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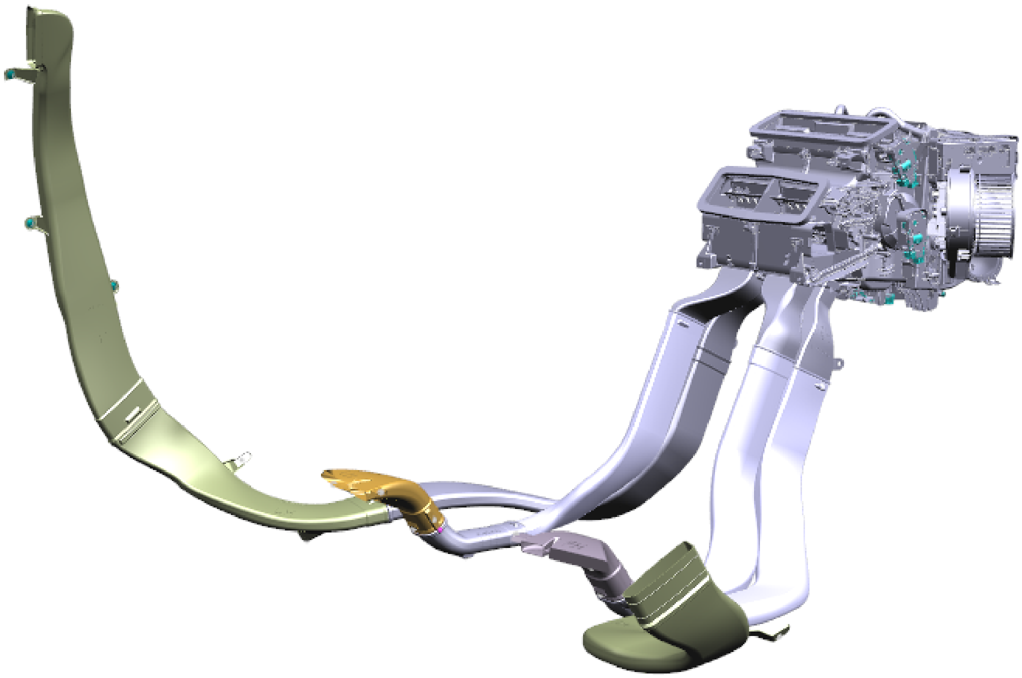

Front-loading short CFD loops to integrate with engineering template

Development of airducts in Volvo Cars

Master's thesis in Master Programme Product Development

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Department of Industrial and Materials Science
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2020

MASTER'S THESIS IN INDUSTRIAL AND MATERIALS SCIENCE

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Develop engineering template and adopt Knowledge -Based Engineering to implement short CFD simulation loops in early product development phase.

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Cover: Air distribution assembly with Heating Ventilation and Air Condition (HVAC) unit.

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Abstract

In this competitive and fast evolving automotive market, it is crucial to progress forward in the product development process effectively and efficiently. One tool to achieve it is using knowledge-based engineering. The design and development of a component in a car is an intensive activity. Engineering template, a knowledge based engineering method is widely utilized to reuse the for-seen knowledge and reduce the lead time for the development.

Though the engineering templates provide us with models that are competent, the model needs to be simulated and analysed before finalisation. In real world, it is not uncommon that the model generated from template, matures before the simulation results are delivered due to newly sprouted issues. This thesis is focused on integration of airducts into engineering template, more specifically airducts in the B-Pillar of a Volvo Car, with short CFD simulation loops in the early phase of product development with which quality models could be created.

A standard product development procedure was followed to develop the solution for the thesis. Planning and pre-study were carried out to evaluate the current market situation and advancements in the field and also in the department. Essential stakeholders were identified and data were collected through interviews and focus groups. With the available information, parametrized template was developed for stable geometry creation for further usage during simulations. The model variants developed through the template were evaluated using the integration methods and results were graphed to compare with the reference result.

This thesis has abridged the gap between CAE and concept design development using quick simulation in the early product development phase. The simulation in early phases is quite difficult, due to the fact, that the available stable CAD model data are scarce and inadequate. The design of the airduct changes rapidly before the CAE team could get back with the simulation result of the product. The developed solution diminish this drawback and carry out short and accurate simulations for the concepts to evaluate them before they are pushed to detail design.

The conclusion of the thesis is, the developed solution to abridge the integration gap by salvaging around 30 minutes of the simulation time and the obtained results are almost accurate as the reference result, deviating between 2 to 10 pascals depending upon the intensity of mass-flow.

Keywords: Engineering Template, Simulation, CFD integration, Short loops, Early product development phase, Simulation and knowledge based design.

Acknowledgements

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I would like to sincerely thank the group manager, Elisabeth Lind, Emilia Lindberg, supervisor at Volvo Cars, Andreas Rydell and Erik Johansson from Climate department for their unceasing support and having unwavering confidence in me.

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I would like to present my sincere thanks to Andreas Dagman, supervisor at Chalmers University of Technology, for his undying support and guidance throughout the project.

Finally, I would like to thank my family and everyone who directly or indirectly supported me emotionally with their advises along the project.

Harish Santhosh Kumar
Gothenburg, September 2020

List of abbreviations

- ART : Agile Release Train
- CAD : Computer Aided Design
- CAE : Computer Aided Engineering
- CFD : Computational Fluid Dynamics
- Gen-Ref : General Referencing model data
- HVAC : Heating Ventilation & Air Conditioning
- KBE : Knowledge Based Engineering
- OEM : Original Equipment Manufacturer
- PDE : Partial Differential Equation
- PLM : Product Lifecycle Management
- SBD : Simulation Based Design
- STEP : STandard for the Exchange of Product
- SUV : Sports Utility Vehicle

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1
Introduction

Volvo Cars, an Original Equipment Manufacturer (OEM), well known for its safety quality, has several components housed inside a confined and complex environment. These housing and clearance issues formulates the ground reasons for various integration and simulation difficulties to achieve the desired target result. These issues are generally resolved by engineers in the later stages of the product development. One such issue, which developed due to the above mentioned issue is addressed in this report to rectify it by front loading the development process.

Knowing the companies background and components produced are essential to grasp the work carried out and this chapter will elaborate about the company's background, problems associated with the complexity of the components and the purpose of the thesis.

1.1 Company Background

Volvo Cars is a premium vehicle manufacturing company which has its Head office located at Torslanda, Sweden. It is a subsidiary of the Chinese automotive company Geely. Volvo Cars Group, though has its headquarters at Göteborg, Sweden, also is wide spread across the world in countries such as America, EMEA and Asia Pacific Region (Volvo Cars Corporation, 2020). They also have production facilities at Sweden, USA, Belgium, China an expanding continuously in other regions as well.

Volvo Cars have been producing various car products such as Sedans, Cross country, wagons, SUVs (Sport utility Vehicle). Volvo Cars has proven its alliance to the world environment cause by stating its phenomenal vision of making 50% of the sales volume, fully electric vehicles by 2025 (Corporation, 2020). The company is devoted to sustainable development.

1.2 Project Background

Generating competent design is paramount. The desires to dominate in the market by producing proficient models, undergo enormous amount of difficulties and ambitious visions as described in chapter 1.1. The difficulties are usual due to complexity of the car and the engineers are aware of it. The engineers at Mechanical architecture and Integration are responsible for integrating these complex components in well defined, constricted spaces. Changes in design, position, size of any of the smallest component, even to merest values, will cause a ripple effect and develop issues which demands for redesign (Persson, 2019).

One of many measure to overcome this issue is utilizing Engineering template, a Knowledge Based Engineering method (KBE). During several years, Volvo Cars has built Engineering Templates in CATIA V5, that contains reusable CAD structures that they reuse for each car project. The advantages with this knowledge-based development process is that it can deliver a greater efficiency, improved data quality and quicker results during development. Engineering Templates has proven very efficient when it comes to creating structured ways of exchanging information between Mechanical Integration, the component owners and the different attributes.

The thesis work is taking this process one step further. The idea is to connect the Engineering Templates output data directly with the Computational Fluid Dynamics (CFD) team, to enable small, fast CFD loops in the early stages as shown in figure 1.1. The black arrows indicate the traditional process which is currently being followed at a traditional company and the green arrow indicates the objective method, to front load the development process with short CFD loops.

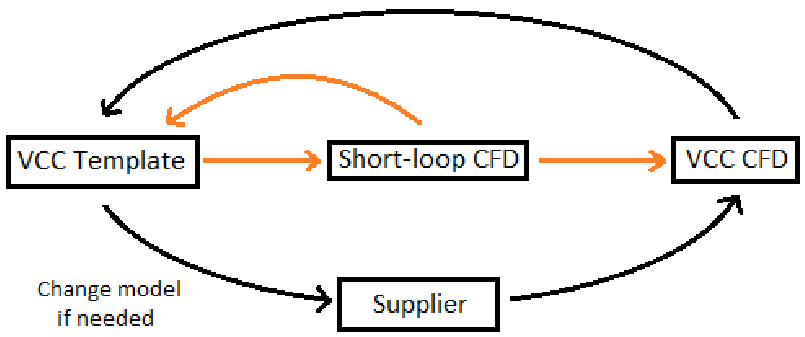

Figure 1.1: Hypothesis of the thesis

The short CFD loop eliminates the involvement of part model suppliers in early stage. Such that the best proposals from the loops could be sent for model development in later phase, rather than depleting resources on counterproductive ideas. The area where it is anticipated is the air ducts of the car. The air ducts are connecting the climate unit with air outlets, and therefore they are routed along the entire car, also through some areas that are very complex and tight from a integration perspective. The air flow simulation feedback from the CFD team is done once the duct routing is completed and part model data is available. In current project, the CFD department are often very late with this feedback which is causing problems and delays in the product development process.

1.2.1 Problem Definition

Current approach to verify the Computer Aided Design (CAD) models using CFD simulation at the end of the development phase are futile, since the designs are modified before the simulation results are obtained.

Volvo Cars being a huge company has several departments working in integration with each other. With this thesis involving departments like Mechanical Integration, Climate technology and CFD team, efforts will be taken to understand, describe the challenges in integrating the air ducts with CFD requirements and develop a solution to resolve it.

The issue under investigation will be that to define an input conditions to the template to provide good simulation output and try to decode an approach for shorter simulation feedback time and faster product development process.

1.2.2 Delimitation

There are few limitations in the thesis which needs to be addressed in this chapter to curtail the scope of the project.

- The constraints and boundary conditions for the flow simulations of the template will not be redefined and they will be reused from previous projects at Volvo Cars.
- The integration of Engineering template with simulation will be focused more in the common area, of the dash and compartment and Climate system of the car, such as the air distribution ducts. For the ease of development process airduct through the B-pillar is taken into account, rather than resolving for the entire airduct system.
- CAD template work will be done in the CATIA V5 environment.

1.3 Purpose

The purpose of the thesis is to use knowledge based engineering to implement CFD simulations in early staged of product development process. To develop a method or a solution to integrate CFD and engineering template to verify various concepts. The purpose with this thesis work is also to investigate the possibility to use the Engineering Template output data as an input to analyse the concepts generated from the template, in order to reach a higher quality and shorten the development process. If feasible, to recommend a method within Engineering Templates on how this process will be conducted. For Volvo Cars, this thesis would benefit in savings of both time and money by building knowledge and ways of working in-house.

1.4 Goal

- The goal with the thesis is to understand and describe the challenges in integrating the air ducts with surrounding limitations.
- Identify the essential boundary conditions needed to create model structures to be able to evaluate the correlation between analysis software and Engineering Template (CATIA V5).
- Try to bridge the gap between CFD models and Template output models.
- Recommend improvement to the current work method and processes.
- Suggest ways to save time within the development process and make the useful tools for Mechanical Integration, Climate Technology Team and CFD team.

Discuss if there are other areas that would benefit from being connected to CFD by the use of Engineering Templates to enable faster looping. Included in the thesis scope is also to generate CAD models that can be used for evaluation of this knowledge transfer. The research questions which have been drafted from the mentioned goals are listed in chapter 1.4.1

1.4.1 Research Questions

- How is it feasible to integrate Computational Fluid Dynamics with Engineering Template in early product development phase?
- How much does the integration methods, to perform short simulation loops, abridged the development lead time?
- How much does the short simulation loop's results does deviates from the actual simulation results?

2
Theoretical Explanation

This chapter withholds the theoretical content and description needed for comprehending the thesis work. Clear explanation about knowledge based engineering an approach to store knowledge and reuse it whenever needed and engineering template, which uses knowledge based engineering. Simulation based design, a method to develop ideas with respect to simulation to obtained quality results and CFD knowledge to comprehend the simulation analysis are addressed in this chapter. The detailed explanation of individual methods already investigated to achieve the goal are discussed in pre-study knowledge section as well.

The product development process as shown in figure 2.1, according to (Ulrich & Eppinger, 2012), starts from phase zero which is the planning phase, where the resources required and need for a product are investigated. Once the resources are determined, the concepts are developed followed by system and detailed design of the selected concept. The concept development phase entitles the process that is described in chapter 3.

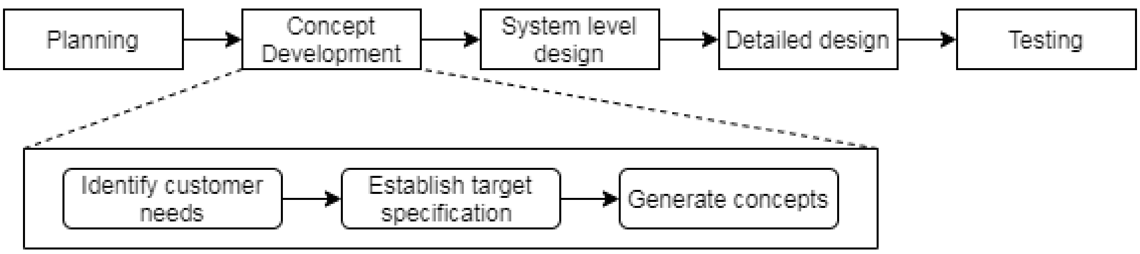

Figure 2.1: Product development process

To carryout the following process, one must gain required theoretical knowledge for the following reasons.

- To familiarize concepts, theories that are needed for concept development.
- To identify existing concepts that could be borrowed to enhance the solution.
- Information which needs to be explained to provide context to existence of current issue of the project.

Integrating Computer Aided Design models, obtained from engineering template, with Computational Fluid Dynamics simulations in the early development phase as described in (Penoyer, Burnett, Fawcett, & Liou, 2000) has always been an issue. This is due to the fact that the output of the engineering template, is completely different to the input of the Computational Fluid Dynamics models. Integrating them directly will be a hurdle, which only could be solved through means which are investigated and will be discussed later in this report.

2.1 Knowledge Based Engineering

The authors of (Josip Stjepandić & Bermell-Garcia, 2015) state that 'Knowledge-based engineering (KBE) is a comprehensive application of artificial intelligence in engineering. It facilitates new product development by automating repetitive design tasks through acquisition, capture, transform, retention, share, and (re-)use of product and process knowledge'. KBE is one of an efficient methodology where the information are stored in a user friendly manner and they are reused, as in Engineering Template, when ever a new product development process is initiated with similar platform as old projects.

Knowledge of intent of the design process has to be acquired, reasoned and communicated to develop a KBE system. Developing a KBE system is similar to developing a solution in the design environment, where the problem is broken down into sub elements and the process is iterated until a satisfactory result is obtained (C.B Chapman, 1999). In this methodology the information are stored in a library and they are retried and (re-)used to achieve different intents of the process.But, this is not the only advantage of using KBE. It finds a faster product development, higher quality, cost reduction and a full automation of lengthy and repetitive activities (Susca, Mandorli, Rizzi, & Cugini, 2000). The architecture of a typical KBE application in the figure 2.2 is described by (C.B Chapman, 1999).

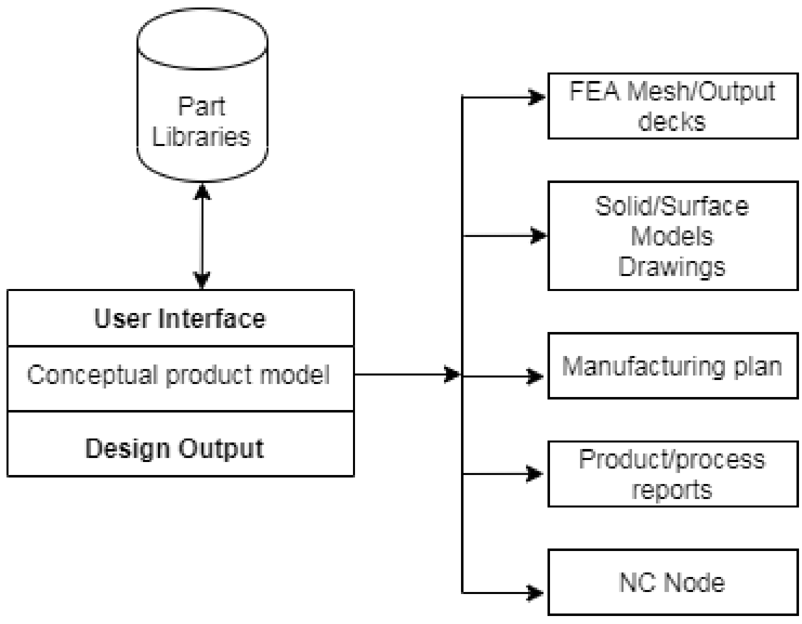

Figure 2.2: Representation of application of typical KBE Architecture

As shown in figure 2.2, the stored knowledge in the library could be retrieved and used for current user interface of the project and the output from the KBE could be anything depending on design intent. It could be a Solid part, surface restriction or manufacturing plan or a FEA Mesh. In our case, the KBE is applied in both engineering templates and in CFD analysis, to store information which could be used later to reduce the product development time, which is discussed in chapter 3.5.

2.1.1 Engineering Template

Engineers at Volvo Cars describe templates to be a master model that is connected in a logical and synchronized flow. It is a way of communicating a collective, agreed, reusable setup that are based on knowledge and experience. This helps in continuous development and handle constant changes. There are various types of templates available at Volvo Cars and its development flow are shown in figure 2.3.

