-post processing events could be added.

ModeFRONTIER defines DOE elements as a node. For instance input parameters or MATLAB that is executive software, are represented by a node. The user needs to set the specifications of each node according to circumstance.

4.2 Input parameters (factors)

In CFD methods, one needs to implement boundary conditions to the problem. In fact boundary conditions act as input parameters in the CFD de-icing method. In this CFD method the physical condition of the problem, the warm up process of windscreen is directly affected by delivered energy through the defroster duct system. Consequently, one can conclude that time-temperature tabular data, which led to warm up process could be converted as heat up curve for convenient expression of this problem.

Two kinds of input parameters are defined for two different steps of experiment design, which is fully described at the following sections.

4.2.1 Setup of input parameters for screening analysis

Input variable(s) need to be defined, in a way that reflect the variation of input variables on output. Heat-up curve is considered as an input variable, since we are dealing with the energy variation. For each outlet there is a specific heat-up curve, which defines the time-temperature functions behavior for the mentioned outlet. The assumption of the problem is that each duct consists of three outlets (zones), so energy via three heat-up curves is delivered for each duct, see *Figure 4-2*. The origin of these curves was the tabular data, which was extracted from the experimental test; then the curve with order 6 is fitted to those tabular data.

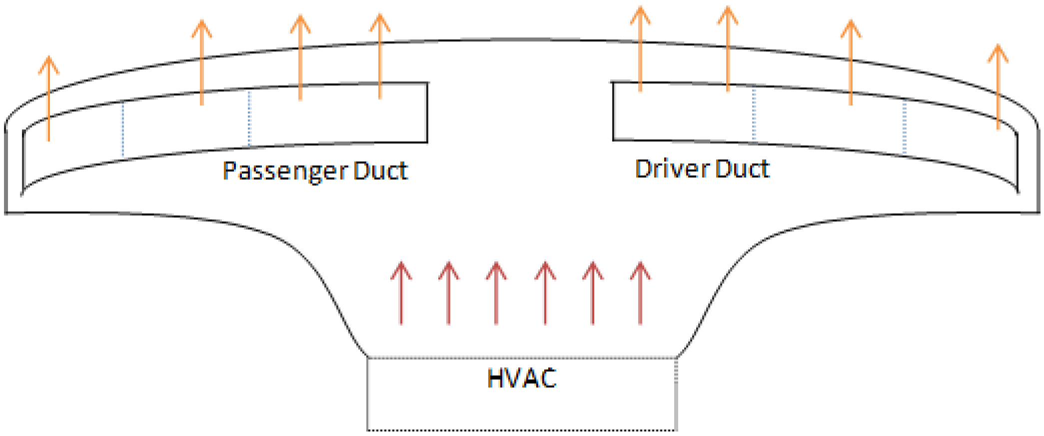


Figure 4-2 Schematic of duct system

In mathematical language, the summation of area under each curve could be assumed as a total energy, which is received from HVAC system. Because of symmetry and reducing the calculation cost, only half of the duct system geometry is considered.

Furthermore, the amount of mass flow rate was assumed to be equal for the different outlets. Calculating the integral of the heat-up curves is a measure which is used to ensure that delivered energy to the system is kept constant for all different experiments.

In this step all the parameters of the heat-up curve are defined as a variable. That means all variables from a_1 to f_3 will be varied. In modeFRONTIER all of a_1 to f_3 are defined as variables. The range of variation came from previous practical test. In fact, previous knowledge helps to avoid unrealistic data enters to our model. The heat-up curves equation extracted from tabular data has the general form given in (4.2.1.1) to (4.2.1.3) equations. *F(T)* defines the function of increasing temperature with time at specified outlet. In *Figure 4-3* each curve refers to heat-up curves equations in (4.2.1.1) to (4.2.1.3). The duct has eight outlets (zones) in each side and in order to simplify the problem, only three heat-up curves considered for all duct outlets. The F_1 ,F_3 and F_5 named after name of outlets that are supposed to be considered during the experiment.

$$a_1t^6 + b_1t^5 + c_1t^4 + d_1t^3 + e_1t^2 + f_1t + 255.15^\circ K = F_1(T) \qquad (4.2.1.1)$$

$$a_2t^6 + b_2t^5 + c_2t^4 + d_2t^3 + e_2t^2 + f_2t + 255.15^\circ K = F_3(T) \qquad (4.2.1.2)$$

$$a_3t^6 + b_3t^5 + c_3t^4 + d_3t^3 + e_3t^2 + f_3t + 255.15^\circ K = F_5(T) \qquad (4.2.1.3)$$

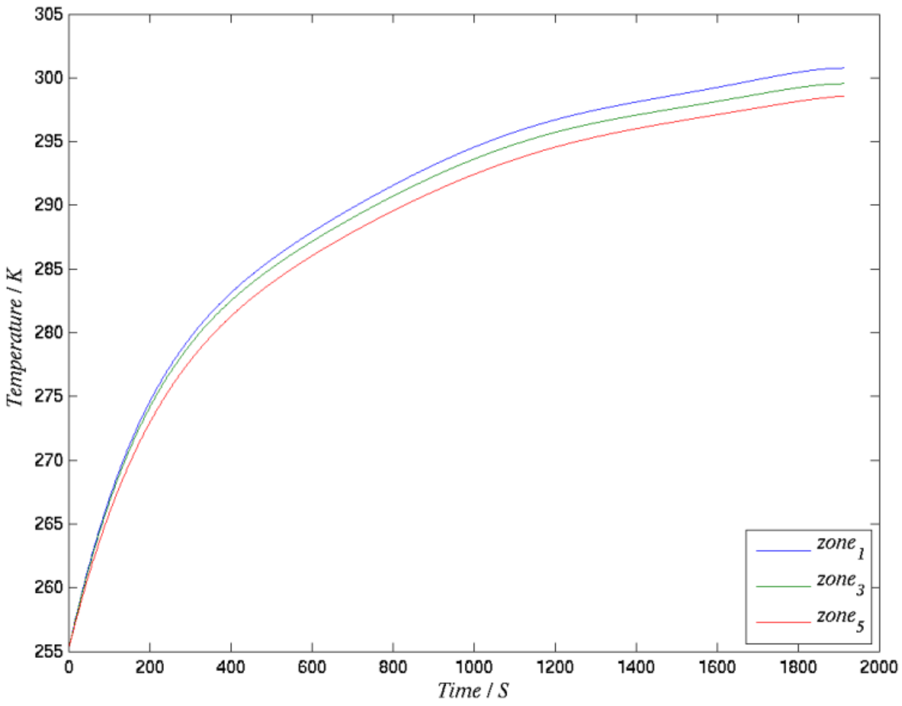


Figure 4-3 The three initial heat-up curves extracted from tabular data. The rest of the variation occurred around them, each zones represents the part of duct outlets

It should be noted that the maximum and minimum value (range) of all design parameters in *Figure 4-3* triple heat-up curves equations (4.2.1.1 to 4.2.1.3) has been chosen from the test data. All the triple curves for each design had a realistic behavior in accordance to real condition. Some restriction due to physical conditions were applied that will be explained in section 4.3.1.

4.2.2 Setup of input parameters for statistical analysis

Both the reference value of energy and the most effective factors in the curves equation are known. In this step, instead of varying the a_1 to f_3 parameters, the amount of energy of each curve is varied. Term *energy* means the area under the heat-up curves or integral of temperature function. In other words the result of curve integral is varied and in this new case, the values of f_1, f_2 and f_3 are unknown. By solving the equations (4.2.2.1) to (4.2.2.3)

$$\int at^6 + bt^5 + ct^4 + dt^3 + et^2 + f_1 t + 255.15^\circ K = energy_1 \qquad (4.2.2.1)$$

$$\int at^6 + bt^5 + ct^4 + dt^3 + et^2 + f_2 t + 255.15^\circ K = energy_3 \qquad (4.2.2.1)$$

$$\int at^6 + bt^5 + ct^4 + dt^3 + et^2 + f_3 t + 255.15^\circ K = energy_5 \qquad (4.2.2.1)$$

the f_1, f_2 and f_3 have been found and the other mathematical operations are possible. Consequently in this part $energy_1$, $energy_3$ and $energy_5$ are the factors instead of f_1, f_2 and f_3.

4.3 Events

This part consists of MATLAB node and Logic node and ANSYS/FLUENT node. The setup properties of each node is explained in the appendix I chapter in detail.

4.3.1 Pre-Processing Nodes, Restrictions

Some restrictions are applied to each experiment, so that unrealistic designs rejected during the experiment and some of these restrictions are performed by the Logic node. The necessary data for physical restrictions are provided by the first MATALAB node. After each design, the specified value from a_1 to f_3 are inserted to the MATLAB code, the desired curve made and afterwards the mean value of curve integrals calculated and compared to the reference value. Also the final temperature of each curve is saved for the next step.

Energy, According to the assumption of the problem, in this thesis, only variation of energy distribution is of interest. Certainly the effect of mass flow rate is considered; as heat transfer occurs mainly due to convection. It means the total energy, which is delivered from HVAC system, in each design should be kept constant. To fulfill this condition, first the Logic node examine the mean value of energy does not exceed further the reference value. The reference value came from the empirical test.

Another considerable point is that the effect of mass flow at each design in statistical analysis step is normalized. According to the assumption of the problem:

$$energy_1 + energy_3 + energy_5 = 3\times energy_{reference} \qquad (4.3.1.1)$$

By considering the effect of the mass flow rate over the energy equation and based on data from steady state part of numerical simulation, the contribution share of mass flow for the three zones are applied to expression (4.3.1.1) and converted to (4.3.1.2).

$$0.5\times energy_1 + 0.28\times energy_3 + 0.22\times energy_5 = energy_{reference} \qquad (4.3.1.2)$$

Expression (4.3.1.2) emerges at workflow as a condition for the first Logic node in the statistical analysis step.

Final temperature difference, According to empirical test observation, the difference between maximum and minimum temperature values at the duct outlet was at range [0-6] degree. This means one needs to neglect the designs for which the final temperature difference is out of the cited range. This has been done by means of the second Logic node.

4.3.2 ANSYS/FLUENT

After confirmation of the Logic nodes, the triple curves in each design, could be obtained by ANSYS/FLUENT node. The a_1 to f_3 values are read as a user defined function (UDF) file. UDF files specified the boundary conditions for each simulation and then used by ANSYS/FLUENT node. Geometry, velocity and pressure profile are prepared as a *case&data* file. The aim of ANSYS/FLUENT is to calculate a temperature distribution over the windscreen. After running for first 6 minutes of de-icing process, the temperatures of all cells over the windscreen are saved as an ASCII file for each design. This ASCII file is transferred to a second MATLAB node.

4.3.3 Post-Processing

The second MATLAB node visualizes the result of the experiment. It reveals the percentage of cells that have reached 0 °C in the desired area and then send that value to the output parameter node.

4.4 Output Parameter

The de-icing of windscreen, based on the description in the background section, is of interest, so defining relevant output parameters, which reflect the de-icing process is required in order to determine the melting pattern of ice over the windscreen. The assumption that has been made is the ice-free area over the windscreen can be interpreted as the number of cells over the windscreen which reaches to 0 °C during the heat up process after specified time. This node only reflects the percentage of ice-free area. ModeFRONTIER can read the data from this point for the statistical analysis.

By reminding the aim of the thesis, which was establishing general DOE procedure and in the same time limitation of time and resources at the moment of doing the thesis, selection of the smaller area C-Passenger (C-P) over the windscreen as a response variable instead of whole windscreen was inevitable.