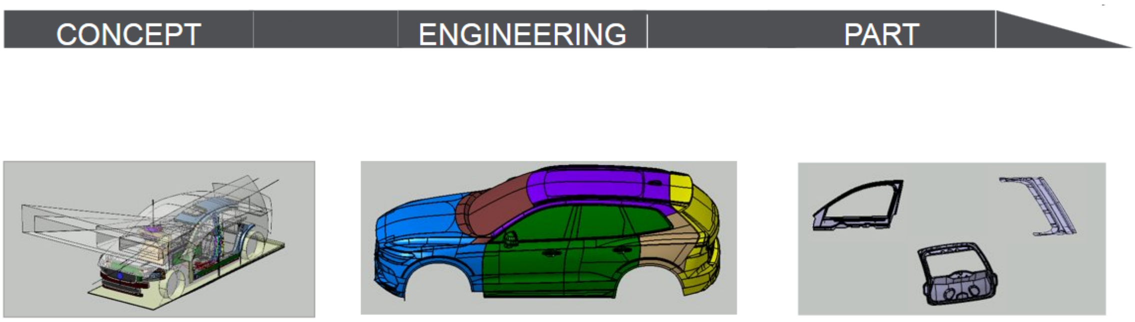

Figure 2.3: Different type of templates and it's development flow at Volvo Cars (*CAD Templates-Engineering templates*, 2019)

The concept templates involves size and requirements that are used in the early concept development of the car. Once the car's concept has been finalised and released, individual component development is initiated. This is when engineering template feeds information to build individual component based on technical input.

Engineering template could be described as, the inputs of design and parameters are fed into the template then a information flow is generated (Persson, 2019). The formation is structured in such a way that the information change in higher level, causes a ripple effect and affects the output in lower levels, but not vise versa. The other way round is avoid because it will create an indefinite loop which will not provide any output.

The development of the engineering template cannot be achieved without cross departmental dialogues and co-operation. Various form of inputs as shown in figure 2.4, from various departments are fed into the model and output such as Volumes, positioning and restrictions surfaces are obtained.

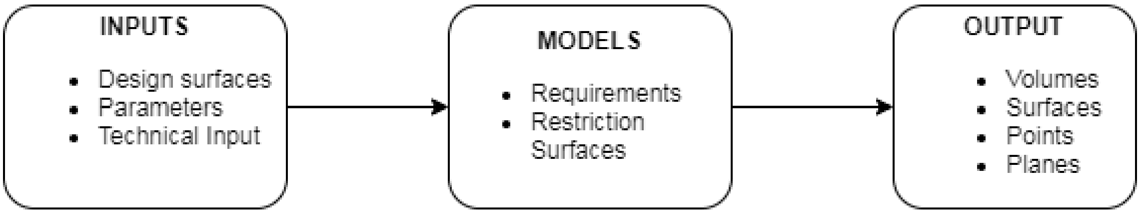

Figure 2.4: Engineering Template Flow

As discussed in chapter 1.2, Engineering Templates has proven very efficient when it comes to creating structured ways of exchanging information between Mechanical Integration, the component owners and the different attributes.

2.2 Simulation Based Design

The ideology of integrating CFD to the CAD output model in the early product development phase could be achieved in multiple ways. But most of it boils down to Simulation Based Design (SBD). In the conventional product development phase, as described in (Ulrich & Eppinger, 2012), a prototype of the model developed and it is tested for it's performance in the post-phases, to verify if it meets the requirements. In this fast, competitive market errors cannot be made and such error if noticed in the prototype testing could be hazardous. It might demand a complete design change or might get lucky with minor changes, but it often costly and time consuming to validate the model. To counter with this, a new approach in the work method was adhered. Simulation of the models to verify them have caused a huge revolution by saving tremendous amount of time.

The article (Shephard, Beall, O'Bara, & Webster, 2004) elucidates the technologies needed to support the application of simulation-based design. Emphasis is placed on the technical components that must be added to existing CAD and CAE tools to enable the application of simulation-based design. The authors discuss that the technology is needed to support SBD and integrating CAD with CAE tools. The need for Simulation Based Design, according to the authors, is due to two situations one primarily to avoid traditional resource consuming, prototyping and testing. Secondly, need for well developed analysis tool to use CAD inputs directly, doing so will reduce enormous time consumed to validate as in traditional approach. Though the SBD is efficient in reducing lead development time by quick validation, it is still requires validation process during development of SBD. This component include a simulation model manager, simulation data manager, adaptive control tools and simulation model generators (Shephard et al., 2004). This approach is implemented in template development which is illustrated in chapter 3.5.

2.3 Computational Fluid Dynamics Concepts

Fluid dynamics is a sub field in Fluid mechanics that deals with the characteristics of the Fluid, namely liquids and gases. Computational Fluid Dynamics is a numerical approach to solve fluid based problems and the fluid flow are studied. The flow can be characterized as either laminar or turbulent flows. The figure 2.5 from (Jamali & Scharfschwerdt, 2017) shows the Laminar, Transient and Turbulent flow in a fluid.

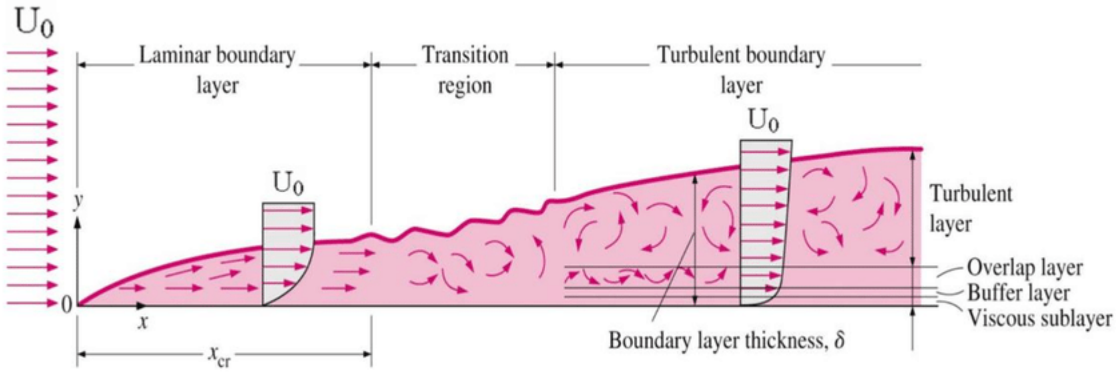

Figure 2.5: Laminar, Transient and Turbulent Boundary layer

They can be simply distinguished using Reynolds number. The Reynolds number is given by the formula

$$Re = \frac{vd}{\nu} \qquad \begin{aligned} Re &\ldots \text{Reynolds number } (-) \\ v &\ldots \text{velocity of the fluid } (\mathrm{mm\,s^{-1}}) \\ d &\ldots \text{characteristic linear dimension } (\mathrm{mm}) \\ \nu &\ldots \text{kinematic viscosity } (\mathrm{mm^2\,s^{-1}}) \end{aligned} \tag{2.1}$$

The flow could be defined, if the Reynolds number falls below 2300, is Laminar flow and if Reynolds number is found to be above 4000, then the flow is Turbulent flow. The flow ranging in between 2300 to 4000 are considered to be transient flow (Khurmi & KHURMI, 2014). Laminar fluid flow is a type of flow where the fluid flows smoothly in parallel without any disruption. In contrast, in turbulent flow where the fluid behaviour changes continuously and create eddies. The formula for Reynolds number, for flow in circular pipe, tubes or for non-circular pipe and tubes could be written as

$$Re = \frac{vD_H}{\nu} \qquad \begin{aligned} Re &\ldots \text{Reynolds number } (-) \\ v &\ldots \text{velocity of the fluid } (\mathrm{mm\,s^{-1}}) \\ D_H &\ldots \text{hydraulic diameter } (\mathrm{mm}) \\ \nu &\ldots \text{kinematic viscosity } (\mathrm{mm^2\,s^{-1}}) \end{aligned} \tag{2.2}$$

The hydraulic diameter for circular pipe is $\mathrm{D_H} = \mathrm{D}$, whereas hydraulic diameter for non-circular pipe is given as

$$D_H = \frac{4A}{P} \qquad \begin{aligned} D_H &\ldots \text{Hydraulic diameter (mm)} \\ A &\ldots \text{velocity of the fluid (mm}^2\text{)} \\ P &\ldots \text{kinematic viscosity (mm)} \end{aligned} \tag{2.3}$$

There are different turbulence models to compute the turbulent eddy viscosity of the fluid, namely

- K - Epsilon turbulence Model
- K - Omega turbulence Model
- Reynolds stress equation Model

2.3.1 K - ε Model

K - Epsilon Model is most widely used turbulence model in the industry. It is a two equation model which is used to calculate the turbulence of the fluid using partial differential equations (PDE). The K stands for turbulent kinetic energy and ε stands for rate of dissipation.

The underlying assumption for this model is that the turbulent viscosity is assumed to be isotropic and the wall effects are not considered within this case. The mesh near the wall are coarser, this leaves to less accurate solutions near the wall.

2.3.2 K- ω Model

K - Omega model is quite similar to the K - Epsilon Model. The different is that the wall effects are present within the case. It performs better for internal flow problems and can accurately compute the flow in the pipes.The ω stands for rate of dissipation.

2.4 Pre-Study knowledge

Despite KBE set out to be very productive, it is not widely used in all industry. Automotive and Aerospace are the two industries which emphasis on knowledge based working. This is because the methodology demands resources and it is time consuming, which not all companies can afford (Colombo & Mandorli, 2011; Hayes-Roth & Jacobstein, 1994). Using KBE to apply CFD in the CAD requires expert engineers in Computer Aided Engineering (CAE) to perform complicated simulations. As (Stefan & Gunther, 2016) describes, The concept changes fast in the early product development phase, raising the need for more efforts to be invested in conversion to simulation model. These adverse aspects should be avoided by making the integration between CAD model and simulation much smoother and easier such that even CAD engineer, who is not an expert in running simulations, is capable of performing it to validate the model's design in early stage. This could be achieved by new software and new technologies.

New methodology and new way of working with software is required to achieve the integration due to compatibility issue between available CAD and CAE. It becomes obvious that to integrate KBE with the simulation, needs changes in classical workflow(Rizzi, Colombo, Morotti, & Regazzoni, 2015). As stated in (Gujarathi & Ma, 2011; Su & Wakelam, 1998), engineers and research such as Su and Wakelam have worked on creating an hybrid system software to solve the issue of integration through a blend of rule based system, artificial neural networks, genetic algorithm into a single environment using parametric approach for model generation. Other method using special software which uses B-spline model, as described in (Kagan Pave1, n.d.), in order to diminish the cost and time associated to developing the model could be used to integrate CAE with CAD.(wan Cao, Chen, Huang, & Zheng, 2009; Gujarathi & Ma, 2011) discusses the integration of CAD with KBE using an API, a software tool for KBE as the CAD system developer. It could be noted from mentioned citations and multiple non-cited findings that software based integration have proven to be advantageous and obvious. Hence software based integration approach was further investigated in this thesis work which lead to multiple software as discussed in chapter 3.6 and its workflows are explained in chapter 3.

2.5 Course Theory

Volvo Cars offered courses on Advanced CAD and templates. It was conducted to feed necessary knowledge to conduct the thesis in a faultless manner. These courses helped to understand and work with templates in CATIA V5 environment.

2.5.1 CAD Advance theory

A two session of CAD Advance course consisted of structured working process of CATIA V5 models at Volvo Cars. The course involved the following topic:

- Flexible link creation - How to build models in a structured link format, such that the part models are created with legitimate dependencies.
- Stable Geometry creation - Building geometries by following building procedure, such as using Boolean operations and proper naming, to avoid causing error when updated with new inputs.
- Surface modeling - How to build surface models and how to build stable structure which could be linked and published.

The course was really productive when creating surface restriction, with links to surrounding components that were published, as described in chapter 3.5. This enabled to create stable structure and conduct the template development without difficulties and failures.

2.5.2 Engineering Template theory

A short crash course on Engineering template was provided instead of complete course due to Covid-19 pandemic disease. It consisted of detailed working and explanation of template in an organization like Volvo Cars. The course explained details about different type of templates available in Volvo Cars and a hands on training on building template models. knowledge about the Information flow and publication of products to reuse without breaking the link were obtained and this was proven to be beneficial while developing the engineering template of airduct in B-pillar area.

2.5.3 FloEFD theory

One of the main drawback as discussed in chapter 5, new software demands knowledge acquisition. To develop a solution using new software, prior knowledge within the software is required. Siemens (*FloEFD Product*, 2020) were generous enough to provide me with necessary materials and a training session to get along with the FloEFD interface. The training provided extreme aid in integration of CFD with Seat and Sill template. Assistance was provided throughout the thesis to resolve multiple issues and errors. The training consisted of familiarising the user interface, running fluid simulation on models and generating parametric analysis to compute and compare multiple model results. An actual simulation was run on the airducts at the end of the training session which showed multiple errors in the model which hindered smooth simulation.

3
Methodology

This chapter describes the workflow the thesis was conducted. The figure 3.1 below shows the pictorial representation of how the work was carried out. The methodology section of the work has separate sub-workflow for template maturity and software integration. This forms the actual result of the thesis which will be further discussed in chapter 4.

The initial step taken during the thesis is planning and pre study, where the existing models and templates were studied and its drawbacks and inefficiencies were broken down and identified. The methods followed to develop a solution are as per (Ulrich & Eppinger, 2012), where the stake holder is identified, interviewed and data are collected. These data are converted into requirement list and customer need, which forms the framework for developing solutions for the research questions that are addressed before in chapter 1.4.1.

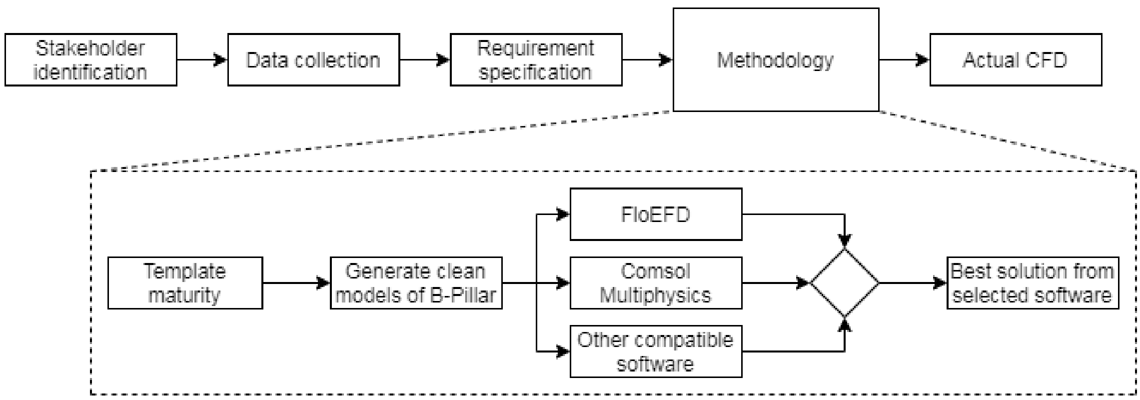

Figure 3.1: Thesis Workflow

3.1 Planning and Pre-Study

According to (Ulrich & Eppinger, 2012),'The product planning process takes place before a product development project is formally approved, before substantial resources are applied, and before the larger development team is formed.' Planning is ultimately necessary to avoid major deviation and resource wastage as explained above. Time planning is part of the planning process.Planning phase also includes mission statement as discussed in chapter 1.4.1 and stakeholder definition.

Apart from resource planning, certain pre-studies have to be conducted to obtain adequate knowledge on thesis area. To achieve this, following studies were conducted:

- Seat and Sill template study
- Airduct routing study

3.1.1 Seat and Sill template study

The current engineering template for the Dash and Compartment sub-group is the Seat and Sill template, Plenum template. It houses all the links and relations to most of the components in the Dash and Compartment of the car. Studying the Seat and Sill template will give the idea of current position and development needed in the template. The template is useful in understanding the available space for the airduct housing in the early product development phase. The space available, though not technically favourable is the only space available which forms the soul reason for birth of this thesis.

The following questions were put forth while studying the template.

- Is the template mature enough?
- What components are critical, for the thesis, in the template?
- How are the parts linked in different levels?
- Where can the solution restriction surface, generated at the end of the thesis be located?
- What drives the space unavailability for the airduct?
- Who are the potential stakeholders?
- Which ART Department's inputs drive the airduct geometry?

3.1.2 Airduct routing study

The study of airduct routing was done primarily for understanding the geometry, dimension and pathway of the airduct. Secondarily to identify adjacent components which drives the position of the airduct, because each car model has different components adjacent to the airduct, depending upon Left Hand Side or Right Hand Side driven car, model of the car etc.

It was noticed from Pilot plant visits and studying all car model's duct routing, that most of the airduct were routed, atleast one-third of it, in the same way as in all cars. This originated the idea of standardizing the airduct section which are common in all cars and simulate the standardized section. This could reduce the simulation time and it is further discussed in chapter 3.5.2.

3.2 Stakeholder Identification

According to (Ulrich & Eppinger, 2012), stakeholders are people or work force who will be influenced by the outcome of the result. The stakeholders could be the end customers as well as the work force which defines the product. The inputs of the stakeholders are essential for developing the best solution.

The pre-study as discussed in chapter 3.1 helped to identify the stakeholders. The seat and sill template study showed already existing stakeholders involved in the template development. Airduct routing study was done to identify other stakeholders which were not included in the already existing template.

As described later in chapter 3.5, the template development also aided in identifying the stakeholders. One could say the previous seat and sill template study and developing a stable template model for the thesis aided in identifying the stakeholders. Initially all departments which are adjacent to the airduct part model were considered a potential stakeholder. In future, the departments which get heavily influenced by changes in the geometry or position of the airduct were considered as vital stakeholders. Mechanical integration engineers, design engineers were focused majorly for the stakeholder analysis, but it was evident in later stages, that it was not just design engineers who influenced the part but also various other departments outside design, such as manufacturing and assembly department, tolerance department.