4.5 Model Simplification

In order to reduce the expense of calculation, half of volume control is investigated. Also coarser mesh has been preferred to reduce the expense of the numerical model calculation due to lack of time and resources. Also only the first 6 minutes of melting process is considered while the complete melting process lasts around 20 minutes. *Figure 4-4* and *Figure 4-5* depict the complete workflow for screening analysis and statistical analysis part at modeFRONTIER, respectively.

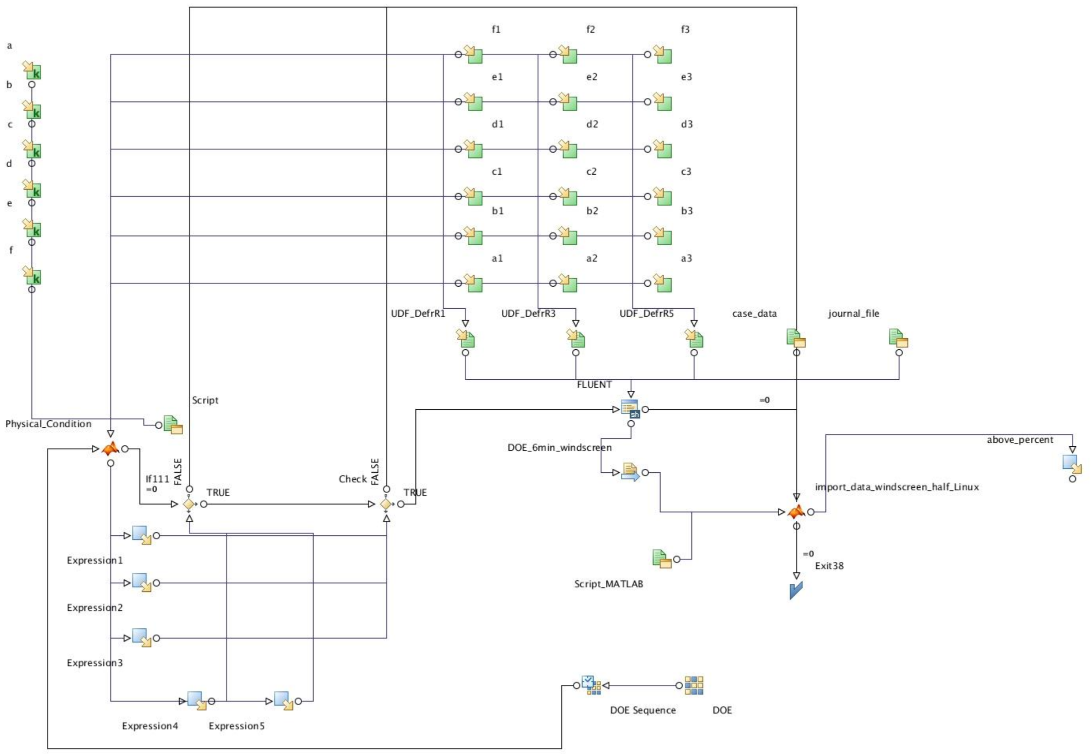


Figure 4-4 workflow at modeFRONTIER for screening analysis part

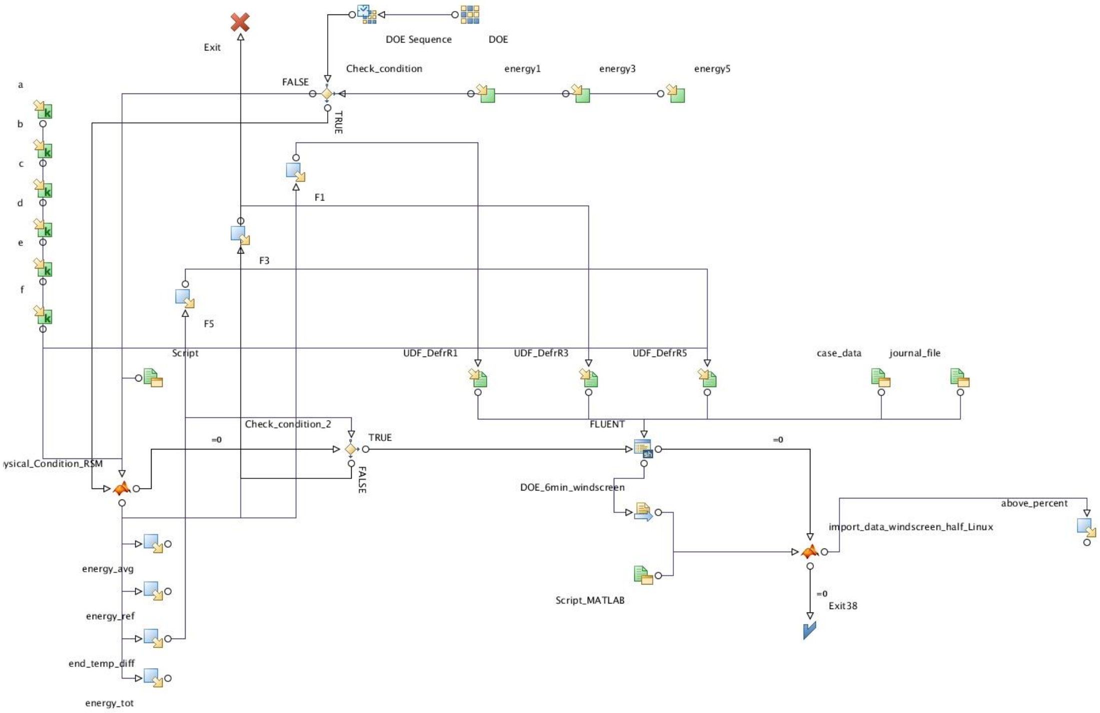


Figure 4-5 workflow at modeFRONTIER for screening analysis part

5 Results & conclusion

The main goal of the thesis is achieved and the procedure is established. Also some statistical analysis has been done. ModeFRONTIER contains a wide variety of tools, which can be used to analyse the data. Summarized information regarding both workflow and some recommendation for similar job are available in this chapter. After performing a DOE, data are stored at Design space, which let the user do the statistical analysis. The following sub sections depict the part of statistical analyses.

5.1 Screening Analysis Result

The result of the screening analysis part is as follows. See *Figure 5-1*. The purpose of screening is to find out most important input variables. The results are obtained by means of smoothing spline ANOVA algorithm [6]. f_1, f_2 and f_3 are the most effective variables and only they were considered for the next step as factors.

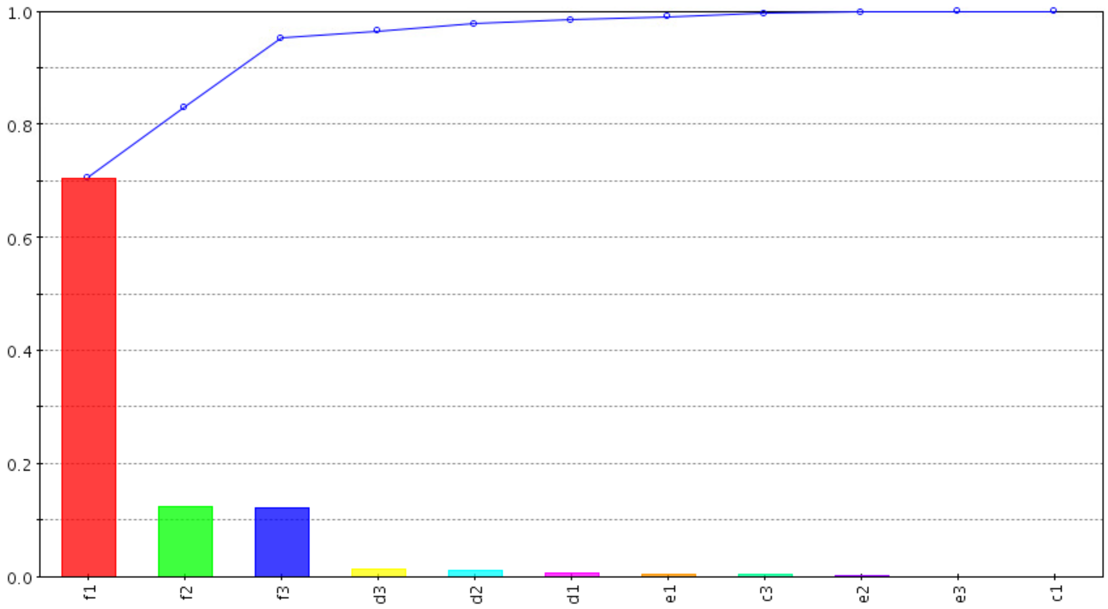


Figure 5-1 screening analysis results shows the effect of f_1, f_2 and f_3 are more than other factors

5.2 Statistical Analysis

Out of all 23 designs, the minimum and maximum values of the responses are considered. Response values are obtained after running numerical simulation for first 6 minutes of de-icing process, which only consider the small C-P area. Afterwards designs with minimum and maximum response value have been run for longer time interval, in order to study in real condition. As mentioned before, due to lack of time and resources the experiments have been run for first 6 minutes of de-icing simulation. The difference between response values at minimum scenario and maximum scenario is insignificant. Spread of melting area shown by dark blue, at the minimum scenario is horizontally. In return, at the maximum scenario the melted area is expanded vertically, see *Figure 5-2* and *Table 5.2.2.*

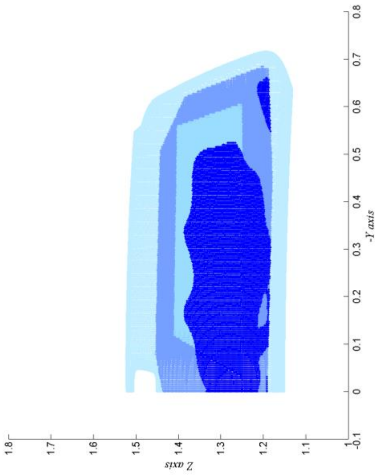
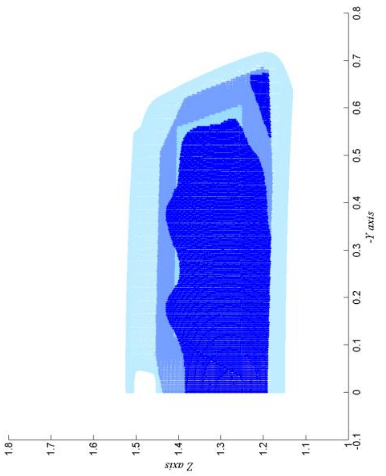
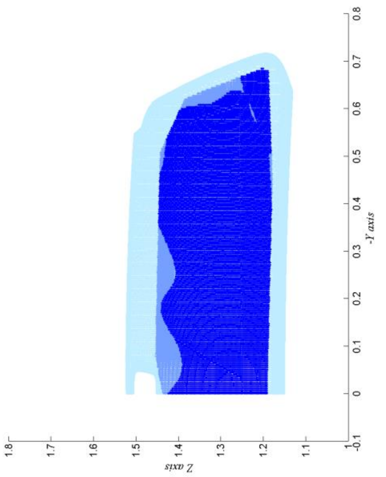
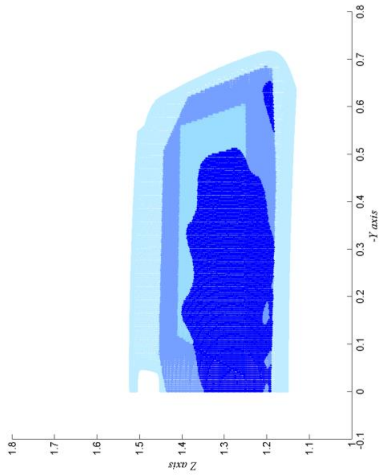
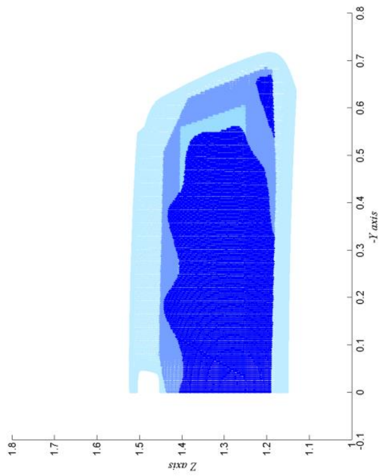
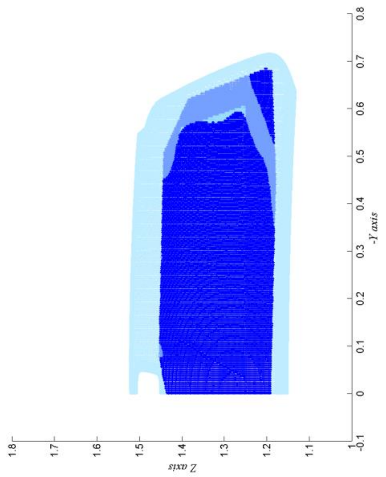
Time	17 min	20 min	40 min
Minimum scenario			
Maximum scenario			

Figure 5-2 Comparison of minimum and maximum scenario in different time steps.

Looking at the geometry of the duct system, it's comprehensible that the particle passed from $zone_1$ has more chance to meet C-P area. In maximum scenario the major part of *energy* is delivered through $zone_1$, so the melted area expanded in the vertical direction. In minimum scenario the main part of *energy* is delivered through $zone_3$ and $zone_5$, thus horizontal expansion occurs. See *Figure 5-3.*

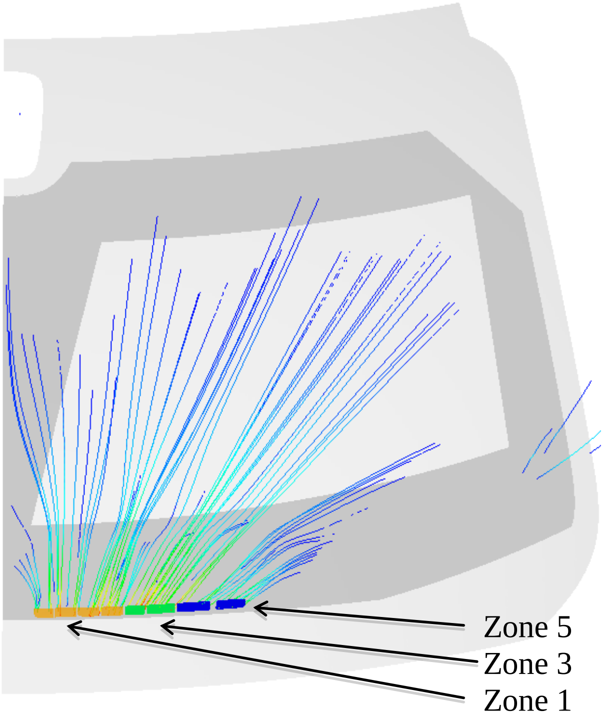


Figure 5-3 Particle direction over the windscreen

Table 5.2.2 The table text should be italic and placed above the table.

	Melted cells after 17 minute		Melted cells after 20 minute		Melted cells after 40 minute	
Area	C-P	A	C-P	A	C-P	A
Minimum scenario	67.9 %	51.0 %	93.6 %	71.7 %	99.9 %	89.3 %
Maximum scenario	68.2 %	52.0 %	91.3 %	71.9 %	98.5 %	87.9 %

The direction of ice melting is quiet convincing. The triple heat-up curves correspond to extreme designs (minimum and maximum) shown in *Figure 5-4* and *Figure 5-5*. At minimum scenario, the $energy_1$ delivered smaller part of energy to the C-P area over the windscreen. This means that more energy is delivered through $zone_3$ and $zone_5$. By considering the geometry of the problem (*Figure 1-1* and *Figure 5-3*), it means that the chances of meeting the C-P area by particle from recent zones are less, so the melted area is extended horizontally.

In *Table 5.2.2*, the melted cells in the minimum scenario for C-P area at 20 minutes and 40 minutes has a bigger value than in the maximum scenario. This is in contradiction with what one expects. The reason is in the minimum scenario, there is inclination toward horizontal expansion. The geometry of C-P area reveals that if the majority of energy is delivered through $zone_3$ and $zone_5$, the melted area inside the C-P area has a reasonable value.

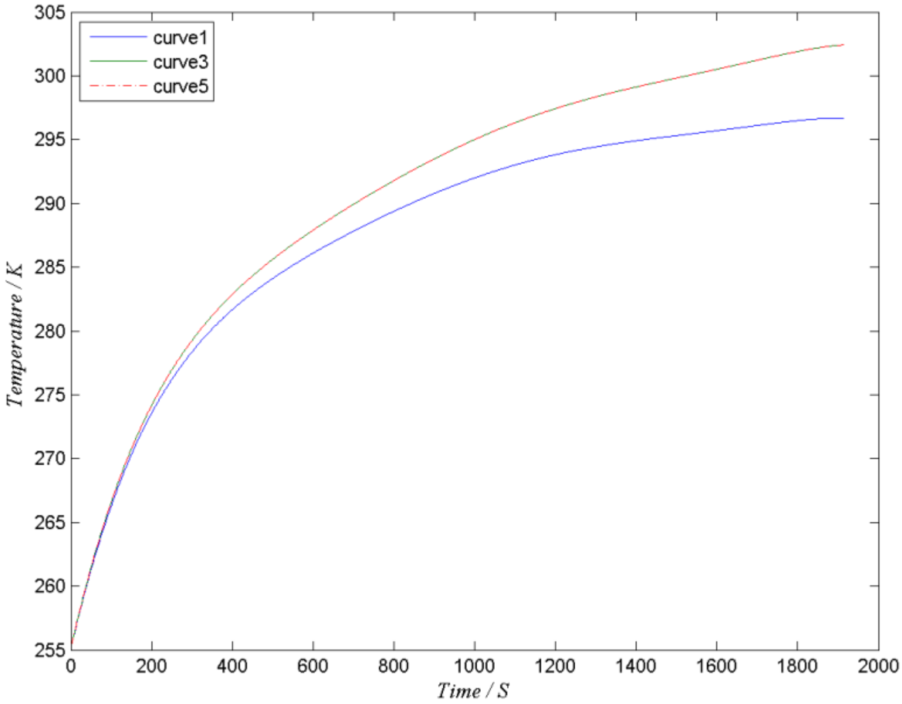


Figure 5-4 Condition of heat-p curves at minimum scenario, heat-up curves 3 and 5 are equal.

In the maximum scenario the majority of energy is delivered through $zone_1$ which is governed by the heat-up curve $energy_1$. It causes the melted area to expand vertically. Therefore the chance of meeting the particle passed through $zone_1$ is increasing at the upper area of the windscreen. See *Figure 5-5*.

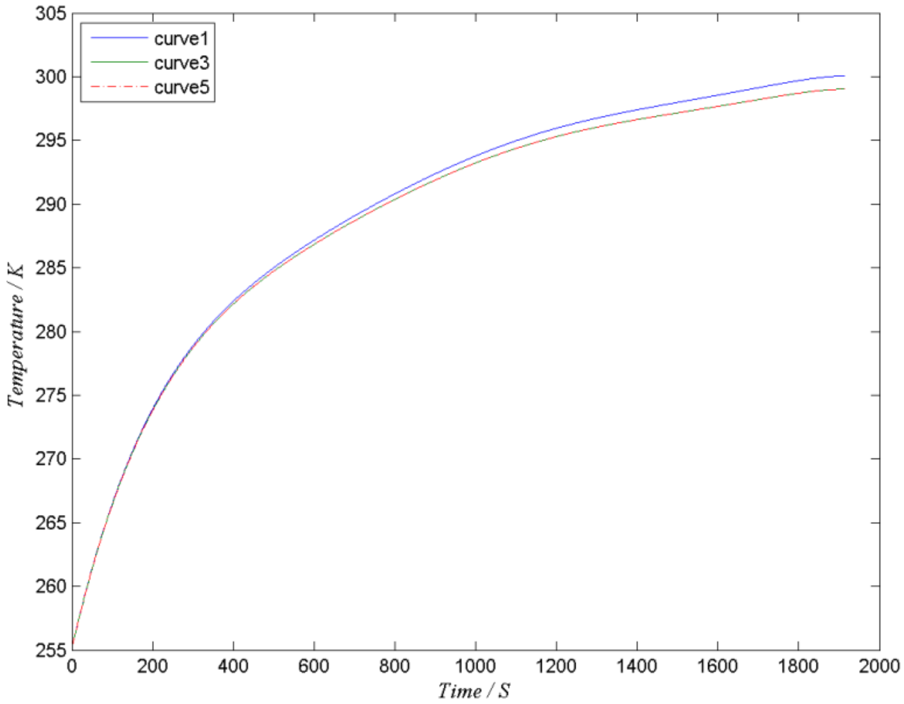


Figure 5-5 Condition of heat-p curves at maximum scenario, heat-up curves 3 and 5 are equal.

It should be mentioned that the best result of the response was obtained when all the curves are quiet similar to each other. This means that they distribute the energy uniformly through the duct outlet panel.

5.3 Statistical Analysis-modeFRONTIER

T-student analysis reveals that $energy_1$ has a direct effect and $energy_3$ and $energy_5$ have an inverse effect on the response, with the same effect size. See *Figure 5-6*.

Also according to the correlation matrix, $energy_1$ and $energy_3$ and $energy_5$ have the same amount of correlation on each other. See *Figure 5-7*. The physic of the problem confirmed this statement. The conditions, which have been set for sampling of design, only approve the designs that are energy and mass independent. As a reminder, in this case study only the distribution of energy over the duct outlet was of interest.