Thus following stakeholders listed below were identified:
- Floor department
- Door department
- B-pillar trim
- Climate department
- EDS department

3.3 Data Collection

Data sets are vital for analysing the information and streamlining the project. According to (Ulrich & Eppinger, 2012) data collection is one of the essential steps in the product development process. The data obtained are utilised to assess the performance and current ability of the product or the project in that case. These data are usually obtained from peers and professionals who are directly or indirectly involved. The individuals usually form the stakeholders of the project. The data obtained is predominantly, in product development process, used to finalise requirements specification. As mentioned in (Ulrich & Eppinger, 2012) and (Kinnear & R.Taylor, 1995) there are various method through which the data can be acquired from the stakeholders such as,

- Surveys
- Prior research
- Interviews
- Focus group
- Observing the product in use

Surveys were considered ineffective for gathering data for this specific thesis since there is not a demand for a huge data set. The part has been handled by handful of engineers. Hence survey would produce abundant data from engineers who might not have had direct involvement with the design and development of airduct part. The evaluation and segregation of the collected data from the survey would be time consuming and might not produce fruitful conclusion

Prior research was conducted as elaborated in chapter 2, where already existing solution and similar approaches have been studied to pave way for understanding and developing the solution. Prior research on already existing car models from other companies were also carried out to identify the deviation of the design.

3.3.1 Interviews

The stakeholders from various ART department as mentioned in chapter 3.2 were interviewed in two stages in the process. In initial stages to understand the progress and drawbacks of the current models and integration. This gave a overall understanding of the project and current prevailing scenario. The second stage of interviews were conducted with more precise questions directed directly to understand the requirements and needs of the customer. People who are potential stakeholders as mentioned in chapter 3.2 were interviews with set of questions as shown in the table A.1, in appendix A.3.

3.3.2 Focus Groups

People who are directly involved form the focus group, since their information drives the majority of the project and they are the individuals who hold the essentials in formations for the project. In this project, the focus group is an amalgamation of different departments who fed the requirements for the template development and integration of the CFD with the template.

The Focus group can still be sub-divided into two cluster for easier understanding and segregation of the data. The first cluster of focus group comprises of engineers who have been involved in template development and design engineers who develop the design surfaces. These input design surfaces form the input for the Level zero in the template tree. As explained in chapter 2.1.1, the templates are built from level zero followed by other inputs from various department which follow the flow of information. Hence interviewing the design engineers to comprehend the relevant data in aid to build the template will form the first set of focus group.

The second cluster of focus group encompasses, CAE engineer and climate department engineers. Interviewing this focus group would give in-depth understanding of flow characteristic, essential inputs for an efficient airflow, pros and cons of airduct body design. These aspects play an enormous role in developing an airduct. In that case, they would also provide an indispensable input for template development, such that the template models that are built are upon a strong simulation verified skeleton. The strong entanglement of both simulation and design inputs in the template structure would provide us excellent models that meets both design and CFD requirements.

The focus group paved way for the development of the thesis. The names of the people interviewed are kept unrevealed due to confidentiality reasons. Questions related to current drawbacks and future plans were discussed in depth with the groups. This gave a clear picture of what needs to be done and what was expected from the project. It could also be said that the information gathered from the focus group scoped the thesis.

3.3.3 Study visit to the plant

Following customer interaction with the product gives multitude of information as much as a focus group interview. It also brings spot light on practical issues and commonalities in the product. To perform something similar to real time interaction with the product, couple of study visit to the manufacturing plant was carried out. Airduct design and positioning of various Volvo car's models were studied. They showed commonalities between different airducts and the fact that many part of the airducts could be standardized were identified. Standardization of the airduct would reduce the manufacturing time and cost to a greater extent. Where design for manufacturing is becoming a thing, standardizing the part for easier handling and immediate availability seems to be efficient. This is further discussed in chapter 3.5.2.

3.3.4 Bench-marking

As discussed above, prior research were carried out to identify variation in airduct models from other companies. Carefully accessing the competitive product is essential to position our new product (Ulrich & Eppinger, 2012). Bench-marking would reveal already prevailing concepts in the industry and one could identify which concepts have been proven to work and which has not. On such bench-marking the airducts, with existing airduct of other competitive car's airducts have helped in fixing the inputs for the template development. It also presented a method to generate restriction surface, which would mark the limit for the best of all airducts, within which the model would provide best results. This is further discusses in chapter 3.5.

As described in (Ulrich & Eppinger, 2012) the raw data obtained from data collection are used to interpret the needs of the customer and the needs can be further segregated to primary needs which are the must to be fulfilled in the process and tertiary needs which may or may not be fulfilled. Based on this, the next chapter 3.4 talks about the specification of the requirements.

3.4 Requirements specification

Identifying the stakeholders and customers needs is itself a process, for which a five step method is followed that is explained in (Ulrich & Eppinger, 2012). To apprehend the customer requirements one must gather data from the customers. These are usually done through interviewing groups of people or individual who will play a vital role. The data collected and methods are discussed in chapter 3.3. There are different means through which you could gather the essential information from the respective individual who is involved in the project. The information obtained during these process are generally crude and not specific. One must have to interpret the raw data in terms of customer requirements to set the specification. Thirdly these specifications have to prioritize since all needs cannot be satisfied completely in a pragmatic world. Hence establishing a relative importance of the needs will be beneficial to focus the development and reflecting on the results obtained from the process.

The data collected as discussed in chapter 3.3 was interpreted and a list of requirements were generated. Since the thesis involves two objectives which works side by side to achieve the integration of the template with CFD, there are two requirement lists.

We can observe the black box method that is showcased in figure 3.2. Black box is a dominant tool to understand the overall function of the product (Ulrich & Eppinger, 2012) and also to evaluate what needs to be done to achieve the required output with the available input. Black box is commonly used tool in product development process. The black box comprises all the sub functions which happens within, to attain the result.

The figure 3.2, shows that the department inputs are the only information we would posses at the initial stages of the project and it is expected to deliver a CFD competent model and to abridge the gap between simulation and the modelling at the early product development cycle. The in between process is unknown, that is exactly what black box comprises of. That is anything which happens within the black box is indeterminable at the beginning stages and one has to prepare a process flow model to understand what happens within the black box. This method gives a guideline how the inputs we hold at the beginning could be streamlined such that the desired outputs are achieved.

In our case, the knowledge from the pre-study of airduct templates already available and simulation methods that are carried out which have been proven to not reach the desired goals were gathered. It is evident and as described in the paragraph above the end result have to a competent model that needs to abridge the gap. This is of course difficult due to the fact, that CFD and model development have different input and output respectively which do not meet and the task is to find a platform on which they could integrate.

The inputs from the ART, departments and knowledge acquired needs to be translated to requirements. The need for two requirements, one for template development and other for CFD simulations was figured and these requirements forge the complete requirement list that would compliment both objectives. Hence two way arrows indicated that the CFD simulations and Template models will aid the requirements and vice versa. But abridging the gap through some means is unknown as denoted by a '?'. By resolving the question mark one would end up developing CFD competent models that would meet both requirements.

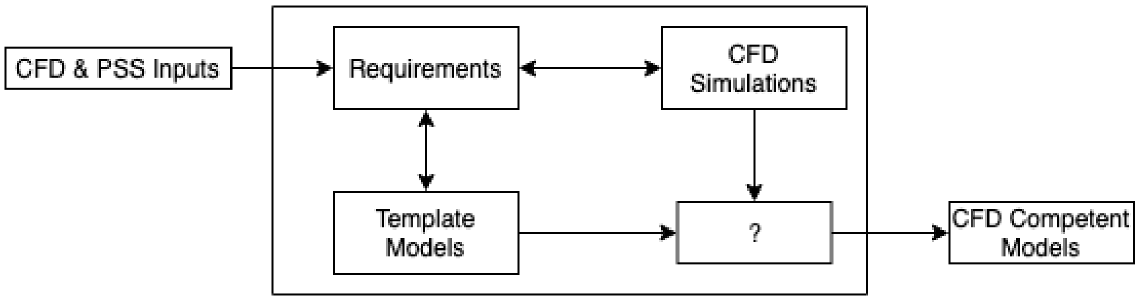

Figure 3.2: Black Box approach to identify the overall process

Due to non existence of airduct template at Volvo Cars, it is necessary to build a airduct template, with respect to surrounding input design restrictions, for future concepts to be developed and simulated. The concept models from the template could be directly utilized in simulation environment to assess the concept's competence even before the concept could be developed in detail in later phases of product development. The template requirement list holds the necessary objectives that need to be satisfied to obtained a robust template and they are as following:

- Flawless information flow through the hierarchy.
- Able to update the model to new designs without errors.
- Flexibility to change the pathway of the airduct with respect to inputs.
- Less time to update the model.
- Standardization of the model.
- Store knowledge in template for future CAD modeller and investigations in platform.
- Use CFD inputs for better quality solutions.
- Models are CFD competent.
- Input to tree such that it does not affect the flow of information in the template much.

It could be noted from mentioned citations and multiple non-cited findings, as discussed in chapter 2.4 that software based integration have proven to be advantageous and obvious. The solution for CFD integration must have the following requirements

- Able to connect Engineering Template output data with CFD.
- Shorter simulation period.
- Faster loops.
- User-friendly interface.
- Able to compare solutions.
- Applicable in early development phase.
- Produce good results/Low error percentage.
- The software could be Inbuilt/Embedded for better user experience.
- Lesser need for meshing.
- Able to simulate turbulent flows.
- K-Epsilon realizable model.
- Pressure/Mass flow rate as output.
- Parametrizable.

These requirements form the inputs for identifying the solutions. The software selected and template developed are based on the above listed requirements.

3.5 Template Development

From the figure 3.1, it is inferred that template maturity is the foremost stage in the methodology. Once the stakeholders, customers and their needs, requirements have been identified, one possess enough knowledge to dive into the process of developing the product. In our case, one need to develop a stable model platform on which each concerned developer or engineer can operate, which is currently not available or not update such that it can be competent. The matured stable models then can further be integrated with the Knowledge based engineering in the early product development cycle. This would integrate the CFD simulations with finely bolstered model, whose structure need not be altered quite often apart from changes in design surfaces, which are design inputs to the model, itself. Hence reduces the chances of failure of integration.

Since such model is not completely fabricated and certainly not built for the sake of integration of simulation with the model, there are various discrepancies which needs to be addressed in the chapter. The development of the template is a humongous and vast job by itself. Hence, inevitable developments which would be profitable for abridging the gab between CAD and simulation in early product development phases were carried out. To do so various approaches and tertiary developments which are directly not linked with abridging the above gabs mentioned, were also performed for smoother transition.

Similar methodology, as followed by (Persson, 2019), were pursued to develop the template. This is for the reason that, Volvo Cars follows a predefined procedure to build template models. The model was developed in CATIA V5 interface. Apart from it, the airduct template model itself was subdivided for Tertiary goals. This is to suffice the need for standardization. This chapter consists of detailed explanation of the structure of the template and necessary inputs from adjacent departments and how the information from neighboring ART were utilized to construct the restriction domain for the airduct. How knowledge based engineering could be utilized to achieve superior airduct models, which would meet the simulation requirements, yet satisfying the integration issues. Finally, how those KBE approach was used to build restriction surfaces. Hence, it could be listed as

- Template structure and model
- Using KBE in Template
  - Restriction surface

3.5.1 Template structure and model

The template for the airduct was built in CATIA V5. The software at Volvo Cars were slightly modified for the convenience of the designers. Training were provided for engineers who were gonna work on CATIA V5 at Volvo Cars in order to cope up with the changes and regulation Volvo Car Corporation has imposed on developing a model. This is explained in detail in chapter 2.5. Hands on training and intense theory sessions were conducted to master topics such as flexible link creation, stable geometry creation, integration with PLM system. These training assisted in developing a stable template geometry at the end.

Once the necessary data has been collected from the data collection method, the information is deciphered to customer requirements and inputs. The inputs for template development were listed in chapter 3.4 and several departments were involved in this stage. Initially departments adjacent to the part model were considered as vital inputs. For example, Door and side department, Floor department, Electrical department and many more. In later stages, the departments or ARTs which gets impacted directly due to changes in the geometry of the airduct were filtered and considered as essential input departments.

The designers or integration engineers who have been involved previously in other car models from those influencing department were shortlisted and interviewed. The models obtained from these departments were introduced in General referencing (Gen Ref), which is the driving level based on which the part model flows its information. It could also be said that the models from department, loaded in Gen Ref formulates the restriction surfaces or driving geometry for the airduct modelling. Floor part model, Seat and sill model, B-pillar surface model, EDS model were loaded in the Gen-Ref since they were the immediate parts which were directly influence by variations in the airduct. The figure 3.3 shows the tree structure of the Gen-Ref in CATIA V5.

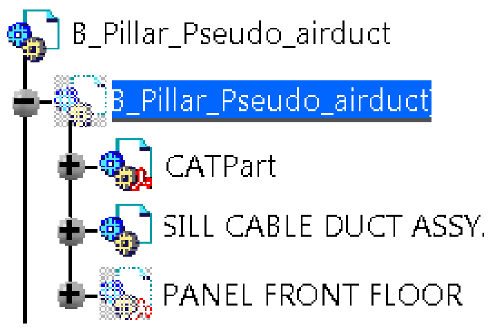

Figure 3.3: General Referencing tree

As mentioned above, the airduct model is subdivided to segments for finer control over construction of the airduct. The HVAC system studied in this case consists of four aiducts, they constitute the technology of vehicular environment comfort. They provide thermal comfort inside the car. The left hand side B-pillar airduct is considered for this analysis. It is divided in three segments as shown in the figure 3.4.

The section 1 is the top most section, which forms the outlet of the airduct. The outlet airflow is directed inside the passenger cabin. The second section is the middle of the airduct and it is the most complicated section. The source of this thesis is predominantly due to integration problem in this section, hence this section would be the most focused area in the entire system. The middle section of the airduct also possess intricate details, along with closely packed models with minimal tolerance, which makes modelling of this section laborious. The third and final section of the airduct is the one which connects it to the HVAC system. Hence, it forms the inlet. This is also commonly used section in all models of the car which allows us to work more on standardization, this is glanced briefly in next chapter.

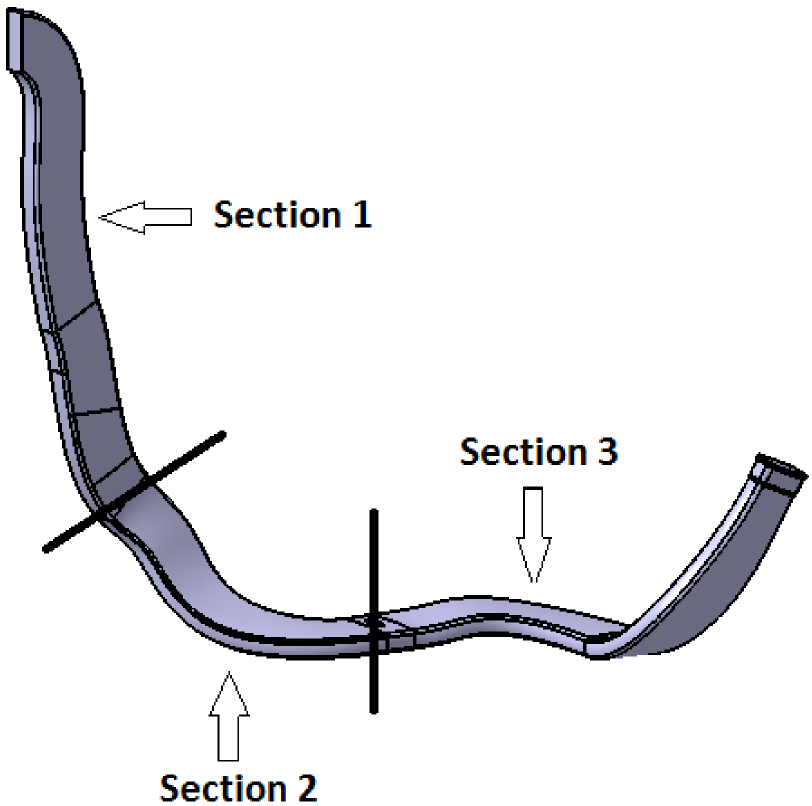

Figure 3.4: Sectioning of the airduct

The EDS system, B-pillar surface and Floor panel, all defines the geometry of the airduct. They are also used as external references in the tree. Each section of the airduct is modelled individually in correspondence to the respective external reference that would be affected. The section 2, as described above, being the vital section is used as the backbone for modelling the entire airduct. Once the mid section is modelled the rest two section is followed using spine command. The shape of the airduct is controlled using parameters in the mid section. the clearance between the B-pillar and the airduct is also controlled using parameters. Two line curve command is utilized to define the intricate twists the mid section undertakes. Hence, two spines are used to achieve the complex twist. Section three is the standardized section and it remains the same for all models.

It could also be said that the end of the mid section was routed in such a way it meets the beginning of section three. This was done to achieve easy interchangeability of section three with any other model and also to maintain a standard airduct section throughout the development. The third section was finalised as a standard section due to various reasons discussed in the chapter 3.5.2. The length of section one is defined based on type of platform the car is developed on. Here, the car class such as Cross Country wagon, SUV, Sedan plays a major role in defining the height of the airduct. The height of top section can be controlled using a spine and a profile which fixes the design of the outlet. Usually a nozzle is attached to the outlet and it was also standardized in future process.

As said before, parameterization was done to achieve flexibility and to save valuable time spent on remodelling for various dimensions and rectifying the errors that arises from remodelling. Parameterization is the agile way of creating a model. Companies now produces excessive design variants and modelling each and every model individually is a arduous task. This is where parameterization plays a vital role. To parameterize the model, it must be built stably. The stability of the model structure is very essential for generating a error-less part. Parameters are usually variables which are linked to the dimensional constraints. This allows the user to vary the input and obtain the new part with respect to the new dimensions. Parameters could also be restricted to a certain range in order to avoid inexperienced users crashing the model. Parametric modelling helps the user to achieve design objectives quicker with real world behaviour. It could be noted that one of the major characteristic of parametrization is attributed that are interlinked possess a flow of information, which allows the model to change its features automatically. Parametrization improves the service provided to the end user.

Parametric models are build upon a set of mathematical equations. Formulas and coding could be incorporated in parametrization, to achieve flexible and stable models. Doing so would provide us a vast range of model variants. Since time is of essence in the product development cycle and we are trying to reduce the lead time in designing the airduct using template, parameters are the finest way to achieve them. It also allows existing design data to be reused which meets KBE, where already stored knowledge can be used to design the model.

Parameterization was done in the airduct template to achieve three different objectives. Firstly to control the shape of the airduct, second to control the clearance between the B-pillar and airduct body and finally to control the EDS floor harness. The EDS harness has two parameters with respect to it,one is the offset value to controls the dimension of the floor harness and other is to regulate the clearance between the harness and the airduct. Initially the airduct shape was decided to be parameterized with respect to hydraulic diameter. But later it was neglected to provide freedom to develop variable design. Using Hydraulic diameter or any other equation would restrict the template, which is the platform to create any design, from generating designs with different attributes. Hence the shape was assigned with simple variables and parameterized, such that the variable are connected to each dimensional constraints. Changing any of the variable within the design limit would produce a new design.

From the figure 3.5, it can be observed that the length of the airduct is assigned a variable 'a' and the width is assigned 'b'. The clearance values for length and width are assigned 'Clearance a'' and 'Clearance b´' respectively. The orange surface is the B-pillar design surface and the green surface denotes the airduct that fits inside the B-pillar.

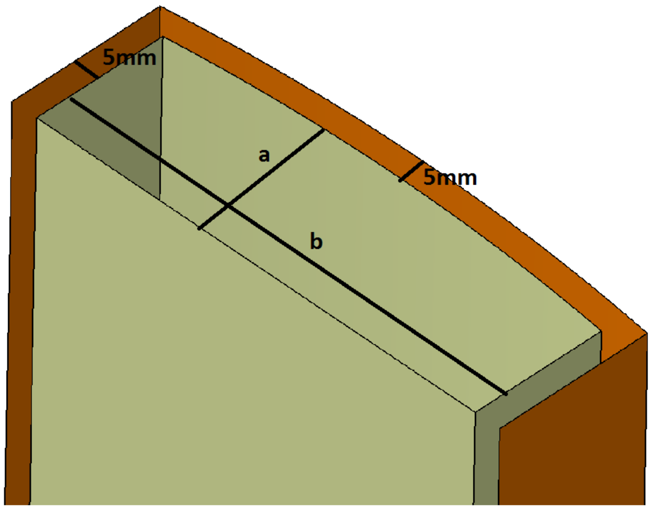

Figure 3.5: Clearance denotation

In the figure3.6, we could see the intersection of the EDS harness offset with the airduct itself. The groove engraved in the airduct as shown in the firgure 3.9, is formed by trimming the EDS harness offset surface from the airduct. EDS harness value is controlled using a parameter called 'Offset' under the EDS geometrical set. The offset value denotes the clearance value plus the radius of the EDS harness. The orange tube denotes the EDS harness and green tube is the offset surface from the EDS cable. The position of the EDS floor harness intersection with airduct can also be manipulated by moving upwards or downwards depending on the design input. The parameters adhere to the rule editor and generates groove on the airduct without delivering fatal errors.

"Offset parameter = EDS clearance + Radius of the EDS harness"

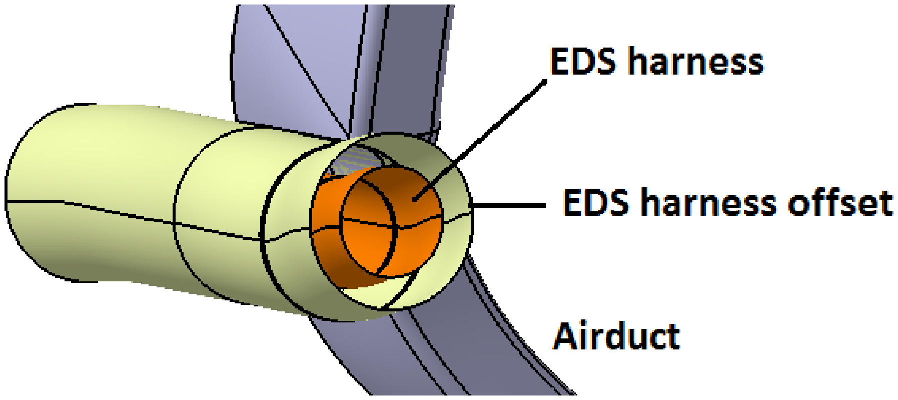

Figure 3.6: EDS harness offset surface intersection with the airduct

The clearance values could be changed based on the class of car to be designed. SUV, Cross Country wagon, Sedan etc will have different clearance values. At times the values differ even with the type of variant within the class of cars. The data obtained from the Robust Design engineer at Volvo Cars, as shown in the figure 3.7, comprises of accumulated, standard clearance values over a period of time. These values provides spotlight on the interaction areas between the EDS harness and the airduct. To be brief, the standard clearance values are obtained for the section two or the mid section of the airduct, with the EDS floor harness and sill. As discussed before the mid section is the most crucial, compacted with many components and cause the source of the integration issues. This is because of which the thesis was originated. Hence, it should also be noted that, the parameters are all assigned to the mid section, it is the complicated section and more emphasis on intricate details would be given to that particular section.

On analysing the clearance values procured from the Robust Design engineer, it could be perceived that all the clearance value between the airduct and the harness ranges between 3mm to 5mm. Therefore, it was decided to maintain a standard 5mm clearance between surfaces. 5mm provides sufficient clearance space in terms of a integration point of view. All the design surfaces were tried to maintain 5mm clearance between each other. Furthermore, the clearance value, which is assigned using a variable in the mid section, is applicable throughout the airduct. Hence change in clearance value in the particular section would drive the entire airduct to maintain the same clearance between the surfaces. This assures that the model maintains the desired constant clearance value throughout.

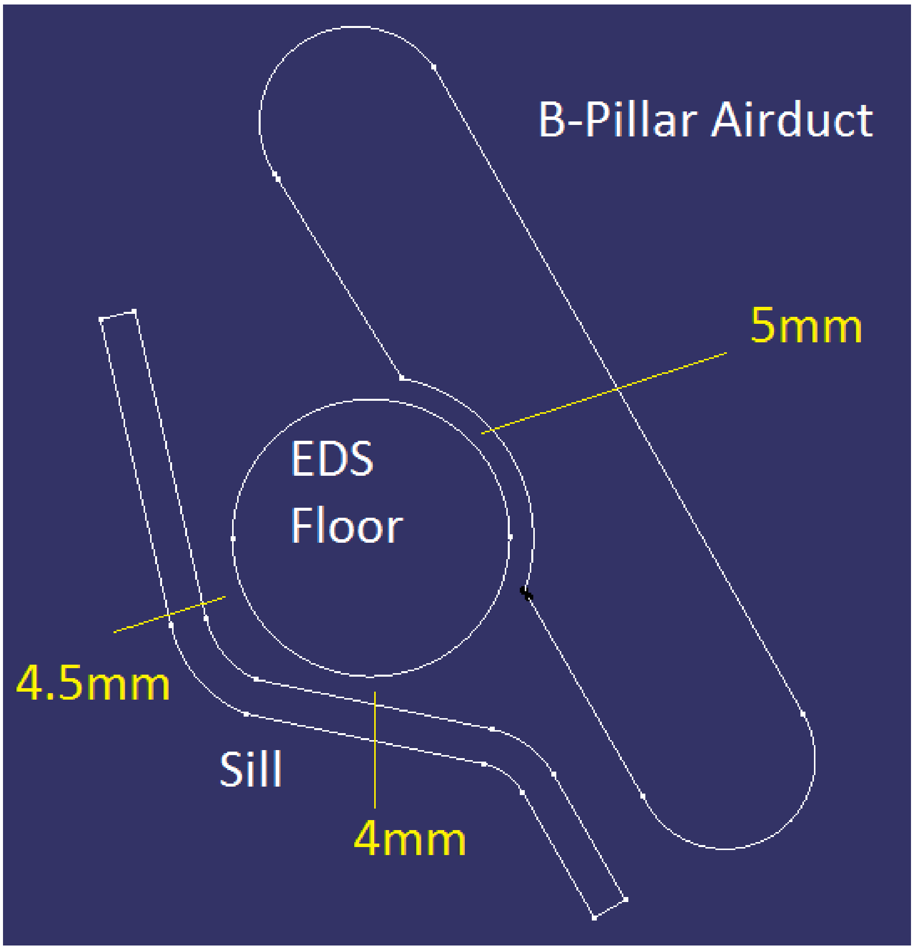

Figure 3.7: Standard clearance values between surfaces in the mid section area

The tree structure from CATIA V5 shown in the figure 3.8, shows the different parameters assigned to the model and relations created between constraints to generate seamless flow of information between them.

These parameters, aided in immediate modulation and availability of models while performing various integration assessments and simulations. Usually without the parameterization, it took more than hours to fix the error and recreate the models. Once the parametrization was done the process escalated and simulation and development time decreased drastically.

Relations can be generated for the surfaces and sketches to control the designing process. Rule editor is generally used to formalize a formula to define the parameters. Simple coding such as the ones used in C programming, can be coded in rule editor for substantial control. The rule editor command used in template is shown in the figure **??**. It could be seen that a simple If-Else programming is coded to trim the EDS offset surface.

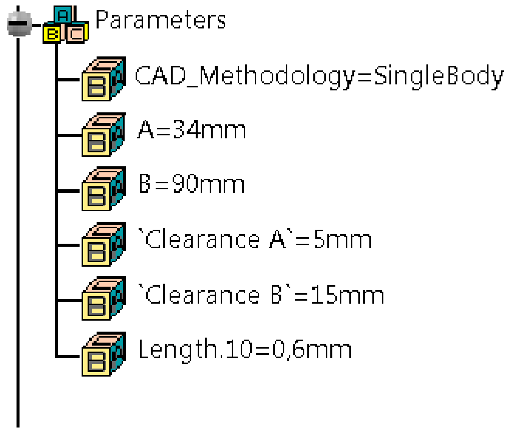

Figure 3.8: Different parameters displayed in the tree

The Rule editor allows us to address the vital issue, because of which the project was forged. The intersection of EDS floor harness, near the sill region, with the airduct always impedes the efficiency of the airflow. The models with varying intersection of EDS with the mid section of the B-pillar airduct was planned to be simulated with varying EDS diameter and different mass flow. To do so, one must create multiple models with varying intersection diameters, for example, as shown in the figure 3.9.

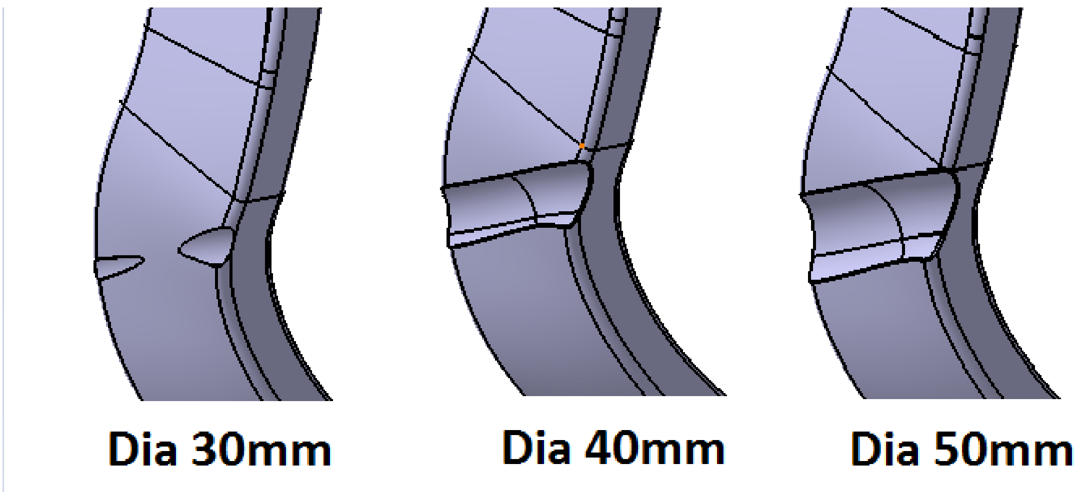

Figure 3.9: Variation of diameter at the intersection of EDS with B-pillar airduct

The rule editor as shown in figure **??** contains the If-Else command to control the trim as discussed above. The rule can be explained as, 'If' the EDS harness is in contact with the B-pillar airduct, the trim command is executed. This section of If-Else code performs the trimming of the EDS on the mid section of the airduct and provides a groove as shown in 3.9. 'Else' the trim command is not carried out. That is, if the EDS harness offset surface is not in contact with the airduct, the trim command it overlooked and a complete airduct without any groove is produced.

The parameterization on the constrains using formulas and coding has helped to minimize the efforts involved in creating the model. It also has created a stable template structure which can be modified for necessary clearance values and dimensions of the airduct. It still holds few minor errors and some manual editing to be done while remodelling the part using parameters which cannot be avoided. Such as, reassigning the fillets and surfaces. Whenever there are changes in position of the design surfaces or if there are any new input models, 'Replace' command could be utilized instead of altering the whole tree. Replace command replaces the current part to the new part, but ofcourse, one has to reassign the surfaces and show/guide CATIA V5 interface which surface needs to aligned to the respective peer surface. This has to be done manually.

3.5.2 Standardization of components in template

Due to a constant demand of revolutionary product from customer end has brought upon immense pressure to build innovative products. The revolutionary ideas are build either from scratch or utilizing existing information and parts. The former do not meet the customer need's delivery time, hence creating a innovative product from scratch would lead the company to deliver the product much later than the customer's expected delivery period. This leads to the fact that, latter is the most suitable approach to meet the customer expectancy in shorter period. This has forced many OEMs to adhere to standardization. Standardization has proven to be a agile and efficient methodology to mass produce competitive product and yet meet the quality and time. There are different forms of standardisation according to (*part-standardization*, n.d.), they are listed below.

- Part standardization
- Tool standardization
- Feature standardization
- Raw materials standardization

Part standardization is the standardization method which was utilized in the project. Standardization of part makes it easier to reuse the part whenever and wherever necessary. Effective standardization needs a common platform where standard components need to me managed, such that they do not get mixed up and becomes arduous to pull out the product when needed. This give birth to the need of Product Life-cycle Management (PLM) systems which could handle massive information and manage it effectively. Fortunately, Volvo Cars utilizes Team Center (*Siemens industry Software inc*, n.d.), a PLM software from Siemens to manage the CAD data. The corporation can utilize this software to handle standardized parts which would be ready to use when needed.

According to (*part-standardization*, n.d.), the benefits of using standardization approach are enormous. The variants and changes in the part are minimized drastically. This leads to lesser design variations and quicker adjustment to changes in the design. Better quality is achieved which increases the reliability and longer life service. The main purpose of standardization, which is to mass produce at shorter time with higher quality can be achieved. Once the part is standardized the component are available easily for replacements and maintenance. Standardization not only aids in reduction of product development type but also has a greater effect on manufacturability. The standardized components can be manufactured and stored, which could be pulled out and used for assembly whenever needed. If not they can store the CAD data and build to order. Standardization also reduce the redundancy of prototyping and analysis of variant changes, thus saving cost wasted on analysing the variants of the part. All this would eventually lead to quicker delivery of quality graded products to the vendors and customers.

When standardizing a part, the engineer must keep in mind both upstream and downstream effects caused due to standardization. If not, the whole process would be unfruitful, since it would cost extra resources and efforts usually in the downstream. To avoid such unnecessary and unproductive result, multiple visit to the manufacturing and assembly plant was carried out as discussed in chapter 3.3.3. Analysing the downstream methods and assembly of the airducts to the HVAC system, along with bench-marking them with other airducts from different competitive companies were carried out during the visit. It was observed that a lot of the airduct sections were common between Volvo car models.

Standardization was a part of template maturity process in this thesis, in order that the template can be divided into sections for easier development and control over designing the part, as mentioned in above sub chapter 3.5.1. Despite all above mentioned merits regarding standardization, there are few benefits which simulation engineers would achieve through this method in this particular objective of the thesis. Reducing the product development time is one of the requirement, mentioned in the requirement specification in the chapter 3.4 and this could be achieved using standardization. Standardizing the part at right areas would not only reduce the design lead time but also reduced the simulation efforts needed to evaluate the new concept.

At Volvo Cars, simulation of airduct is conducted complete on the entire airduct for every variation or new concept developed. According to a CAE engineer, it was hard to run simulation from any particular selected section since there wouldn't be enough data at that section which could be used as input. To avoid the above shortcoming, creating a plane at particular section of the airduct as illustrated in figure 3.10, beyond which the product could be standardised, will provide us with a section on which simulation could be run. The output data obtained at the plane, from simulating the standard part can be presumed as input for the unique, varying section of the airduct. The output data at the plane would be the intermediate values at that particular point of the airduct.

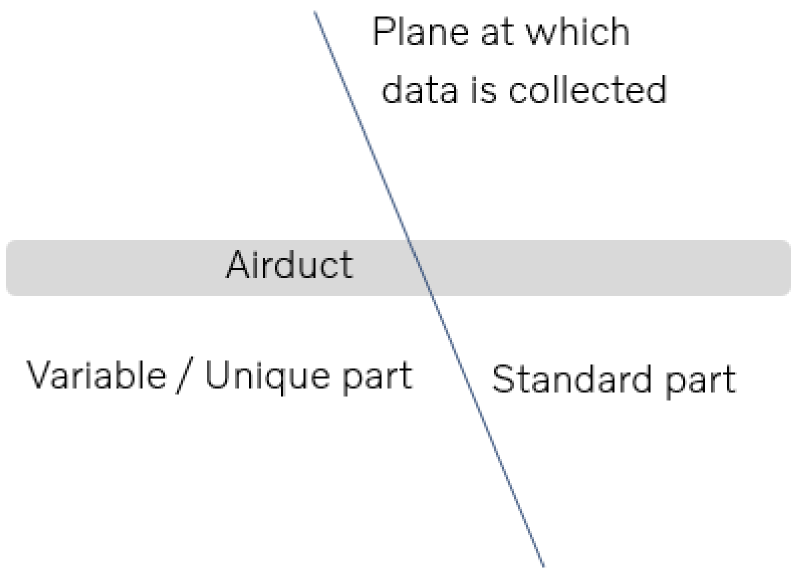

Figure 3.10: Illustration of standardizing the airduct using plane to measure the values

The output data of the standard part would serve as the input data for the non-standard part. Hence, it is sufficient if one simulation is done on standard part. The output data stored can be pulled out and reused over and over for various variants of the variable part. The basic ideology behind this approach is that, the simulation software takes much time to run the simulation if the CAD data model fed to is heavier. This is because, the software has to mesh the entire model and evaluate the values for every single mesh cells that has been meshed. By reducing the CAD data, one can obtained much quicker result. Therefore by standardizing the airduct and eliminating those parts for frequent assessment of the variants, would provide us with subsequent reduction in simulation lead time. Smaller model to simulate would yield lesser simulation time. But one of the drawbacks is that the values obtained might not be accurate enough to be used as an input. This is overlooked due to the fact that, the simulation for initial concept phase assessment need not require exact values. Error tolerances are quite high during this phases.