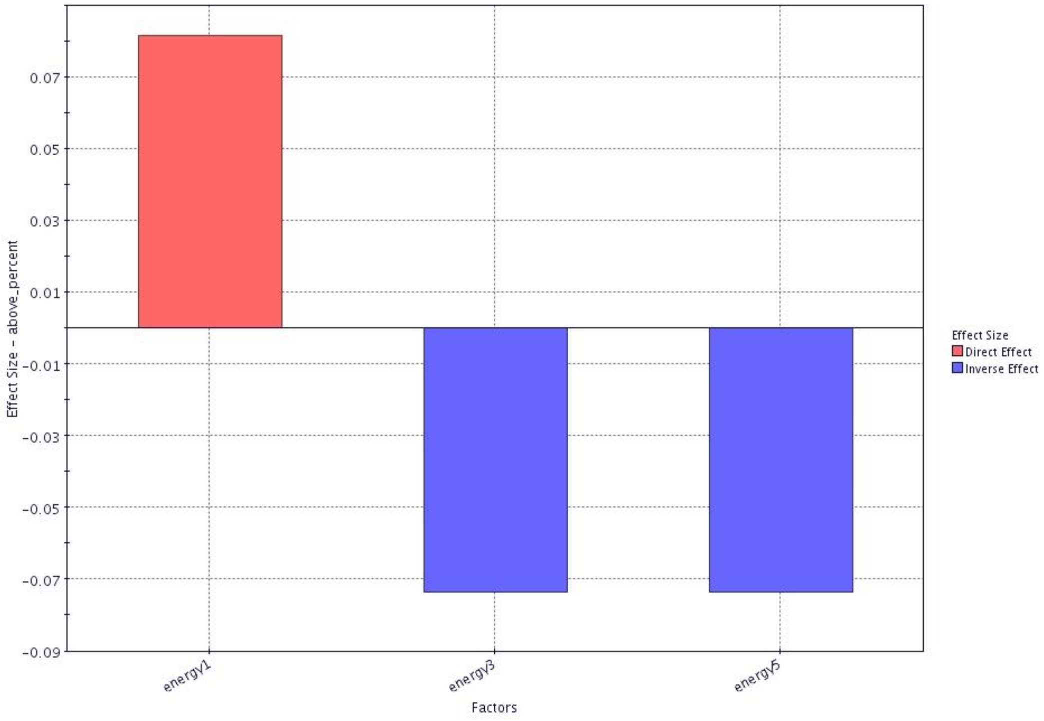


Figure 5-6 T-student analysis

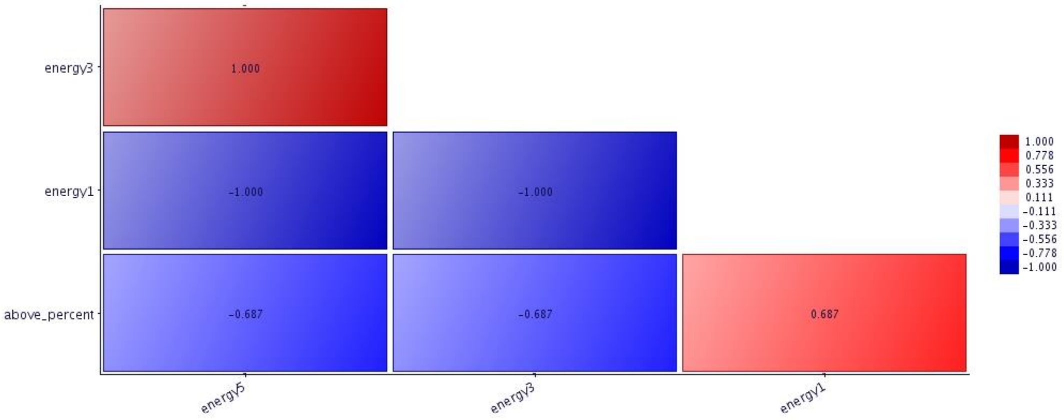


Figure 5-7 Correlation matrix

If one consider the particle distributions that pass through the *zone*$_1$, *zone*$_3$ and *zone*$_5$ it is obvious that most of the particles, which reach to C-P area, come from *zone*$_1$. See *Figure 5-8* that is repeated from section 5.2. It can be the reason for the positive linear effect of *energy*$_1$. If the C-D area or bigger A area over the windscreen has been considered, the results would be totally different. Another notable point is that one couldn't expect to see positive effect of *energy*$_3$ and *energy*$_5$ after 6 minutes over the response.

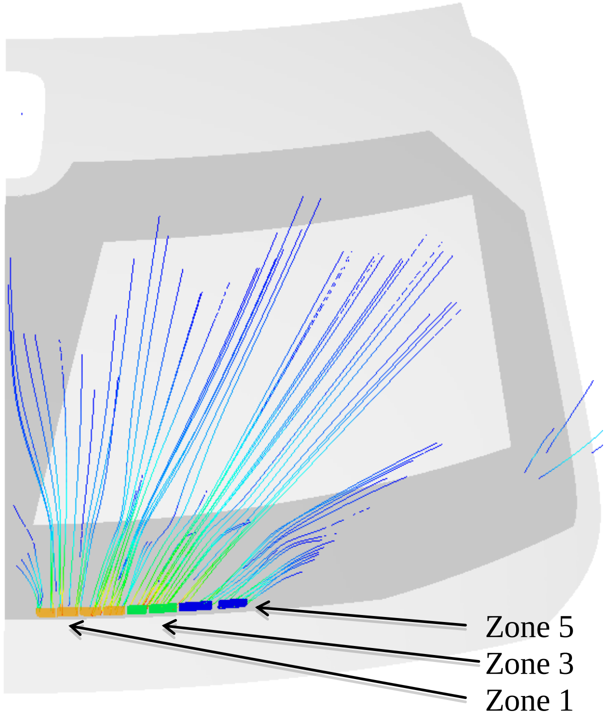


Figure 5-8 Particle direction over the windscreen

5.4 Robustness Analysis

The physical condition of the problem should be considered before studying the robustness. As the smaller C-P area as a response variable is defined, the description of robustness in this particular case is strongly effected by the response domain. $Energy_1$ has a positive linear effect in comparison with $energy_3$ and $energy_5$. In scatter plot, by looking at correlation between input parameters, one can find that inputs are strongly correlated on each other and this means that by increment of $energy_3$ or $energy_5$ one can expect the reduction of the response value.

Furthermore, the dashed line represents a threshold, and one can recognize different trend after and before. The trend switched between linear positive and negative depending on parameter type.

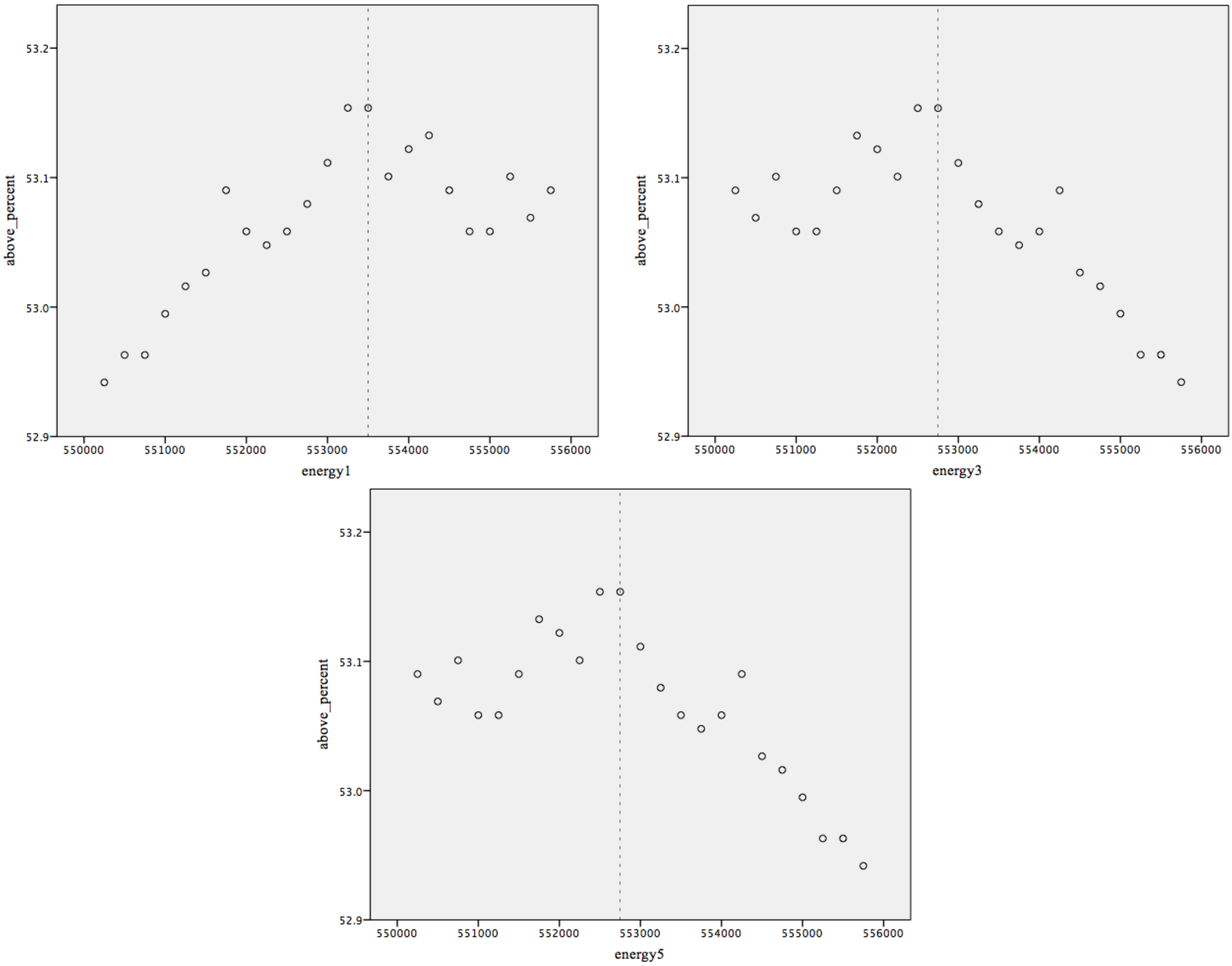


Figure 5-9 Scatter plot of $energy_1$*,* $energy_3$ *and* $energy_5$ *as factors versus above_percent as a response. above_percent shows percentage of ice free area.*

For the scatter plot in upper left *Figure 5-9*, increasing $energy_1$ until dashed line and after that decreasing $energy_1$ determined the behavior of the response. The dashed line could be seen as a turning point. That point could be considered as a local extreme. More or less the same scenario happened for other factors. As long as our design settled in the vicinity of the dashed line, our design is robust.

Another perspective of robustness could be concluded from part 5.2. An insignificance difference between minimum and maximum scenario (*Table 5.2.2*) is another reason of robustness of the defroster duct with regard to variation of energy since the response value after the longer simulation has an almost similar value in minimum and maximum scenario.

5.5 Time Aspect

As mentioned before, the thesis considered shortened version of the real case simulation. Calculation times of each design were made for simplified case, by ignoring the time needed for writing *case&data* file by ANSYS/FLUENT lasts around 20 minutes with 240 CPU's.

Before starting the DOE the user has an estimation of the total job time span. In the screening analysis part 35 designs were run and with consideration of queue, the DOE lasts around 12 hours. For the statistical analysis part there was 23 designs and it lasts around 8 hours.

According to this fact that the CFD methods are computationally expensive, preliminary steps get more important. Comprehensive definition of problem, proper selection of input and output parameters and also sampling method could efficiently save time. In particular at screening analysis step, one can reduce the trial and error time to find the most important factors.

5.6 Experience & Conclusions

There is a large number of statistical analysis software available. The special option, provided by the modeFRONTIER, is the ability of the integration of several softwares inside the unite environment with capability of data communication between them. This data transmission is multi-sided. User can send and receive data to several units concurrently. Also it is possible define loop and conditional unit inside the modeFRONTIER environment.

Apart from the defined built in component, by the shell node, the user can utilize undefined software and link them to the other defined software. Furthermore the capacity of collecting and classifying data is very useful. The user can manage the capacity of computational power, by controlling the number of concurrent jobs within modeFRONTIER environment.

The ability of creating systematic and logical DOE method makes it usable for many applications. The wide range of design parameters could be considered as well as constraints.

The primary plan was using modeFRONTIER options for calculation as much as possible without using further auxiliary software like MATLAB. But some steps have been done manually that was expected to be done within the created workflow inside the modeFRONTIER atmosphere.