The picture 3.11, shows the aggregated view of all the airducts Volvo cars have created. The lower black box at the inlet of the airduct, marks section three. This section, as seen, is common for all variant cars, with very insignificant variations. The section three of the B-pillar airduct, which is close to the inlet is standardized in this report. Keen observation would reveal that, quite some of the section two in the airduct, has common structure. They can also be standardized as well. This is avoided since it complicates the designing and standardization process. The section three is already available in the PLM system at Volvo Cars. Hence, it is advisable to directly use the section three as standard section without considering the extended commonality. The lower section of the section one in the airduct, could also be standardized to increase platform usage and ease of assembly and study. It could be noted that from the intersection from section two to section one until three-fourth of the section one has common features. Standardising the common area of the section three would elevate the benefits of standardization. The top section of section one varies based on the platform of the car. The output is connected to a nozzle and the nozzle placement also varies depending on the class and variant of the car. It could be said that the top portion of section one could be varied based on type of nozzle placement and the rest of the section one until section two is standardized.

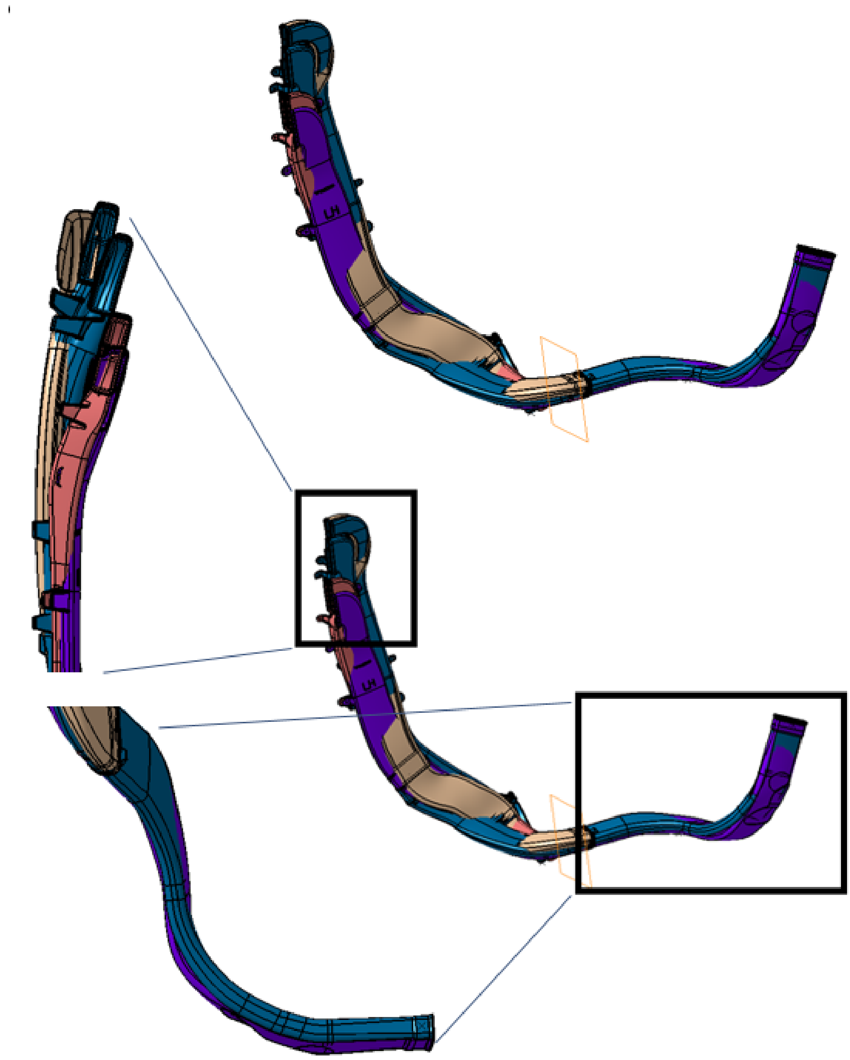

Figure 3.11: Aggregated study of all airducts

3.5.3 Using KBE in Template

Knowledge Based Engineering (KBE) is practised universally in many major Multi National Companies and Volvo Cars is not an exemption. The point of utilizing KBE as explained by (Susca et al., 2000) is primarily to reduce the product development time and achieve more by investing less resources. The current competitive market is cruel and anything which fetches profit with low resources and development time is considered a gold mine. KBE proves to be that gold mine in this current industrial era. Knowledge Based Engineering, as the name describes is engineering the product with already obtained or available knowledge through pre-existing simulations data, experience, lessons from failure and other.

The issue with conventional approach is, already carried out development process of the product is iterated again without prior knowledge that the information is being available. This is slightly related to the issue of not maintaining a standard PLM system which manages all the information in the company. Hence, the work is carried out all over again, the errors and difficulties raised during this process have to be addressed once more, which consumes more time and resources which were already spent initially. (Gianfranco, La Rocca, & Van tooren, 2007) shows how KBE is utilized for automatic generation of Finite Element models in aircraft design. We can observe that, the models are generated avoiding all the iterations using KBE and those knowledge is used to do necessary workaround to avoid future geomtric errors.

As shown in figure 3.12, during template development, inputs from the design stakeholders are fed into the template model. CFD constrain models, which hones the geometry of the part with respect to fluid dynamics to achieve greater efficiency, are developed from the template model. To achieve a CFD constrained template model, one must externally feed the available CFD requirements and knowledge obtained from previous simulation or through experience, to the CFD constrain model. The obtained output model then would adhere to both CFD requirements and design requirements without iterating the process multiple times.

3.5.3.1 Simulation Based Design- An KBE approach

There are different ways through which one can make use of the existing information. Simulation Based Design, Design Optimisation are few such ways through which it could be achieved. Simulation Based Design is a branch of KBE where the simulation data are used to build the design geometry of the product. Simulation information and history of data are evaluated and optimum result is used as input in early CAD data. This is generally difficult due to the fact described in chapter 2, that the design model's inputs are completely different to simulation data. The difficulty in integration is also debriefed by the authors of (Shephard et al., 2004).

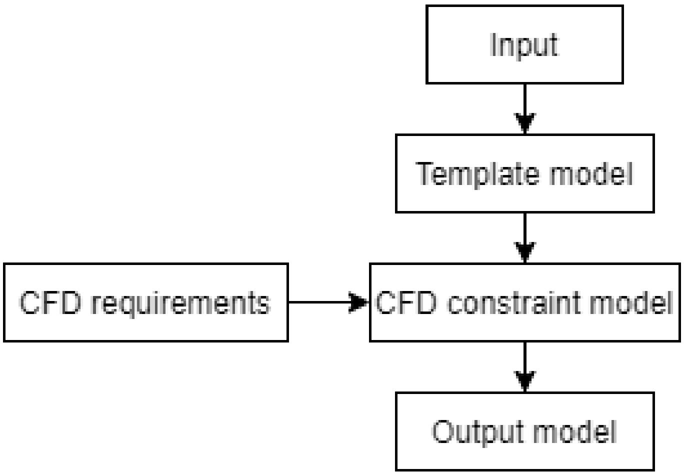

Figure 3.12: KBE application in template development

While addressing the issues in the thesis, it became clear that the measures taken were to integrated the engineering template with the Simulation of fluid dynamics in airduct. However, the loop is constantly addressed within the template model creation and analysing the model using simulations, as shown in the figure 3.13 below.

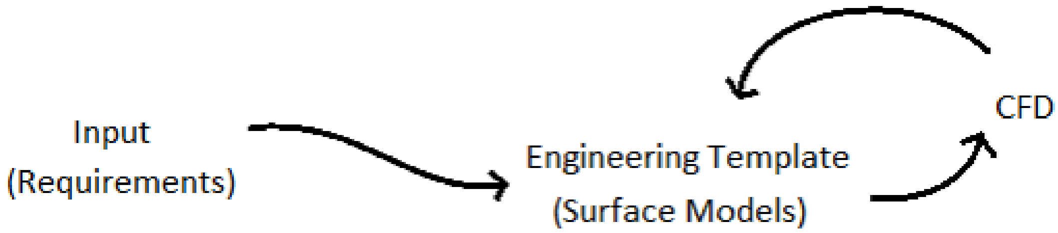

Figure 3.13: Initial approach to address the template development

To cure any problem, one has to address the source, where the issues arises. By doing so, it not only rectifies the current issues but also prevents future errors developed because to it. The figure 3.14, shows the cure, by following KBE approach, to the problem addressed in the thesis. Instead of incorporating SBD, in Engineering Template, the data from simulation is incorporated both in engineering template, to fix the immediate issues while building the template, and also store the knowledge in a KBE data storage. Where the data stored are analysed and optimum result is converted into inputs, which is then fed as inputs to requirements. These analysed optimum results will fix the issues in the requirements list which will in turn rectify any issues in the future development of the engineering template.

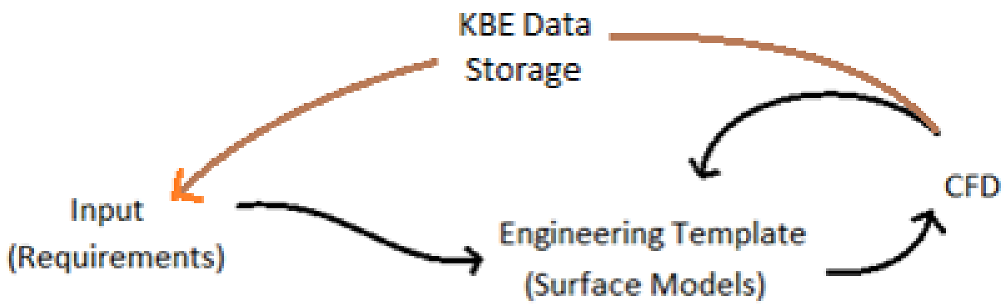

Figure 3.14: SBD approach to address the template development

These stored information in KBE storage can be converted into inputs in different manners. They could be values, models, restriction surfaces, colour coded limits, points or even lines. In the template developed for the B-pillar airduct, a dead surface could be added to it, as input which defines a work area within which the simulation results have proven to be beneficial.

The development of the restriction surfaces were focused in the crucial segments of the airduct, which is section two. One of the issue, which was identified in this thesis is the intersection of EDS floor harness, in the sill region, with the airduct, which forces the integration engineer to create a cut out in the B-pillar airduct which causes deprivation of the efficiency. To address the above mentioned issue, a restriction surface was generated which hold the simulation information. The data from the CFD simulations were translated into a surface model and this surfaces were loaded in the lowest level in the engineering template. This to make sure the information in this level will not affect the flow of information in the template. The output pressure and R-values of all the airducts at Volvo Cars were evaluated based on specific class and the best simulation results were filtered. Those airducts were aggregated in a single CATIA V5 product and the limits were designed as shown in figure 3.15. The violet strips denotes the left and right extreme restriction, an airduct can me manipulated and the red bottom surfaced indicated the lowest extent to which the B-pillar airduct could be manipulated. Manipulation beyond this restriction surfaces would yield non-beneficial results.

The lower red restriction surface was not built completely based on the aggregated best simulation data. The EDS design variations were also taken under consideration. The supplier history of EDS system was analysed and tracking of variation in Floor EDS harness geometry were done. The data were accumulated and the maximum extent to which an EDS diameter would vary were also taken into consideration for developing the lower restriction surface. The ideology behind this SBD approach is that, these surfaces could be used as a scale to measure approximate result or a reference to build the new concept. Any model which adheres to this restrictions and if they lie within the surfaces would return better simulation results. By doing this, the design engineers could avoid spending unnecessary time and resources on concepts which will not produce favourable results.

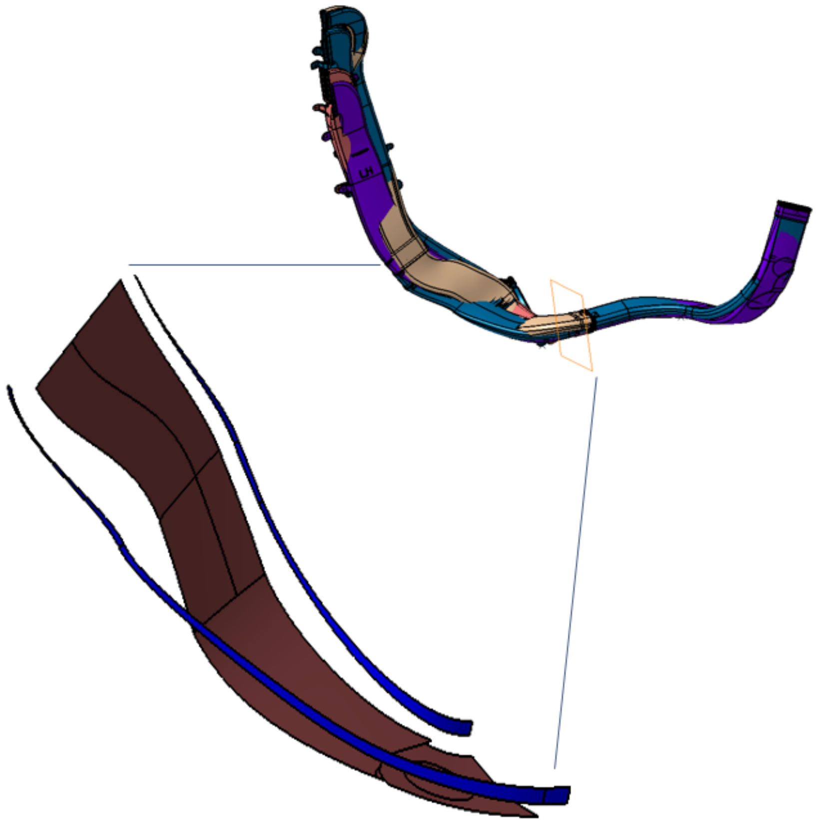

Figure 3.15: Restriction surfaces for Section two of airduct using SBD

Another method to use KBE is utilizing Design optimization process. The approach is simple and iterative, as shown in the figure 3.16. The part solid model constructed from the template is sent for design optimisation. There are numerous software which provides this service and StarCCM+, which is already used for simulation at Volvo Cars, could also be used for design optimisation. Design optimization is a modern approach and it build effective structures which will produce at most results. The optimisation could be done topologically and the modified airduct model is fed into CFD software for short simulation. The data obtained from it can be verified using already available information and also stored in KBE data storage for future references. If the obtained results are satisfactory and meets the essential requirements, then the model is pushed for actual full scale analysis. If not, the knowledge available in the KBE storage could be compared and design update can be made to generate concept wihtout re-iterating already developed concepts.

This idea was not pursued because, this contrasts the ideology of standardization. Despite it being a ingenious idea, to develop quality and efficient airducts, it will lead to multiple variants of airducts depending on change of requirements. It also possess

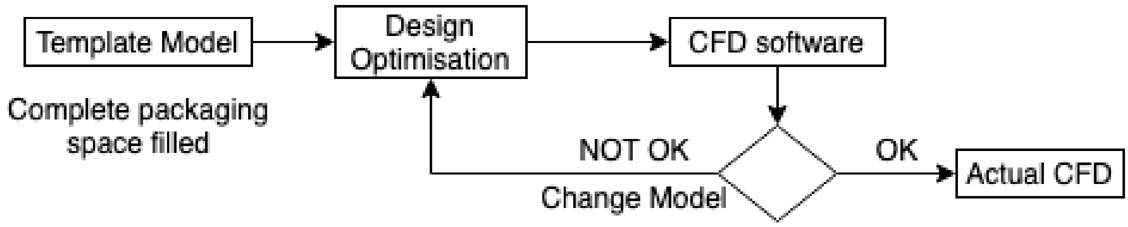

Figure 3.16: Design optimization flowchart

its own disadvantages such as manufacturing difficulties, tooling cost increase and new integration issues. Hence, this method was eradicated from the plan to develop the template models.

3.6 Investigation of simulation tools

From chapter 2, it was bolstered that the integration would be seamless and uncomplicated using software based integration. Once the template maturity, the phase one of the thesis approach has be successfully completed, the second phase is initiated. There are multitude of ways and approach through which this integration can be achieved. To make an design engineer to carry out short simulation loops in early product development phase needs simplistic approach that makes both end meet. Such methods needs to be identified as mentioned above. The second phase involved the integration phase for which the suitable software with which integration can be achieved needs to be analysed.

Many software were identified and investigated. Due to unavailability of sufficient time and resources, going through all was a mammoth task. Hence, software which didn't posses uncomplicated specification of simulation setup and simple user interface, that would aid easier understanding for design engineers, who did not posses sufficient CAE knowledge were disregarded. This brought down to diverse, competent software that are listed below,

- SCCM+ Macro
- PreonLab
- Ansys Fluent
- Comsol Multiphysics
- CS Flow
- FloEFD
- AVL Fire
- CATIA V5 analysis

The software selection was also based on CFD requirements and predominantly, if the simulation would provide quality result in short period of time. The current simulation duration using StarCCM+, depending upon the specific system and processor configuration, last almost around one hour to 45 minutes and the goal is to achieve equivalent results with much shorter duration. Hence simulation was run on old airduct modes using the shortlisted software to identify how fast and accurate the software can achieve the target values. Here, the target values are simulation data obtained from running simulation using StarCCM+ on old model. For example, running the simulation in FloEFD as shown in the figure 3.17, on the airduct of an old sedan model, delivered almost the same results as the target value obtained from StarCCM+. Hence, FloEFD was considered as potential software for final integration. Similarly, subsequent analysis on different software were done to filter the best of best software, which meet the requirement.