At the first step of set up, diagnosing of the errors due to queue system was confusing. In industry the equipment shortage is inevitable. In case of running DOEs with several inputs, the mentioned problem is more substantial. Coupling ANSYS/FLUENT was challenging part and 90 percent of working time spent on establishing procedure.

Generally, modeFRONTIER is not a user-friendly software. There are lots of options that you need to adjust them before execution a workflow. The default value could impose unwanted error to the workflow. Of course this is the nature of problems, but the GUI could be more clear and helpful.

5.7 Reliability

The general method is applicable to other methods. The main structure of employed workflow consists of three distinctive parts, pre-processing, solver and post-processing. Some conditional nodes are included to check if each design satisfies the physical condition of the problem or not. In fact this check nodes by filtering the designs, decreases the computational time.

The developed procedure is compatible to CFD methods that are used in climate CFD team. For all CFD methods there are physical restrictions that should be considered. This data manipulation on input parameter is not compulsory, but available in case of necessity. In the next step, the solver provides the response. Different solver easily could be replaced by FLUENT. Finally post processing for demonstration of result is accessible.

5.8 Future Work

In this case study, by adding more input parameters i.e. geometry dimensions, impingement angles and wall boundary properties, the user can validate more data and analysis. As a complementary job examining the variation of the convection coefficient over the windscreen temperature is of interest.

Sensitivity analysis considers extreme values to give a better perception of the dynamics of the problem to the parameters. In our terminology this means a wider range of variables result in surveying a wider response space. If one look at the problem like an optimization problem, then can define the objective of the problem as a reducing melting time. ModeFRONTIER is a powerful tool for optimization problem as well.

The modeFRONTIER offers possibilities to extend the analysis into optimization and creating meta-models for the future applications. One of the advantages of applying DOE methods in such a numerical modeling could improve the performance of employed model by reducing the number of runs to finalize the ultimate numerical technique. [2]. Using response surface methodology (RSM) to achieve a quantitative understanding of the system behavior over the region tested is another promising option. One can develop a metamodel. In case of large number of input parameters and complicated equations, to have a reasonable response of model, one needs to spend time and resources. The real model assumed is the following:

$$y=f(x_1,\dots, x_n)\equiv f(x),\ x\in M$$

where $x=(x_1,\dots,x_n)$ is the input parameter and y is the response and M is the experiment range. The aim of creating a metamodel is to reach an approximate model $g(x)$ with regard to the real model $f(x)$, where the value $|f(x)-g(x)|$, could be as small as possible. *g(x)* is assumed to be simple as much as possible. Hereby a large amount of time and resources is saved by reducing the complexity degree of *f(x)*. [8]

I Appendix, modeFRONTIER setup

I.1 ModeFRONTIER Version

At the moment of performing this thesis, version 442 to 452 was available. In this thesis version 452 has been used. The Linux OS has been chosen. ModeFRONTIER demonstrates faster and more reliable performance at Linux OS rather than Windows OS.

I.2 Creating Workflow

This section creates a workflow that contains all elements of the discussed DOE approach. At the Node Library toolbar, one can find all required components. Each of the mentioned elements is represented by a special node that is available at modeFRONTIER workflow desktop. In our case, the workflow consists of following main group of components:

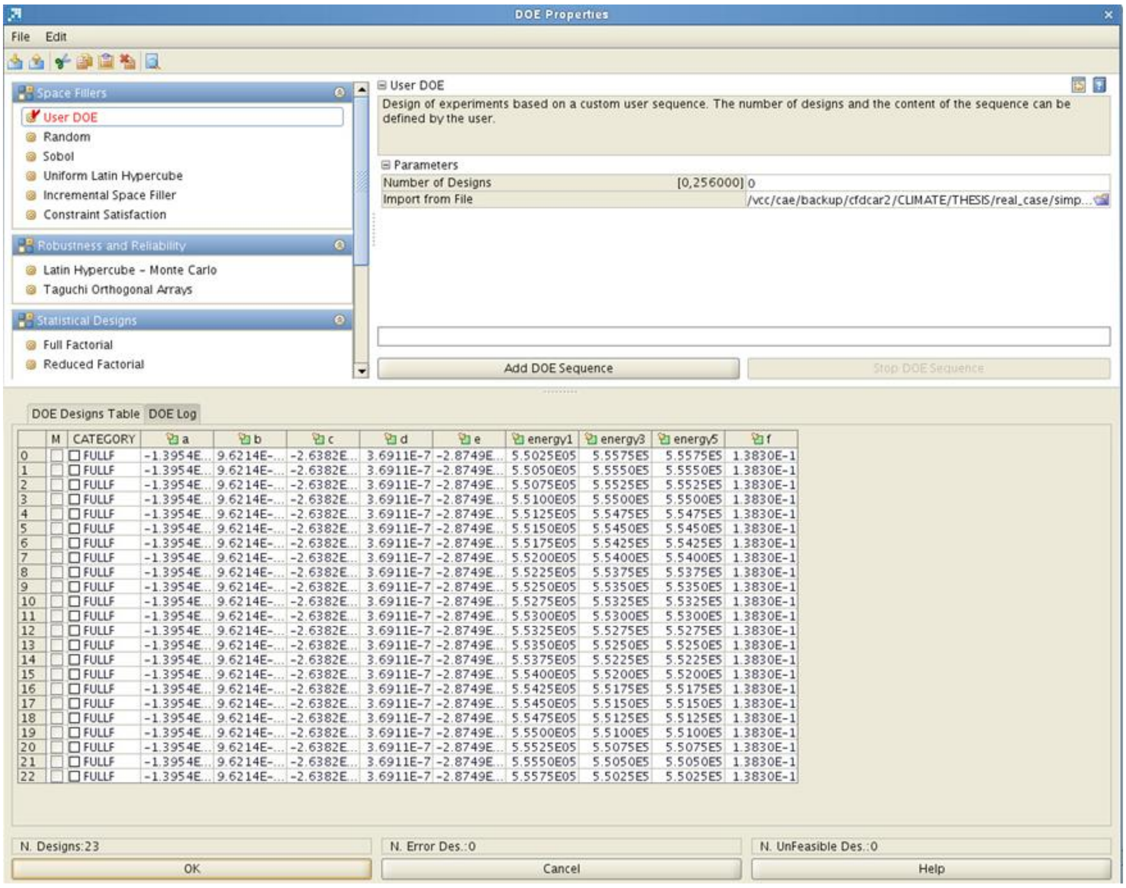
- DOE and DOE sequence nodes
- Input variable node
- Input file node
- Logic If node
- MATLAB node
- Support file node
- Transfer file node
- SH shell script node
- Output variable node
- Exit node

The components above will be described in detail by considering the order of building up the workflow.

I.2.1 DOE and DOE sequence node

At the DOE node, the user will define a proper DOE method. Different DOE methods are available for different application. In statistical analysis part, the full factorial

DOE is selected. In case of choosing full factorial DOE design, the user needs to define the levels. Also if one is going to use manually created designs table, it can be easily imported as an Excel file *Figure I-1*. In the screening analysis step, Latin hypercube method has been chosen.



User DOE

Design of experiments based on a custom user sequence. The number of designs and the content of the sequence can be defined by the user.

Parameters

Number of Designs	[0,256000]	0
Import from File		/vcc/cae/backup/cfdcar2/CLIMATE/THESIS/real_case/simp...

	M	CATEGORY	a	b	c	d	e	energy1	energy3	energy5	f
0	☐	☐ FULLF	-1.3954E...	9.6214E-...	-2.6382E...	3.6911E-7	-2.8749E...	5.5025E05	5.5575E5	5.5575E5	1.3830E-1
1	☐	☐ FULLF	-1.3954E...	9.6214E-...	-2.6382E...	3.6911E-7	-2.8749E...	5.5050E05	5.5550E5	5.5550E5	1.3830E-1
2	☐	☐ FULLF	-1.3954E...	9.6214E-...	-2.6382E...	3.6911E-7	-2.8749E...	5.5075E05	5.5525E5	5.5525E5	1.3830E-1
3	☐	☐ FULLF	-1.3954E...	9.6214E-...	-2.6382E...	3.6911E-7	-2.8749E...	5.5100E05	5.5500E5	5.5500E5	1.3830E-1
4	☐	☐ FULLF	-1.3954E...	9.6214E-...	-2.6382E...	3.6911E-7	-2.8749E...	5.5125E05	5.5475E5	5.5475E5	1.3830E-1
5	☐	☐ FULLF	-1.3954E...	9.6214E-...	-2.6382E...	3.6911E-7	-2.8749E...	5.5150E05	5.5450E5	5.5450E5	1.3830E-1
6	☐	☐ FULLF	-1.3954E...	9.6214E-...	-2.6382E...	3.6911E-7	-2.8749E...	5.5175E05	5.5425E5	5.5425E5	1.3830E-1
7	☐	☐ FULLF	-1.3954E...	9.6214E-...	-2.6382E...	3.6911E-7	-2.8749E...	5.5200E05	5.5400E5	5.5400E5	1.3830E-1
8	☐	☐ FULLF	-1.3954E...	9.6214E-...	-2.6382E...	3.6911E-7	-2.8749E...	5.5225E05	5.5375E5	5.5375E5	1.3830E-1
9	☐	☐ FULLF	-1.3954E...	9.6214E-...	-2.6382E...	3.6911E-7	-2.8749E...	5.5250E05	5.5350E5	5.5350E5	1.3830E-1
10	☐	☐ FULLF	-1.3954E...	9.6214E-...	-2.6382E...	3.6911E-7	-2.8749E...	5.5275E05	5.5325E5	5.5325E5	1.3830E-1
11	☐	☐ FULLF	-1.3954E...	9.6214E-...	-2.6382E...	3.6911E-7	-2.8749E...	5.5300E05	5.5300E5	5.5300E5	1.3830E-1
12	☐	☐ FULLF	-1.3954E...	9.6214E-...	-2.6382E...	3.6911E-7	-2.8749E...	5.5325E05	5.5275E5	5.5275E5	1.3830E-1
13	☐	☐ FULLF	-1.3954E...	9.6214E-...	-2.6382E...	3.6911E-7	-2.8749E...	5.5350E05	5.5250E5	5.5250E5	1.3830E-1
14	☐	☐ FULLF	-1.3954E...	9.6214E-...	-2.6382E...	3.6911E-7	-2.8749E...	5.5375E05	5.5225E5	5.5225E5	1.3830E-1
15	☐	☐ FULLF	-1.3954E...	9.6214E-...	-2.6382E...	3.6911E-7	-2.8749E...	5.5400E05	5.5200E5	5.5200E5	1.3830E-1
16	☐	☐ FULLF	-1.3954E...	9.6214E-...	-2.6382E...	3.6911E-7	-2.8749E...	5.5425E05	5.5175E5	5.5175E5	1.3830E-1
17	☐	☐ FULLF	-1.3954E...	9.6214E-...	-2.6382E...	3.6911E-7	-2.8749E...	5.5450E05	5.5150E5	5.5150E5	1.3830E-1
18	☐	☐ FULLF	-1.3954E...	9.6214E-...	-2.6382E...	3.6911E-7	-2.8749E...	5.5475E05	5.5125E5	5.5125E5	1.3830E-1
19	☐	☐ FULLF	-1.3954E...	9.6214E-...	-2.6382E...	3.6911E-7	-2.8749E...	5.5500E05	5.5100E5	5.5100E5	1.3830E-1
20	☐	☐ FULLF	-1.3954E...	9.6214E-...	-2.6382E...	3.6911E-7	-2.8749E...	5.5525E05	5.5075E5	5.5075E5	1.3830E-1
21	☐	☐ FULLF	-1.3954E...	9.6214E-...	-2.6382E...	3.6911E-7	-2.8749E...	5.5550E05	5.5050E5	5.5050E5	1.3830E-1
22	☐	☐ FULLF	-1.3954E...	9.6214E-...	-2.6382E...	3.6911E-7	-2.8749E...	5.5575E05	5.5025E5	5.5025E5	1.3830E-1