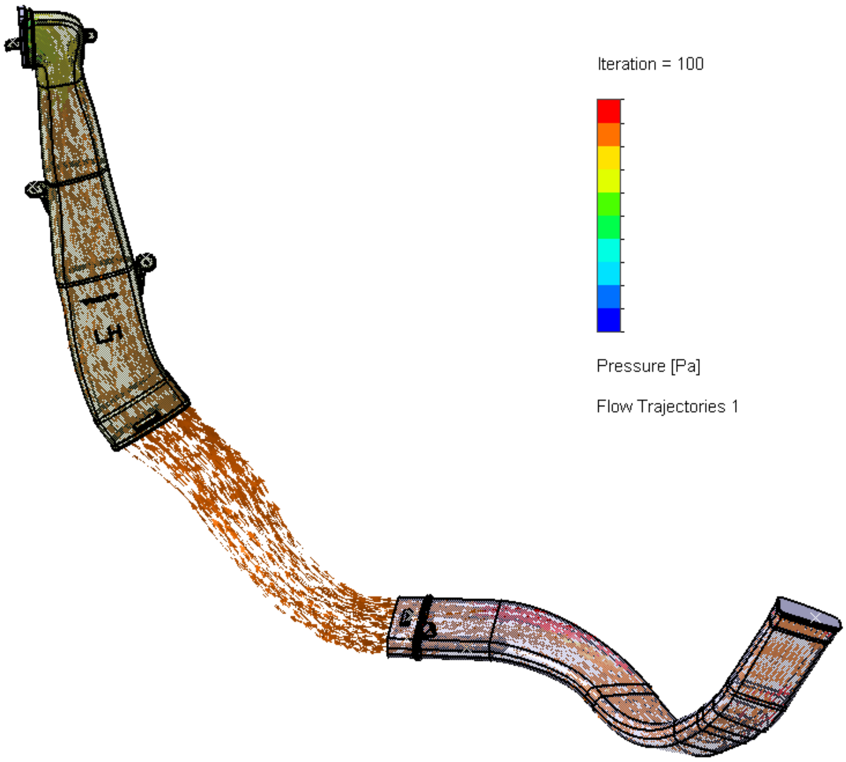

Figure 3.17: FloEFD result on the old airduct model

The thesis approach figure 3.18, shown below describes the flow. Once a clean model are generated from the template, that is worth running simulation on, they are fed to the software finalised to run short simulation. If the simulation are 'OK' and produce tolerable results, then they are moved further for complete CFD simulation. If the data obtained are arguable or if the model generated meshing, uploading errors in the software, then they are recreated in the template.

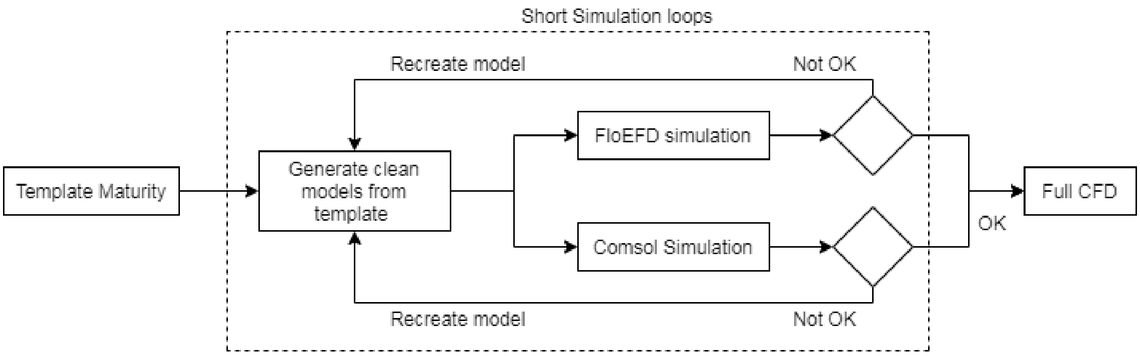

Figure 3.18: Thesis approach for investigating potential software

Only hand-full of software passed the stringent filtration process and only four were finalised. Consequent sub-chapters discusses about the working of these software and why it was selected or why not for further analysis.

3.6.1 PreonLab

PreonLab is a fluid analysis software, which was first identified from the neighbouring department. The software was used to analyse water leakage and fluid motion in the doors, windows and windshield. The software was capable of analysis any sort of fluid and not just water. The flowchart shown in figure 3.19, explains the process in which the preonLab was intended to be integrated with current methodology and abridge the gap in integration. PreonLab was meant to be the short simulation platform on which the model could be analysed faster. The PreoLab as such, when run from the initial setting up stages, needs boundary conditions and the environment to be set for running a simulation. This requires a experienced CAE/CFD engineer. The need for such expertise, contradicts the requirement of easy integration. The software needs to be user-friendly and easily apprehensible by design engineers, who do not possess sufficient simulation experience. Setting up the analysis tree is certainly not an cake walk for a design engineer without enough background.

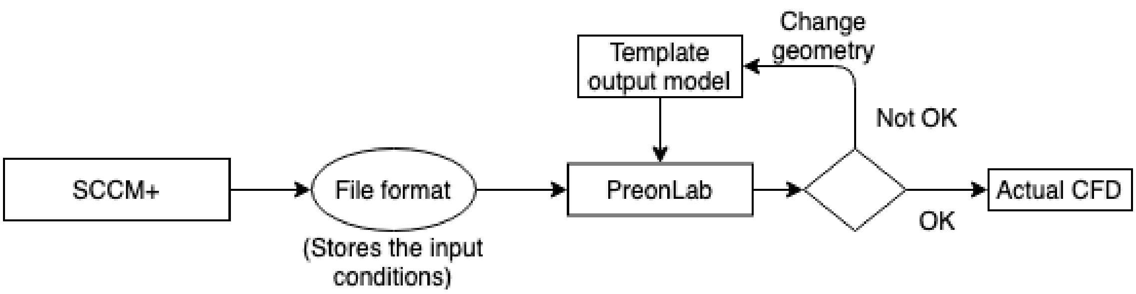

Figure 3.19: Flowchart describing PreonLab integration with StarCCM+

Hence as shown in the figure 3.19, StarCCM+ was intended to be linked with PreonLab. The initial simulation run by a CAE expert in StarCCM+ would be obtained and a special file format, such as Macro, could be extracted from StarCCM+ and fed in to PreonLab. By doing so, the initial involvement of StarCCM+ is eradicated in consecutive analysis. The extracted file format holds the required information for setting up the software. The file format can be reused again and again, unless the boundary conditions for the simulation changes. If the short simulation loop produces satisfactory result, then the model is moved to actual CFD analysis. If not the geometry is changed, a new concept is created using template and fed into preonlab. Using the same boundary conditions in the file format, simulations are run in PreonLab again until a feasible concept is achieved. The reuse of boundary conditions using a file format, reduces the software setup time and expertise needed by the engineers who do not posses knowledge in setting up a simulation software.

This approach was not feasible at the end, despite being a efficient way to evaluate the concepts. This was because, in the later stages, it was identified that the software was not mature enough to run simulation on turbulence flow. The airduct simulations are run on realisation K-Epsilon modelling. Rather the model could be run on Laminar flow, but it would not produce realisable results.

3.6.2 SCCM+ Macro

Similar to integration of PreonLab, using the Macro alone to run simulation in StarCCM+, would save time in setting up the boundary conditions. The macro can be used to different iterations of StarCCM+ simulations. As shown in the figure 3.20, the macro which stores the formation can be loaded for different simulations which could be run simultaneously. Each simulations denotes a unique concept that needs to be evaluated. The macro can be changed if the boundary conditions are changed. To reduce the simulation period even more, the concept models needs to be defeatured, that is features like fillets, joints, fixtures needs to be defeatured to reduce time and power utilized for meshing. Removal of unnecessary features would yield in drastic reduction in analysis time.

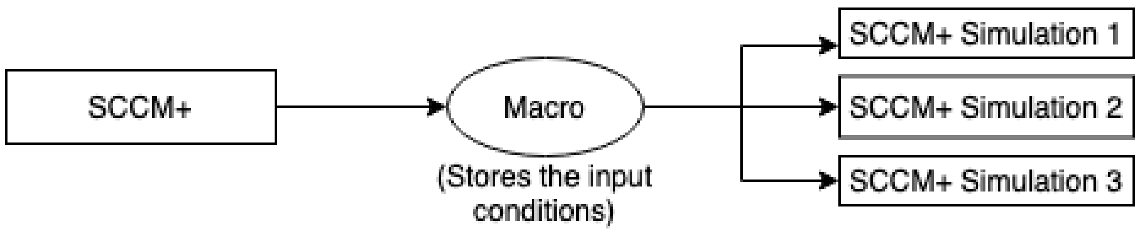

Figure 3.20: Using Macros in StarCCM+ to run simultaneous simulations

This method was also rejected because, it does not reduce the overall simulation duration. Reduction in set up time was insignificant. StarCCM+ is already used to evaluate the airducts and the duration usually taken to run the simulation is around 45minutes. Reduction in set up time might have reduced the time to half an hour, but the simulation duration is still quite long. The additional work of defeaturing to make the process easier, compensates the time reduced for set up. Hence this method was not preferred.

3.6.3 FloEFD

FloEFD is a Siemens's business product which excels in the field of fully CAD-embedded CFD software. They claim that, they are are the only software with CAD embedded CFD. According to (*FloEFD Product*, 2020), they state that. 'FloEFD helps design engineers conduct up-front, concurrent CFD analysis using the familiar MCAD interface. This reduces design times by orders of magnitude when compared to traditional methods and products.'

The FloEFD software is embedded with CATIA V5, thus makes the user experience non-arduous. It also makes the workbench and data transition seamless. They also have concurrent simulation facilities, which helps the engineer to simulate multiple concepts concurrently and compare the result in the same front. The process flow is described in the figure 3.21. The concepts are generated in the engineering template and they are saved as a unique product, breaking the links with the template. Once the links are broken and stored in a separate CATIA product, FloEFD analysis workbench is activated. FloEFD boundary conditions setup are not as complicated as the other simulation software and ceaseless FloEFD support, for error correction and setup help, was delivered from France and Britain help centers. They are straight forward and the surfaces needs to be assigned respectively to their input and output. That is, the initial mass-flow and desired total output pressure are assigned to the inlet and outlet surfaces.

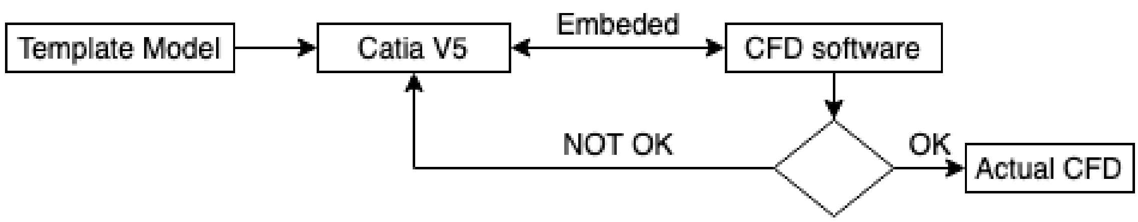

Figure 3.21: Process flow of concept evaluation using FloEFD embedded in CATIA V5

The simulation is run using an adaptive meshing which saves time drastically. The test simulation was completed within two minutes with equivalent results, when compared to the target values. The results are displayed in multiple ways depending on the user selection, one such example is discussed above in 3.6, where the figure 3.17 shows the output airflow trajectories of an airduct in an old sedan Volvo model.

Another major advantage is that, the features can be modified in the current workbench itself and new concept need not be generated in the template, the necessary changes can be done in the same part and re-evaluated using the same input conditions. The fluid domain identification, lead tracking and identification of leak areas are other special features that are available in FloEFD which makes the simulation process convenient and efficient. Due to all the above beneficial aspects, an already focused development of software to integrated CAD with CFD, FloEFD was considered as a potential software.

3.6.4 Comsol Multiphysics

Comsol Multiphysics is a general purpose design software, which is widely used in academic projects at Chalmers University of Technology. It is a competent software which can run simulation on several physics, thus gets its name Comsol Multiphysics. The software is capable of running two or more physics simulation on the product at the same time. The set up is pretty similar to other simulation software's boundary condition setup. The main reason why this software was preferred, despite having similar setup approach, is due to a special feature that is not available in other software. The feature to create application and make it available through web or mobile, is an extraordinary means through which the simulation is made easily operable and integratable it with the CAD.

The initial setup requires expertise in Comsol Multiphysics to code the application and build the interface.However, unceasing support from Comsol help desk was available to build the application and rectify the errors. The interface development are user defined and easy to build. They are usually drag and drop approach, to build the required buttons and features in order to construct the application. Once the application is built, the concepts in template are constructed as solids and stored as '.stp' format. The STP file is then loaded in the application. Input values are given to respective input surfaces and the simulation is run. The feature development and the interface are explained further in chapter 4.2. The application development reduced the setup time, product load time drastically and the solution were obtained within 10 to 15 minutes, with results close to the target values. Hence, Comsol Multiphysics was considered as another potential software for integration.

The 'Application Builder' button in Comsol launches the forum to build the user defined application. The application is code driven and it has automated specification input. Once the comsol tree, as shown in the figure 3.22, is built with required mesh type and type of flow, the model is then moved to application builder by clicking the 'Application Builder' button on top left.

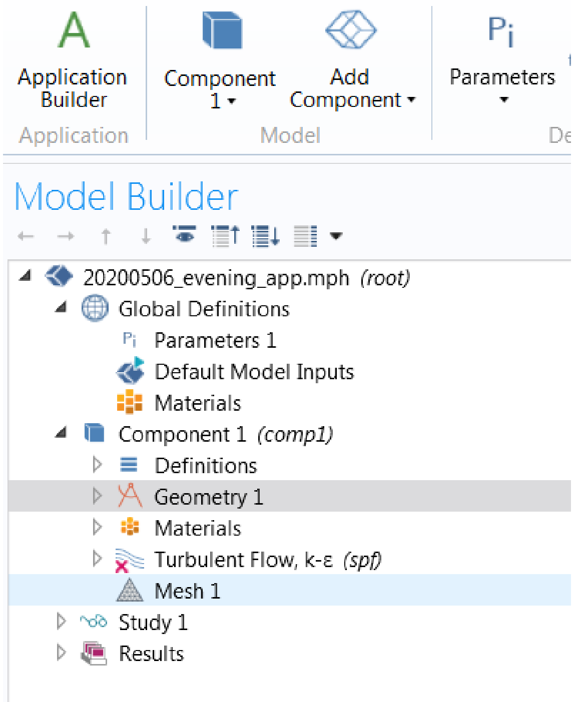

Figure 3.22: Tree structure of Comsol Multiphysics

As explained in this chapter, the application is built using the drag and drop function. The compute, import, result display screen and mass flow input value section are generated and placed based on easy user experience. The completed application looks like as shown in the figure 3.23.

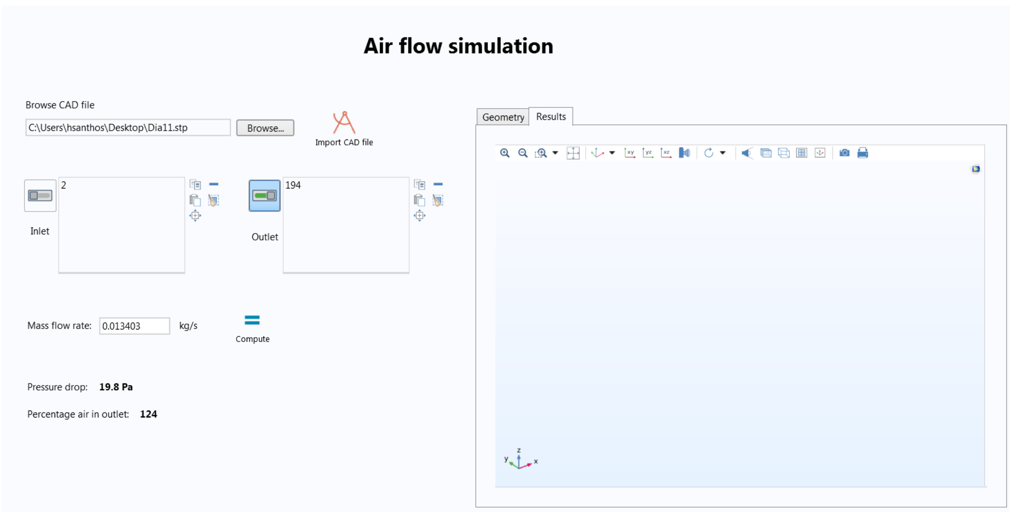

Figure 3.23: Comsol Multiphysics application's user interface

The selection of surfaces to assign input and output boundary conditions are similar to FloEFD. The main difference in assigning the surfaces between the FLoEFD and Comsol is the biggest advantage for Comsol, that is, the layers can be pre-selected by the system itself using 'Explicit selection' function. Explicit selection can be briefly explained as, a cubical domain, within which the surface that need to be assigned will lay.Then those surfaces can be directly clicked in input and output selection box. The domain dimensions are need to be wide enough, to facilitate any changes in the surface position and also non-intersecting with the main body surfaces, to avoid the system misinterpreting the body surface as input surface. To avoid the above mentioned misinterpretation the explicit selection can be altered to only consider surfaces, which are completely inside the domain. In the figure 3.24, three different airduct design, each showing various position and height, all lay within the explicit selection domain. The surface when clicked in the selection box, if lies completely within the selection domain, will get assigned as input or output surface depending upon which selection box is used to assign.

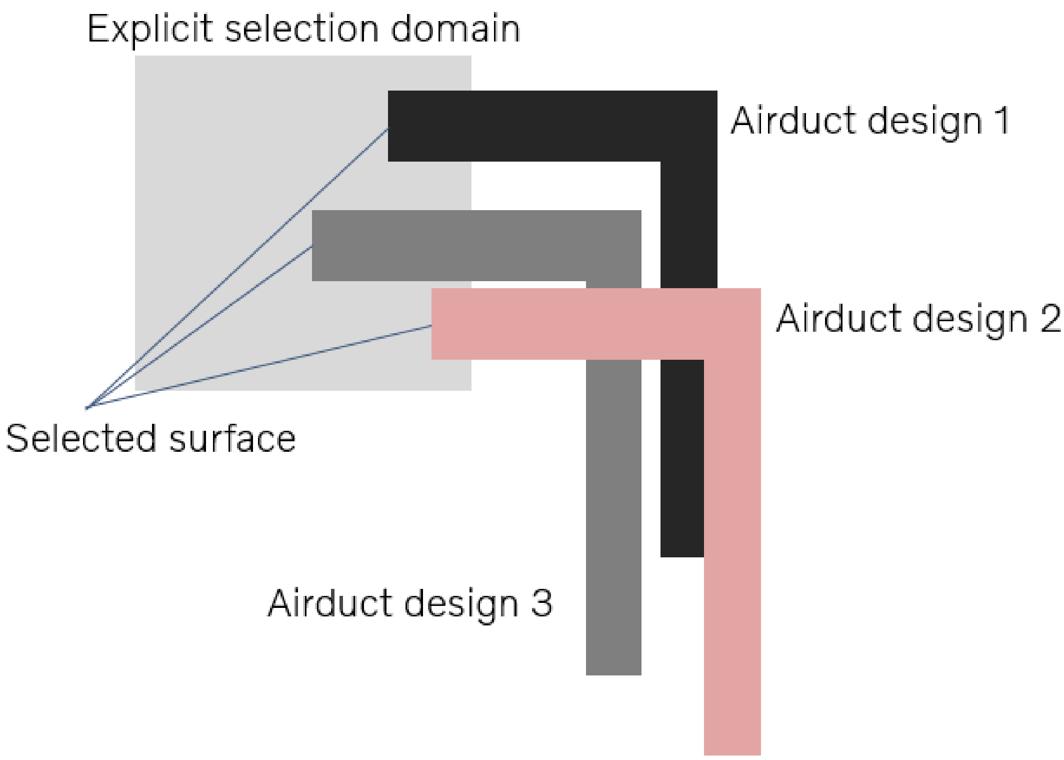

Figure 3.24: Explicit selection in Comsol Multiphysics

The method code for import CAD files are generated using the code as shown in the figures 3.25 and figure 3.26. The computation in the application needs to receive boundary condition information from the tree. This is achieved by generating a method code for computing the model. This code searches for information required for simulation from the tree and loads it to the model. The mass flow value entered in the input section of the application builder and simulation is run by hitting the compute button.

```
model.component("comp1").mesh("mesh1").feature().clear();
model.component("comp1").mesh("mesh1").automatic(false);
with(model.component("comp1").mesh("mesh1").feature("bl1").feature("blp1"));
  set("blnlayers", 2);
endwith();
model.component("comp1").mesh("mesh1").run();
model.study("std1").run();
useGraphics(model.result("pg1"), "form3/graphics1");
pane = "form3";
//zoomExtents("/form3/graphics1");
```

Figure 3.25: Comsol code in methods to compute the simulation

```
//model.component("comp1").geom("geom1").feature("imp1").importData();
model.component("comp1").geom("geom1").run();
useGraphics(model.component("comp1").geom("geom1"), "/form2/graphics1");
pane = "form2";
//zoomExtents("/form2/graphics1");
```

Figure 3.26: Comsol code in methods to import the .stp model

With all above finalised software, simulations were carried out with different mass flows and different designs as described in the next chapter 4.

4
Results

The results are obtained from simulating models from the template in FloEFD and Comsol Multiphysics. It was later compared and analysed with a reference simulation result. The reference simulation results, as shown in the table 4.1, are from the already practised software, StarCCM+. The values have been changed to alphabets due to confidentiality issue. Initially it was intended to select the top three or four airduct models from old Volvo Cars, run it in both software and compare the results with already available simulation result from StarCCM+. But, requests were raised from the Climate department to verify the software with the developed template models in order to assess the compatibility, if the template generated models are directly induced to the software.

Unlike previous simulations, where a standard mass-flow was used for all simulations, various mass flows were applied as input to identify the sensitivity of the software and how much the pressure drop fluctuate depending upon the mass-flow. Five different mass-flows which were obtained from the Climate team. Geometry changes were also carried out on the model to analyse how the simulation results fluctuate. The primary concern of the thesis, the EDS intersection was selected as apt geometry to vary. Hence, EDS floor harness diameters of 30mm, 40mm, 50mm were constructed and also the positions were changed upward to 10mm, downward to 10mm from the initial assembly position, which delivered five different designs. This was achieved using Rule Editor in CATIA V5, which is thoroughly explained in the figure 3.9, incorporated in the chapter 3.5.1. Finally, two evaluation tables each for individual software were obtained using the various mass-flows and designs.

Design variants	**Mass-flow rates (Kg/s)**				
	m*1	**m*2**	**m*3**	**m*4**	**m*5**
EDS Dia 30mm	X_1	Y_1	Z_1	A_1	B_1
EDS Dia 40mm	X_2	Y_2	Z_2	A_2	B_2
EDS Dia 50mm	X_3	Y_3	Z_3	A_3	B_3
EDS upward	X_4	Y_4	Z_4	A_4	B_4
EDS downward	X_5	Y_5	Z_5	A_5	B_5
EDS without	X_6	Y_6	Z_6	A_6	B_6

Table 4.1: StarCCM+ pressure drop (Si unit:Pascal) simulation result table for various designs and mass-flows

4.1 Measurement methods

The airduct values are usually measured in pressure drop or R-values. The pressure drop is the most convenient way to access the airduct. R-values are more complicated when tried to compare with the other airducts. This is because, the R-value requirement changes specific to the car. Hence the values cannot be bench marked for and compared with cars of different class. Whereas, the pressure drop are easy to compare and simple in nature. The lower the pressure drop the better the airduct. The equation to measure the R-value is shown below formula (4.1).

$$\Delta P = R * Q^2 \tag{4.1}$$

Where, Δ P is change in pressure; Q is the Flow rate.

The figure 4.1, shown below denotes a approximate representation of the Airduct distribution from the Climate unit through the entire car. The arrows denoted the airflow and exit of the air from the HVAC unit. A total mass flow of 100% is generated in the climate unit and it flow through the airduct. At the point of distribution, the complete 100% mass-flow is divided and flows through four different airducts. The outer two are the B-pillar airducts and inner two for the tunnel airducts. One easy way for measurement as shown in the figure 4.1, is to measure the percentage of total mass flow that comes out of the specific airduct. It could be assumed that the airduct design is competent if 70% of total mass-flow is obtained at the outlet of the B-pillar airduct and 30% of total mass-flow is acquired at the outlet of tunnel airduct. This would reduce the amount of knowledge needed regarding the pressure characteristics.

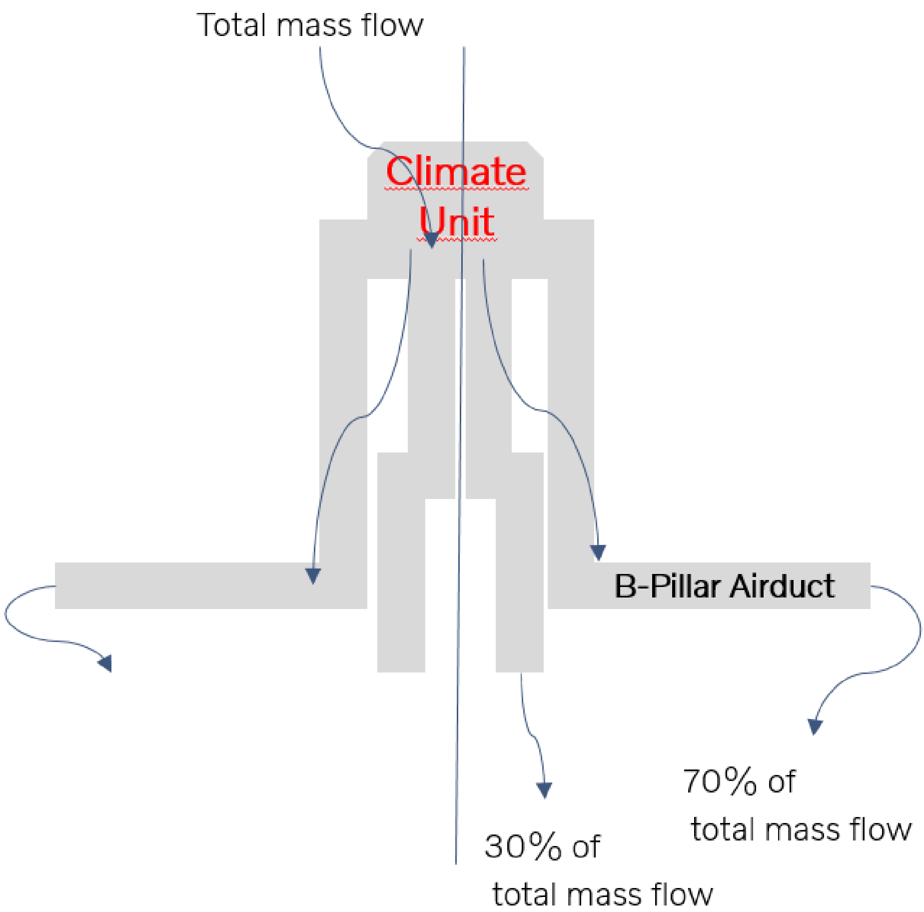

Figure 4.1: Measurement of percentage of total pressure at the outlet

Another important aspect to be noted during measuring the pressure is that, the output pressure P_2 is not measured exactly at the outlet nozzle of the airduct. An approximate passenger space is generated, as shown in the figure 4.2, and the outlet pressure P_2' is measured at the end of the passenger space. This pressure P_2' is the assumed P_2. Hence, $\Delta P = P_1 - P_2$. Where, P_1 is the inlet pressure at the HVAC unit and P_2 is the outlet pressure at the nozzle will become $\Delta P = P_1 - P_2'$. It is necessary that the outlet pressure P_2' must be approximately zero. Upon reviewing all P_2' in the car models, it was confirmed that the P_2' were zero. Hence, during our simulation we considered P_2' to be zero. In that case, $\Delta P = P_1 - P_2'$, will become $\Delta P = P_1$, since $P_2' = 0$ and hence, pressure is measured from the inlet surface. By doing so, we can disregard the computation of passenger domain, which would save a lot of difficulties and time during simulation.

This method seemed convenient and direct. Therefore, it was selected as the method to measure the pressure. The following simulation results contain pressure change values measured at the inlet of the airduct. This method saved enormous time and complexity while running the simulation.

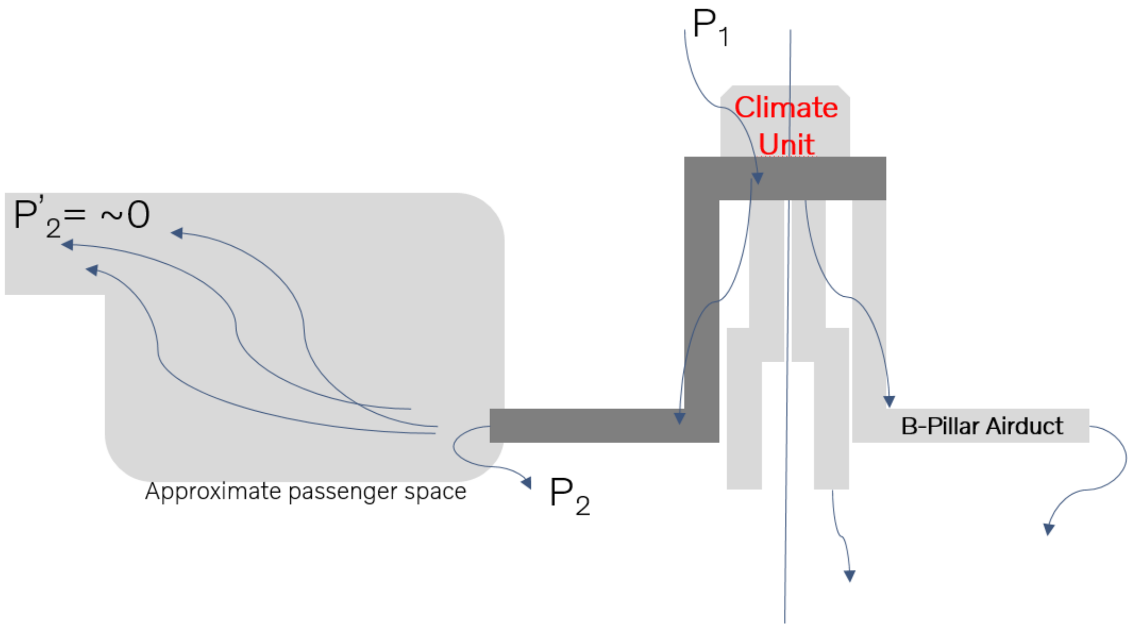

Figure 4.2: Passenger space and outlet pressure measurement

4.2 Integrated Results

The integration process, as explained in above chapters, obligates models from the developed template. The models are directly loaded into simulation workbench and simulated using defined boundary conditions. The geometry and position of the EDS floor cable harness were varied at the intersection section of the airduct. These designs were analysed with five different mass-flows as described before. The pressure drop value ΔP is noted for each simulation as shown below in the tables. There are two tables each for one software. The tables for both the software are explained in sub-chapter 4.2.1 and sub-chapter 4.2.2, respectively.

The variations in flow trajectories were investigated while running the flow simulation within the airduct. The pressure values increased considerably at the intersection region of the EDS floor cable harness with the B-pillar airduct. The pressure increased as the EDS floor cable harness diameter increased were distinguishable. This work in compliance with basic physics, that a sudden obstruction in the flow causes drastic increase in the pressure. It was also observed, the pressure drop increased with increase in mass-flow. The greater the mass-flow, the greater the flow got obstructed. Hence, resulted in immense pressure drop. The figure 4.3, manifests a clear and exquisite representation of change in pressure with increase in mass-flow. The figure hold the comparison of simulations run with intersection of EDS diameter 30mm which is moved 10mm upward, in Comsol Multiphysics, with extreme mass-flows m_1^* and m_2^*. It can be acclaimed that the maximum pressure drop value, for the same EDS intersection diameter, with low mass-flow rate is around 0.55 Pascal and maximum mass-flow is above 8 Pascal.

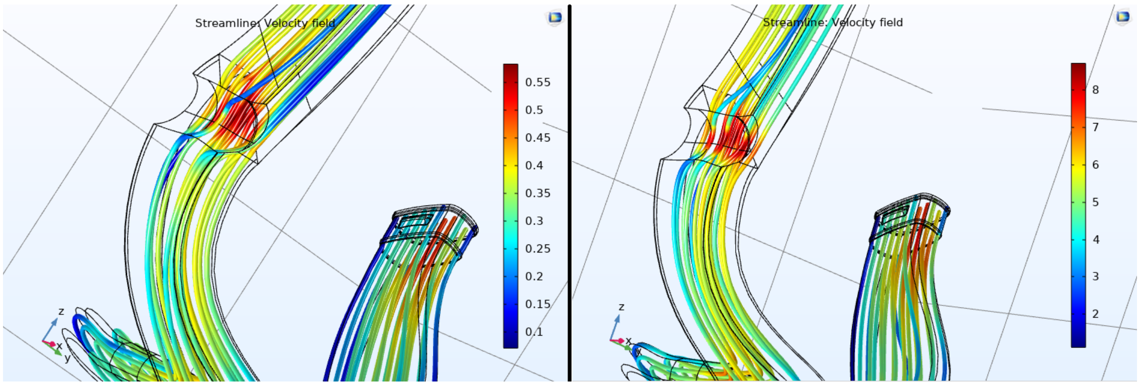

Figure 4.3: Pressure drop trajectories comparison between EDS 30mm intersection region with extreme mass-flows

The trajectories and values of the extreme mass-flows of the airduct with same 30mm EDS diameter and airduct with two EDS diameter 30mm and 50mm with same mass-flow, will be explained in consequent sub-chapters. Simulation results of all other variants are presented in the appendix A.1 and appendix A.2.

4.2.1 FloEFD results

The FLoEFD result consists of two images per simulation. One delivering the goal plots of Bulk average total pressure and Maximum total pressure along with its convergence graph, as shown in the figure 4.4 and other presenting the flow trajectories, as shown in figure 4.5. The convergence graph in the figure 4.4 gives a idea of whether the result is converged or not. The results are acceptable only if the graph is converged. The result also contain information about how long and how many iterations it did takes for the result to converge.

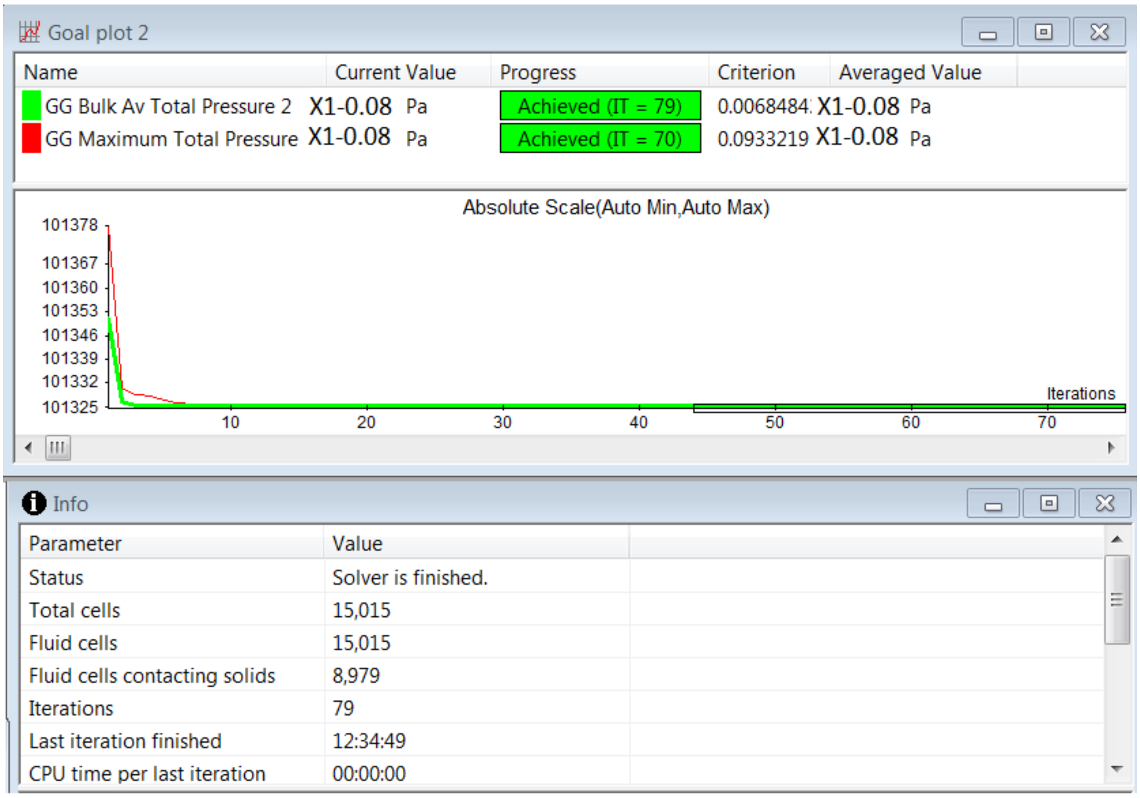

Figure 4.4: FloEFD result for airduct with EDS intersection diameter 30mm and mass-flow m_1^*