N. Designs:23

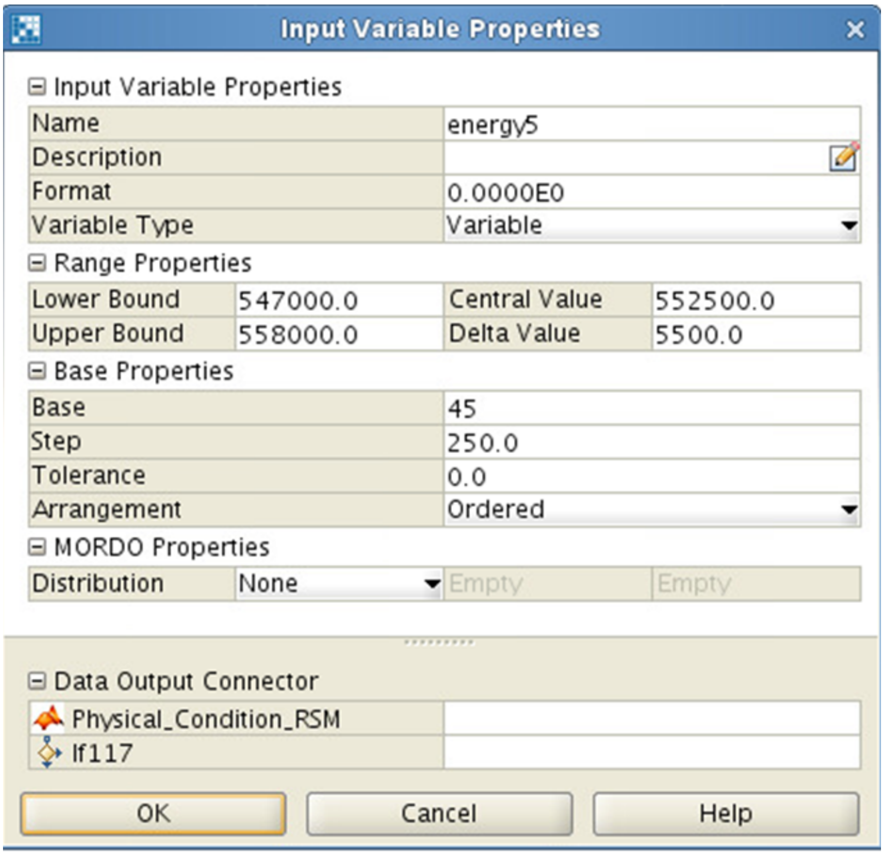
N. Error Des.:0

N. UnFeasible Des.:0

Figure I-1 DOE properties-imported DOE

I.2.2 Input variable node

Since MATLAB node has recognized input variable names, the similarity of input names should be considered throughout the workflow. One needs to define input type, which could be selected as a variable or constant. Also Lower Bound and Upper Bound field will define the minimum and maximum value of variable (range). There are two fields, Base and Step, at Base Properties which in case of necessity, should be defined. Base and Step field take a zero as a default value, which means that the variables are treated as continues variables. See *Figure I-2.*



Input Variable Properties

Name	energy5
Description	
Format	0.0000E0
Variable Type	Variable

Range Properties

Lower Bound	547000.0	Central Value	552500.0
Upper Bound	558000.0	Delta Value	5500.0

Base Properties

Base	45
Step	250.0
Tolerance	0.0
Arrangement	Ordered

MORDO Properties

Distribution	None	Empty	Empty

Data Output Connector

Physical_Condition_RSM	
If117	

Figure I-2 Input variable variables

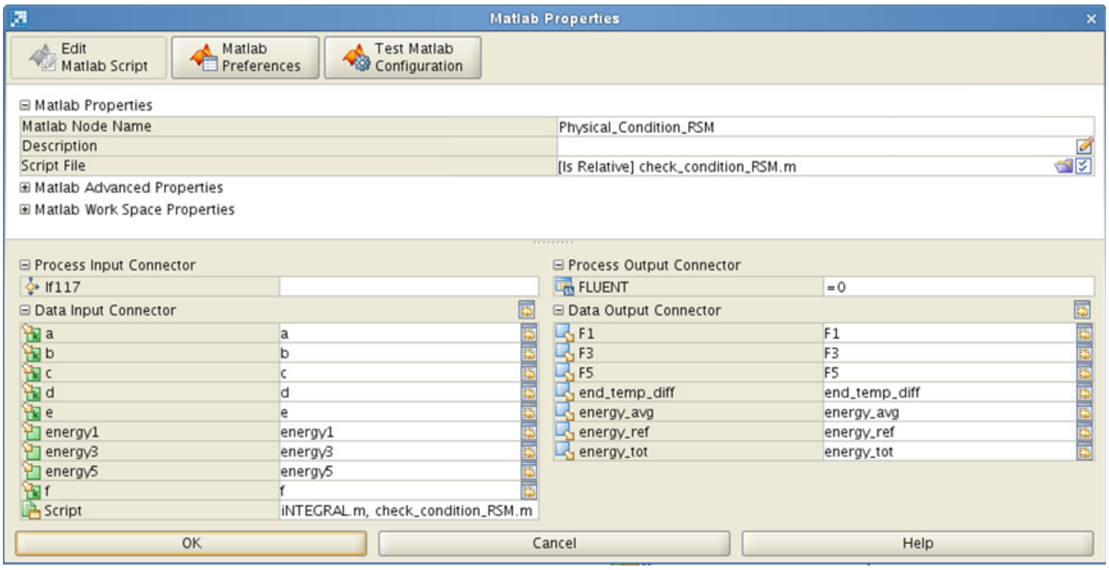
I.2.3 MATLAB node

The workflow contains two MATLAB nodes. The first one which came before SH shell script node (ANSYS/FLUENT), provides information to verify the physical condition of the problem for each deign. The defined input variables are inserted in the MATLB script, while the general structure of MATLAB scripts is saved beside the Script node. In other words, the MATLAB script structure is refreshed by new input variables at each design.

The first MATLAB node provides data for the Logic node(s) to confirm whether the design meets the physical requirements. In case of accepting the design values, data will be used as UDF function in FLUENT node. At the second MATLAB node, which is mainly used for post processing, the temperature data of the windscreen cells will be manipulated to extract desirable information, which here is a percentage of cells that passed the zero degree.

In both MATLAB nodes, the user needs to check the similarity of the names at the Data Input Connector as well as the Data Output Connector. Also the location of the Script File needs to be defined. There is an option, '*is relative*' which allows the user to have updated values for parameters in each design. At the MATLAB Preference tab, the root of MATLAB executable file should be addressed. At the Test MATLAB

Configuration tab, the user can be check if everything is in working condition by MATLAB node. See *Figure I-3*.



Matlab Properties

Matlab Node Name	Physical_Condition_RSM
Description	
Script File	[Is Relative] check_condition_RSM.m

Matlab Advanced Properties

Matlab Work Space Properties

Process Input Connector

If117	

Data Input Connector

a	a
b	b
c	c
d	d
e	e
energy1	energy1
energy3	energy3
energy5	energy5
f	f
Script	INTEGRAL.m, check_condition_RSM.m

Process Output Connector

FLUENT	=0

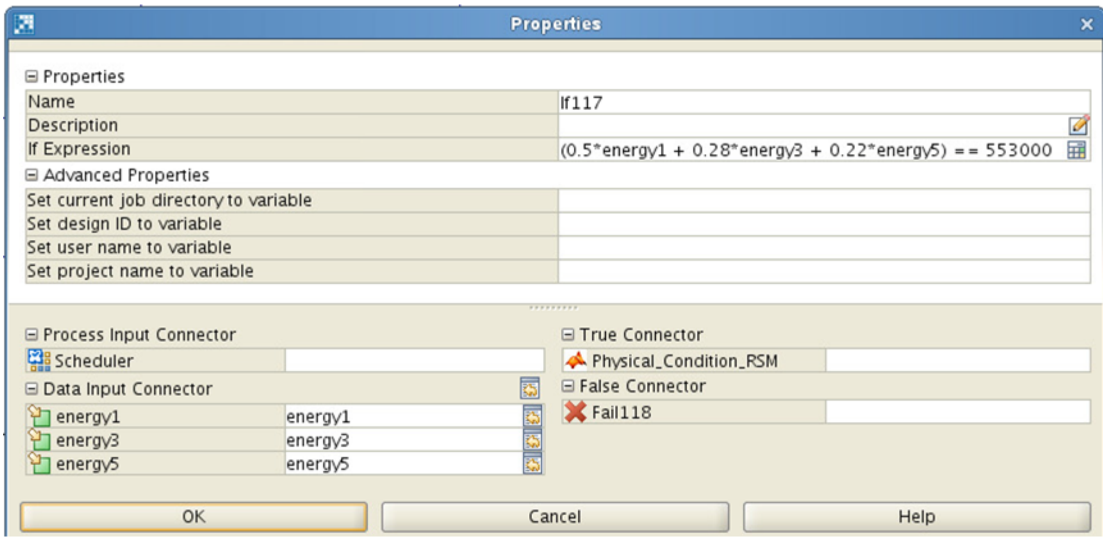
Data Output Connector

F1	F1
F3	F3
F5	F5
end_temp_diff	end_temp_diff
energy_avg	energy_avg
energy_ref	energy_ref
energy_tot	energy_tot

Figure I-3 MATLAB node properties

I.2.4 Logic node

The manipulated data provided by MATLAB node will examine by the Logic node, to be checked if the physical requirements are met or not. In this way, the time is saved in case of improper design so that improper data are prevented before the time consuming numerical calculation step. See *Figure I-4*. The condition(s) are entered in "*If Expression*" field. There are some logic operators available at the Expression Editor.



Properties

Name	If117
Description	
If Expression	(0.5*energy1 + 0.28*energy3 + 0.22*energy5) == 553000

Advanced Properties

Set current job directory to variable	
Set design ID to variable	
Set user name to variable	
Set project name to variable	

Process Input Connector

Scheduler	

Data Input Connector

energy1	energy1
energy3	energy3
energy5	energy5

True Connector

Physical_Condition_RSM	

False Connector

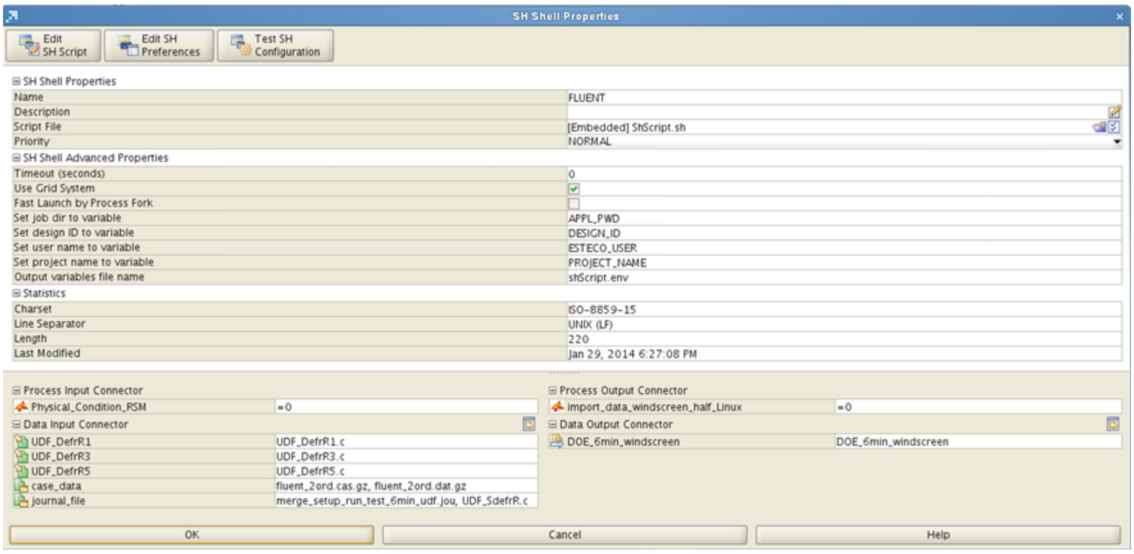
Fail118	

Figure I-4 Logic node properties

I.2.5 SH shell node

With the SH shell script node, the user can run the external solver (or another application) inside the workflow. In this thesis ANSYS/FLUENT is the numerical solver.

Figure I-5 shows the SH sell properties. In the Script File field, *ShScript.sh* file has been located. For this node, '*embedded*' situation instead of '*is relative*' is selected, for the mentioned file. The reason is that the file content should remain unchanged.



⊟ SH Shell Properties	
Name	FLUENT
Description	
Script File	[Embedded] ShScript.sh
Priority	NORMAL
⊟ SH Shell Advanced Properties	
Timeout (seconds)	0
Use Grid System	☑
Fast Launch by Process Fork	☐
Set job dir to variable	APPL_PWD
Set design ID to variable	DESIGN_ID
Set user name to variable	ESTECO_USER
Set project name to variable	PROJECT_NAME
Output variables file name	shScript.env
⊟ Statistics	
Charset	ISO-8859-15
Line Separator	UNIX (LF)
Length	220
Last Modified	Jan 29, 2014 6:27:08 PM

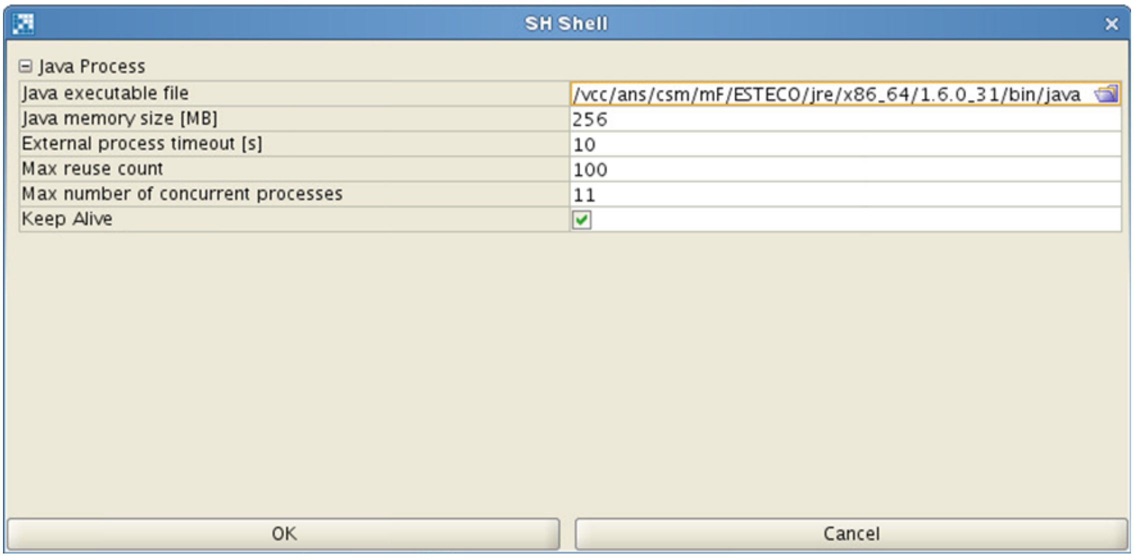
⊟ Process Input Connector	
Physical_Condition_RSM	=0
⊟ Data Input Connector	
UDF_DefrR1	UDF_DefrR1.c
UDF_DefrR3	UDF_DefrR3.c
UDF_DefrR5	UDF_DefrR5.c
case_data	fluent_2ord.cas.gz, fluent_2ord.dat.gz
journal_file	merge_setup_run_test_6min_udf.jou, UDF_SdefrR.c

⊟ Process Output Connector	
import_data_windscreen_half_Linux	=0
⊟ Data Output Connector	
DOE_6min_windscreen	DOE_6min_windscreen

The ShScript.sh file is a bash shell script file which serves as an ANSYS/FLUENT executer.

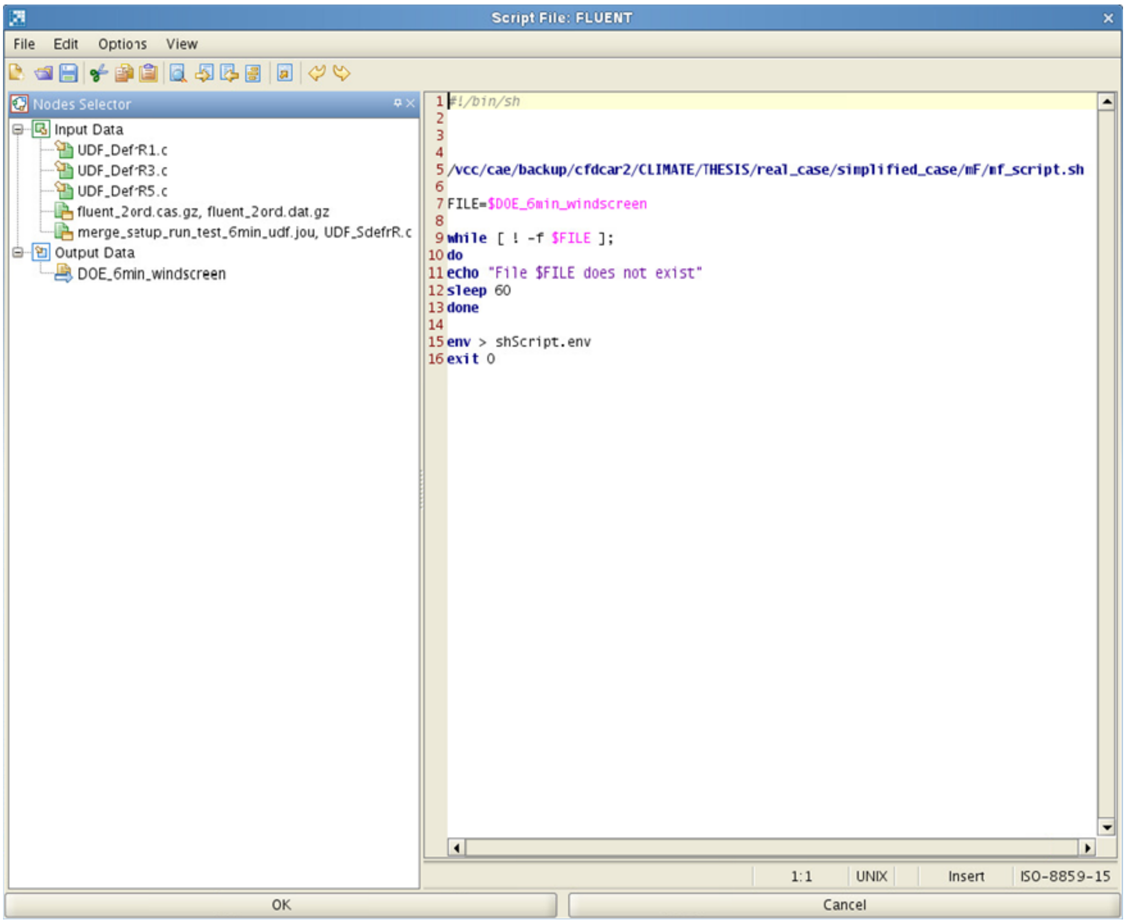
Figure I-5 SH shell node properties

The main configuration for this node is located at the Edit SH Script tab. Proper settings are shown in *Figure I-6*. The while-loop lines secure that since the required data file for second MATLAB node is not prepared, the second MATLAB node will hold and there would be no crash during the calculation. Similar to the MATLAB node, the user needs to define the root address of ANSYS/FLUENT at Edit SH Preference. See *Figure I-7*.



⊟ Java Process	
Java executable file	/vcc/ans/csm/mF/ESTECO/jre/x86_64/1.6.0_31/bin/java
Java memory size [MB]	256
External process timeout [s]	10
Max reuse count	100
Max number of concurrent processes	11
Keep Alive	☑

Figure I-6 Edith SH preference tab settings



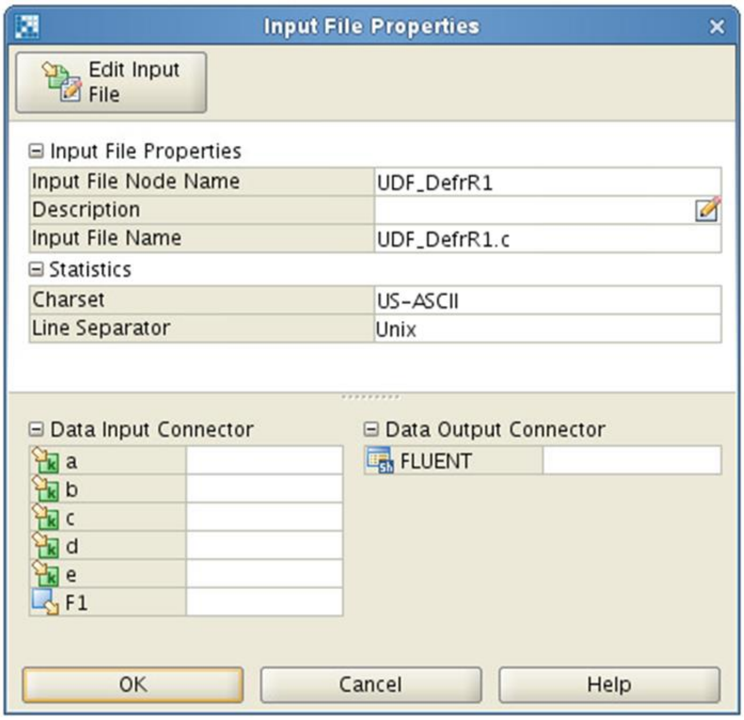
```
#!/bin/sh



/vcc/cae/backup/cfdcar2/CLIMATE/THESIS/real_case/simplified_case/mF/mf_script.sh

FILE=$DOE_6min_windscreen

while [ ! -f $FILE ];
do
echo "File $FILE does not exist"
sleep 60
done

env > shScript.env
exit 0
```

Figure I-7 Script editor

I.2.6 Input file node

Since the mathematical function is a variable, instead of scalar variable, one needs to define it as an input file. The input file contains UDF (user-defined function), being utilized by ANSYS/FLUENT. In our case, UDFs are the heat-up curves. The UDF file structure will be imported inside the Input file node. See *Figure I-8.*

Inside the "Edit Input File" tab, firstly, the user needs to locate the desired file and then specifies characters, which will be representative of variable parameters. By selecting the desired characters, in each design, new values for input parameters are updated automatically. The input parameters are came in columns, below the Template Input Editor, to be introduced as a variable. See *Figure I-9.*



Input File Properties

Input File Node Name	UDF_DefrR1
Description	
Input File Name	UDF_DefrR1.c

Statistics

Charset	US-ASCII
Line Separator	Unix

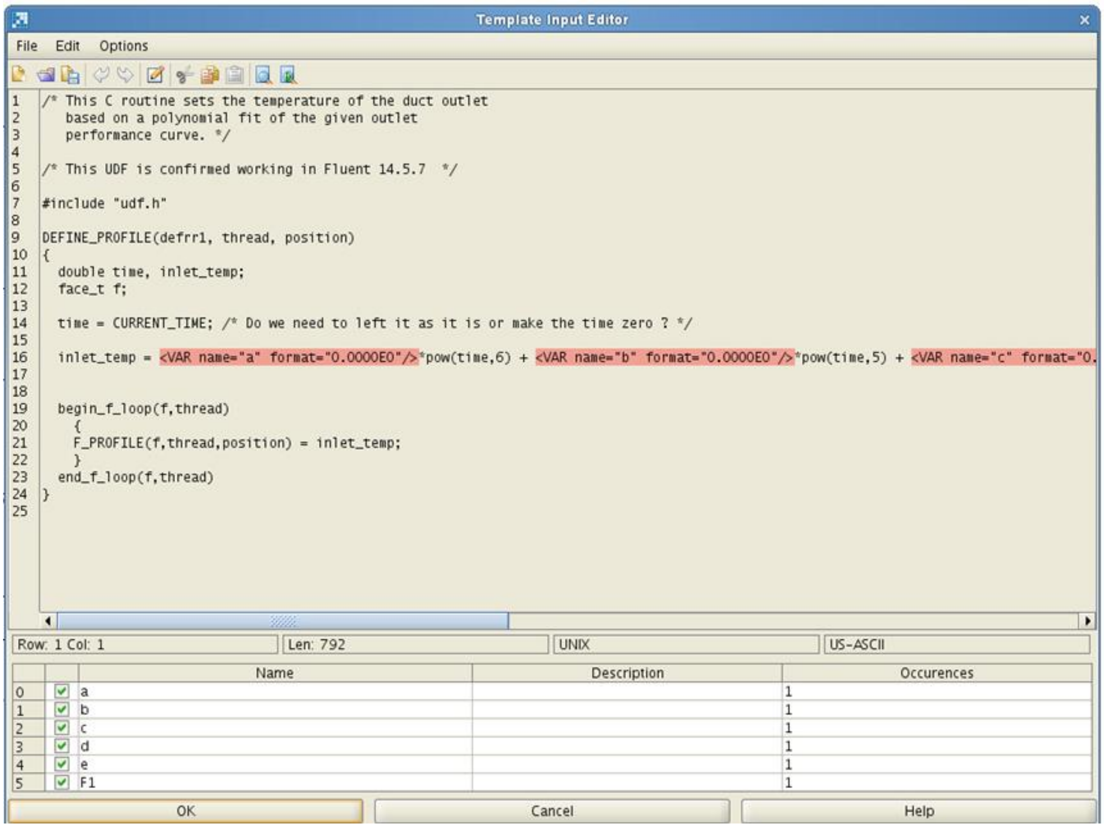
Data Input Connector

- a
- b
- c
- d
- e
- F1

Data Output Connector

- FLUENT

Figure I-8 Script editor



```
/* This C routine sets the temperature of the duct outlet
   based on a polynomial fit of the given outlet
   performance curve. */

/* This UDF is confirmed working in Fluent 14.5.7  */

#include "udf.h"

DEFINE_PROFILE(defrr1, thread, position)
{
  double time, inlet_temp;
  face_t f;

  time = CURRENT_TIME; /* Do we need to left it as it is or make the time zero ? */

  inlet_temp = <VAR name="a" format="0.0000E0"/>*pow(time,6) + <VAR name="b" format="0.0000E0"/>*pow(time,5) + <VAR name="c" format="0.


  begin_f_loop(f,thread)
    {
    F_PROFILE(f,thread,position) = inlet_temp;
    }
  end_f_loop(f,thread)
}

```

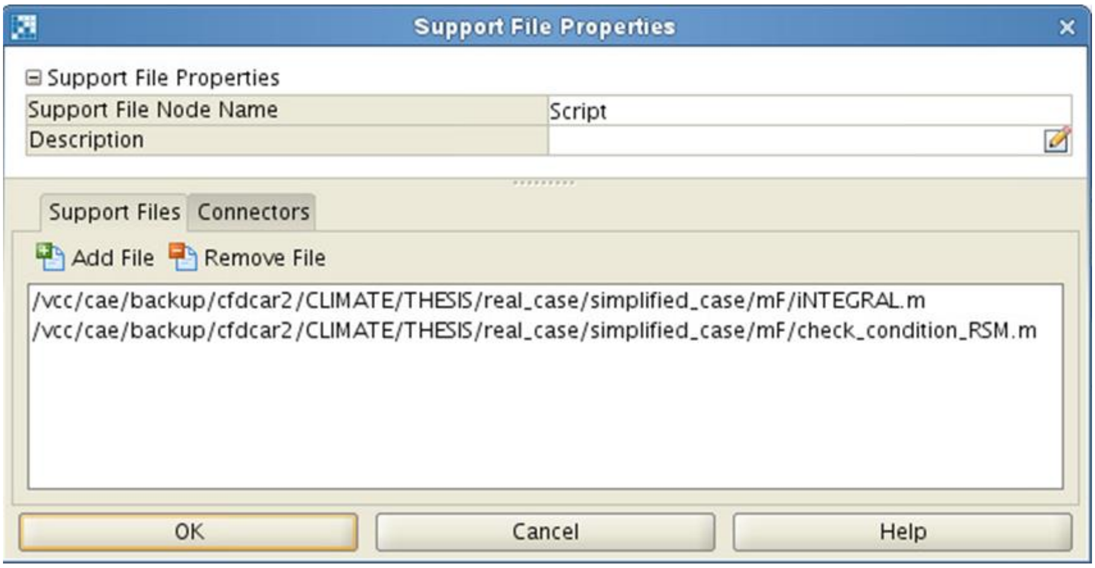
Row: 1 Col: 1 | Len: 792 | UNIX | US-ASCII

		Name	Description	Occurences
0	☑	a		1
1	☑	b		1
2	☑	c		1
3	☑	d		1
4	☑	e		1
5	☑	F1		1

Figure I-9 Highlighted areas show the selected character to be the representative of variable character

I.2.7 Support file node

ANSYS/FLUENT needs to access the *case&data* file and the *journal* file to be executed. One can provide this with the help of the Support file node. In the *case&data* file, the necessary information regarding steady state physical properties and geometry properties are stored. The journal file is a text user interface (TUI) file, which contains the group of commands to run the numerical simulation. The user needs to specify a location of mentioned files and add their address in the correct place. See *Figure I-10*. Also at the MATLAB nodes, the MATLAB script file is addressed via the support file node.



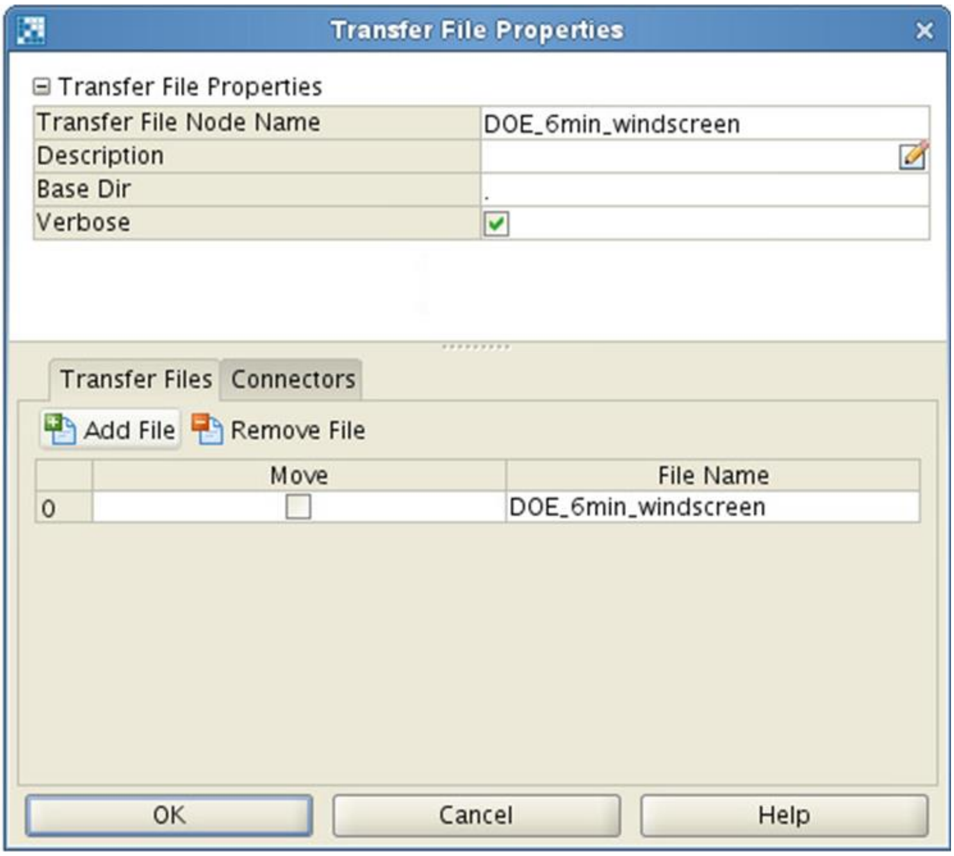
Support File Node Name: Script
Description:

```
/vcc/cae/backup/cfdcar2/CLIMATE/THESIS/real_case/simplified_case/mF/iNTEGRAL.m
/vcc/cae/backup/cfdcar2/CLIMATE/THESIS/real_case/simplified_case/mF/check_condition_RSM.m
```

Figure I-10 Support file properties

I.2.8 Transfer file node

In this case, output variable is the percentage of cells, which exceeded specified temperature over the windscreen in a specific area. Accordingly, windscreen temperature data need to be transferred from the solver ANSYS/FLUENT to a second MATLAB node for post-processing. In modeFRONTIER, the Transfer file node is a proper option for this goal to make sure that the input file for the second MATLAB node is available. The ANSYS/FLUENT creates windscreen temperature data as an ASCII file. The Transfer file node will send it to second MATLAB node directory. The user has to specify the name of the desired file for transferring as well. See *Figure I-11*.



Transfer File Properties

Transfer File Node Name	DOE_6min_windscreen
Description	
Base Dir	.
Verbose	☑

	Move	File Name
0	☐	DOE_6min_windscreen

Figure I-11 Support file properties

I.2.9 Output variable node

The Output variable node will express the result of experiments. The name of this node came exactly at second MATLAB node script.

I.2.10 Exit node

It shows the finishing of the one cycle of experiment. User needs to complete the workflow by adding this node after last operational node.

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[3] Santner, Thomas J., Brian J. Williams, and William Notz. *The design and analysis of computer experiments*. Springer, 2003.

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