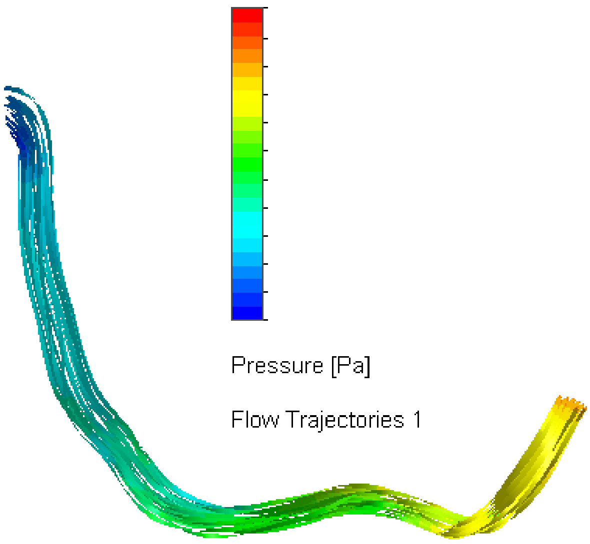

Figure 4.5: FloEFD flow trajectories for airduct with EDS intersection diameter 30mm and mass-flow m_1^*

Design variants	Mass-flow rates (Kg/s)				
	m*1	**m*2**	**m*3**	**m*4**	**m*5**
EDS Dia 30mm	X_1-0.08	Y_1-1.26	Z_1-4.25	A_1-8.46	B_1-13.8
EDS Dia 40mm	X_2-0.08	Y_2-0.97	Z_2-3.37	A_2-6.96	B_2-12.65
EDS Dia 50mm	X_3-0.07	Y_3-1.44	Z_3-3.09	A_3-6.62	B_3-11.19
EDS upward	X_4-0.10	Y_4-1.24	Z_4-3.6	A_4-9.19	B_4-16.08
EDS downward	X_5-0.12	Y_5-1.64	Z_5-5.46	A_5-11.38	B_5-22.40
EDS without	X_6-0.09	Y_6-1.46	Z_6-4.47	A_6-8.92	B_6-17.17

Table 4.2: FloEFD pressure drop (Si unit:Pascal) simulation result table for various designs and mass-flows

The table 4.2 indicates the deviation from the reference value in terms of alphabet. This is followed for both Comsol and FloEFD result tables. Upon investigation, it is noted that the pressure drop is insignificant for various design along low mass-flow rate. It could be comprehended, that the low flow rate do not get obstructed by the intersection and the results are the same. But, as the mass flow increases the pressure drop also increases. For example, let us consider first design variants along the different mass-flows. The pressure drop jumps from 0.40 Pascal to around 34 Pascal. That is an enormous jump for a small variation in the mass-flow. This signifies, how much the mass-flow along an ordinary intersection influences the pressure drop. As noticed in the last column, EDS without, the airduct with no intersection gives the least pressure drop, whereas this cannot be achieved, in all projects, due to various integration and clearance constraints imposed on the airduct.

The results and trajectories of other 29 simulation in FloEFD are presented in appendix A.1.

4.2.2 Comsol Results

The Comsol multiphysics results obtained from the application built are quick and more accurate to four decimal digits. The mass-flow rate are entered and the pressure drop are obtained in pascal, as shown in the figure 4.6. The result unlike FLoEFD, does not provide a convergence graph and an iteration information. They simply provide the trajectories and end pressure drop result. However, the application be user defined and necessary information needed can be generated by using the drag-drop function. The model can be manipulated and investigated at any particular section. This provides a great upper-hand to investigate the intersection of EDS floor cable harness.

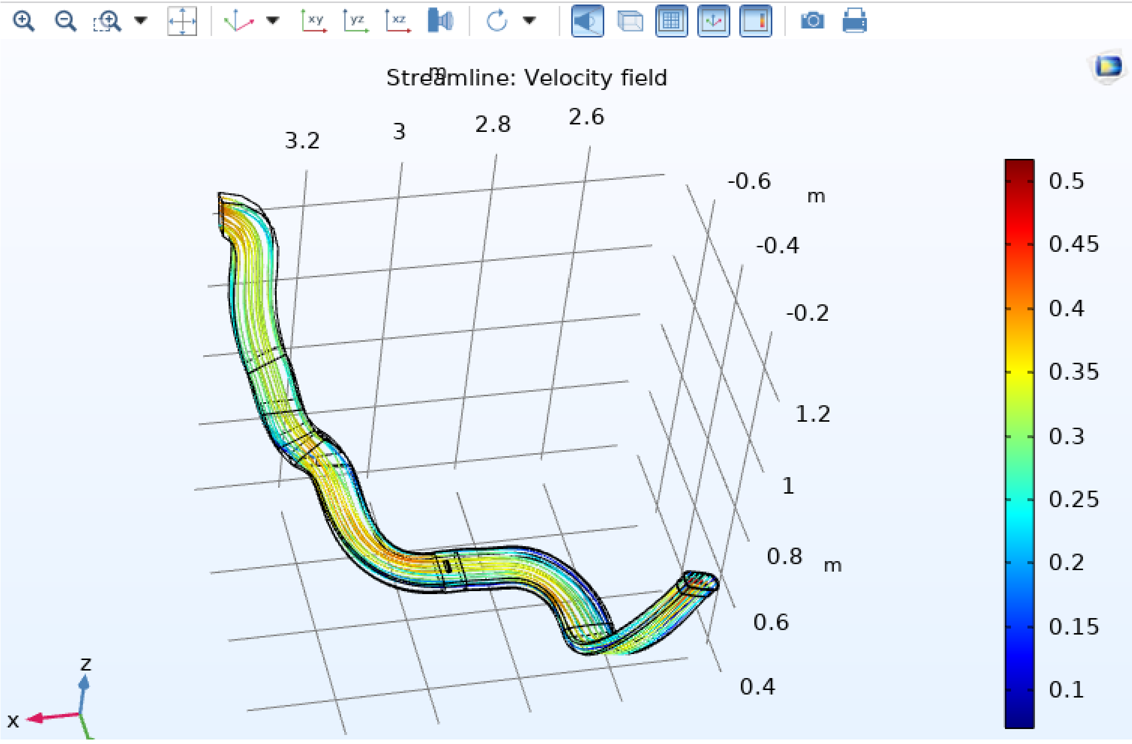

Figure 4.6: Comsol Multiphysics result with trajectories for airduct, with EDS intersection diameter 30mm and mass-flow m_1^*

A similar table, generated for FLoEFD results was created for Comsol Multiphysics results as well. The results obtained were almost similar to the result in FLoEFD, as shown in the table 4.3. The pressure drop in pascal, varies exponentially along the various mass-flow for a single design variant. Similar mass-flows and design variants, as used in FLoEFD, were utilised for Comsol as well, in order to evaluate them against each other.

Once they are compared with each other they are compared with the reference simulation result from StarCCM+. The initial comparison help to identify if the results are consistent and equivalent. The second comparison with reference result, individually, will provide which one of the two software based integration method is the foremost solution.

Design variants	**Mass-flow rates (Kg/s)**				
	m*1	**m*2**	**m*3**	**m*4**	**m*5**
EDS Dia 30mm	X_1-0.08	Y_1-1.26	Z_1-4.25	A_1-8.46	B_1-13.8
EDS Dia 40mm	X_2-0.08	Y_2-0.97	Z_2-3.37	A_2-6.96	B_2-12.65
EDS Dia 50mm	X_3-0.07	Y_3-1.44	Z_3-3.09	A_3-6.62	B_3-11.19
EDS upward	X_4-0.10	Y_4-4.49	Z_4-3.6	A_4-9.19	B_4-16.08
EDS downward	X_5-0.12	Y_5-1.64	Z_5-5.46	A_5-11.38	B_5-22.4
EDS without	X_6-0.09	Y_6-1.46	Z_6-4.47	A_6-8.92	B_6-17.17

Table 4.3: Comsol Multiphysics pressure drop (SI unit:Pascal) simulation result table for various designs and mass-flows

The results and trajectories of other 29 simulation in Comsol Multiphysics are presented in appendix A.1.

5
Discussion

Despite having produced such strong abridgement of the gap between template and CAE in early product development phase, there are some drawbacks and improvements that needs to be addressed. This chapter deals with the discussion of those future development and drawbacks.

If the additive manufacturing technologies becomes much more commercial and inexpensive, it would open a wide room for development. Most of the designs obtained from design optimisation, as explained in the figure 3.16 in the chapter 3.5.3.1, are complex and arduous to manufacture. However, those designs deliver the best outcomes. From the integration perspective, they would save a huge space occupation. Hence providing much more room to work with. The design load on the engineers would reduce drastically, since the optimization tool will carry out the necessary modifications in the airduct, if the conditions are set righteously.

The biggest issue which was witnessed during this thesis, is the inconsistency of data that needs to transferred between design phase and analysis phase. There is a huge model incompatibility while transferring the models from design workbench to any analysis workbench. Identifying a integration tool that would resolve the issue was the main focus and it was indeed not a easy task. The models when viewed through design workbench in CATIA V5 seemed well stitched and tightly fitted with each other. When imported to the analysis workbench, ended up in failure to recognise fluid domain due to gaps and leaks. This issue can be addressed only if Simulation Based Design is followed. The design engineer must keep the simulation criteria while modelling the part.

This brings down to the point that essential knowledge needs to be available to the engineers, who work with SBD and analysis of those designs. The importance of necessity of knowledge regarding the simulation software used and development of design with regards to the simulation cannot be overlooked.

FloEFD and Comsol multiphysics have their own bugs that needs to be kept in mind while working with them. In FloEFD, one has to update the product after generating the lids and fluid domain in the assembly workbench, followed by checking the geometry in analysis workbench to verify the existence of solid body. The simulation file (1.lfd) needs to be stored in the correct directory to load the results. Hence save management must be used to store the model separately in the desktop, rather than in Teamcenter.

Gaps between the airducts are huge when directly imported from Teamcenter, hence they need to be translated for few millimeter inside until the touch each other. This needs to be performed to avoid failure to recognise the fluid domain. In Comsol, the application can be built only using the windows version and not in Linux workbench. The models cannot be huge and needs to be completely solid, rather than hollow, to run the simulation. The comparison between FLoEFD and Comsol is given in the table 5.1 below.

FloEFD	**Comsol Multiphysics**
It runs single phsyics	It runs multi-physics
Needs to be saved separately rather than in Teamcenter	Needs to be saved separately rather than in Teamcenter
Run on embedded CAT product as hollow model	Requires Solid model in STEP file format
Needs setting up boundary conditions for every new simulation	Application built does not require setting up Boundary condition
Identifies fluid domain automatically	Need to build the fluid domain while setting up the application
Tightness and defeaturing can be compromised	Tightness and defeaturing cannot be compromised

Table 5.1: Comparison of identified two software for integration.

The models generated from the template are foundation for developing much better, clean and perfect designs. The models obtained are not clean and robust, but sufficient enough to run concept simulations and determine if the concept would suffice the requirements. There is no need to worry about singularities and convergence error, since the airduct geometry has to change in steady transition and not in sudden abrupt manner. This removes concepts with sharp corners or dents. Therefore, no singularity would be created.

A possible issue, while following standardization approach, as explained in chapter 3.5.2, is that the intermediate values obtained at the junction of section two and three of the airduct might not be accurate. Since, the values obtained at the junction are only reliable to that specific geometry, mesh and iteration. This would change slightly while considering the whole airduct geometry. Hence, this approach can be utilized just to overlook the verification process and cannot be completely trusted on.

5.1 Future works

Creating a robust template which delivers models with no fault requires constant fixing of the structure. for example, the fillets built on the body in template, might create errors while parametrizing. These issues needs far more expertise or a completely new project to hone the model and make it stable. It is a vital area to focus for further development.

The technology grow exponentially everyday. There will be new methodology through which we can address the same situation more effectively in the future. Technology such as Artificial Intelligence and many other could be incorporated, but they are whole another level of development and a lot of work needs to be put in developing the foundation in the far future. The immediate foreseeable development is in already existing methodology. For example, PreonLab which was supposed to a potential software for integration was not selected due to its immaturity in the field of simulation. If in case, PreonLab decides to develop the turbulent flow analysis of fluid, it would serve as a good alternative for integrating template with CAE.

Addressing the above mentioned developments needed more time and resources which are not affordable for a 30 credit thesis' time plan, which was further hindered due to the pandemic COVID-19. The at most development possible, despite the difficulties during the pandemic, were carried out. The progress can be considered as initial stepping stones for front loading the CFD simulations and further development as discussed above needs to be done to make the ideology behind the thesis robust.

Other department from Volvo Cars seemed interested in the developed solution and the methods were incorporated in their workflow to solve few of their own issues. It is promising to see that the developed integration solution would be beneficial for addressing different problems, other than the one specified as the focus area in the thesis.

6

Conclusion

To conclude, the analysis results, for different design models from template, obtained from StarCCM+, Comsol Multiphysics and FloEFD were plotted in a graph. The figure 6.1, shows the graph plotted between different mass-flow rates versus the pressure drop for various designs in Comsol Multiphysics. It could be elucidated that, the trend of the lines goes up for increase in mass-flow rate and bigger the EDS dimensions. Fortunately the trend is similar in the FloEFD as well, as described in figure 6.2. while comparing the StarCCM+ result graph, as shown in the figure 6.3, with other graphs of the software, it is promising that the trend is consistent. This proves that both software produce almost identical solutions and follow the trend of the bench-marked software closely. Hence, both software pass the evaluation phase and both can be utilized for the integration process.

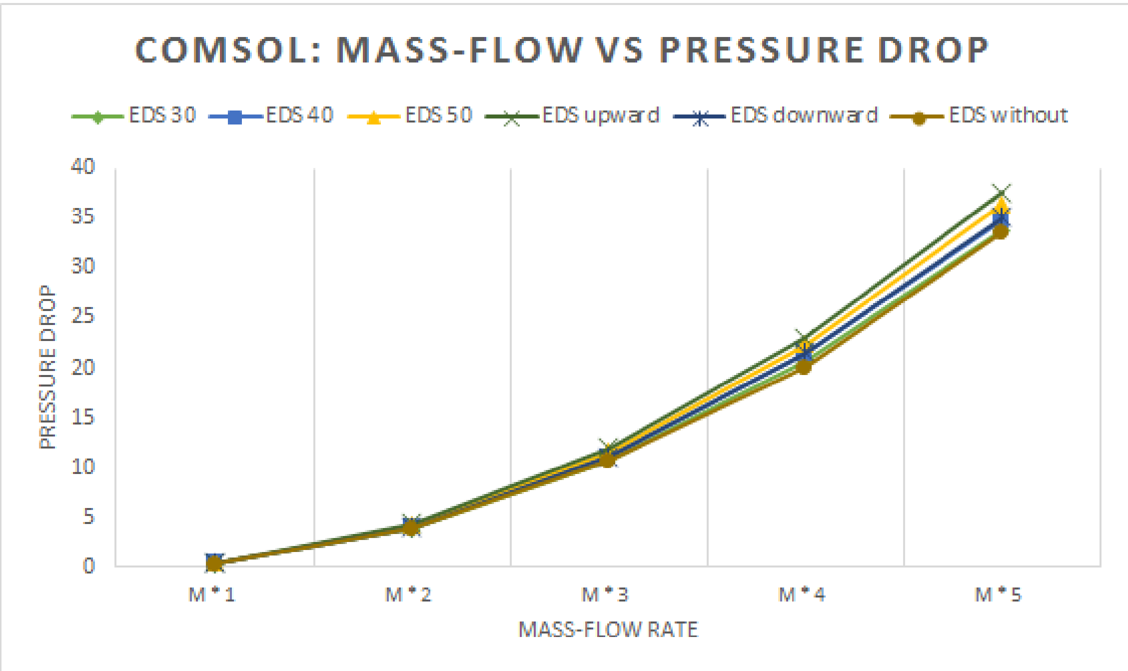

Figure 6.1: Graph plotted against mass-flow and pressure drop in Comsol Multiphysics for different design

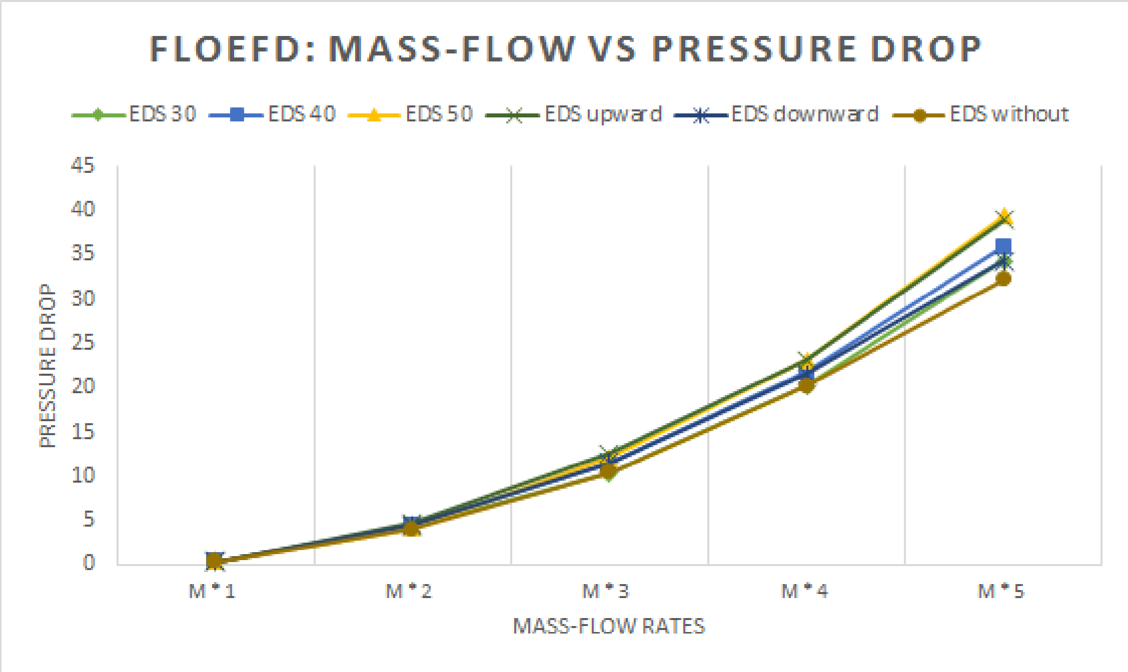

Figure 6.2: Graph plotted against mass-flow and pressure drop in FloEFD for different design

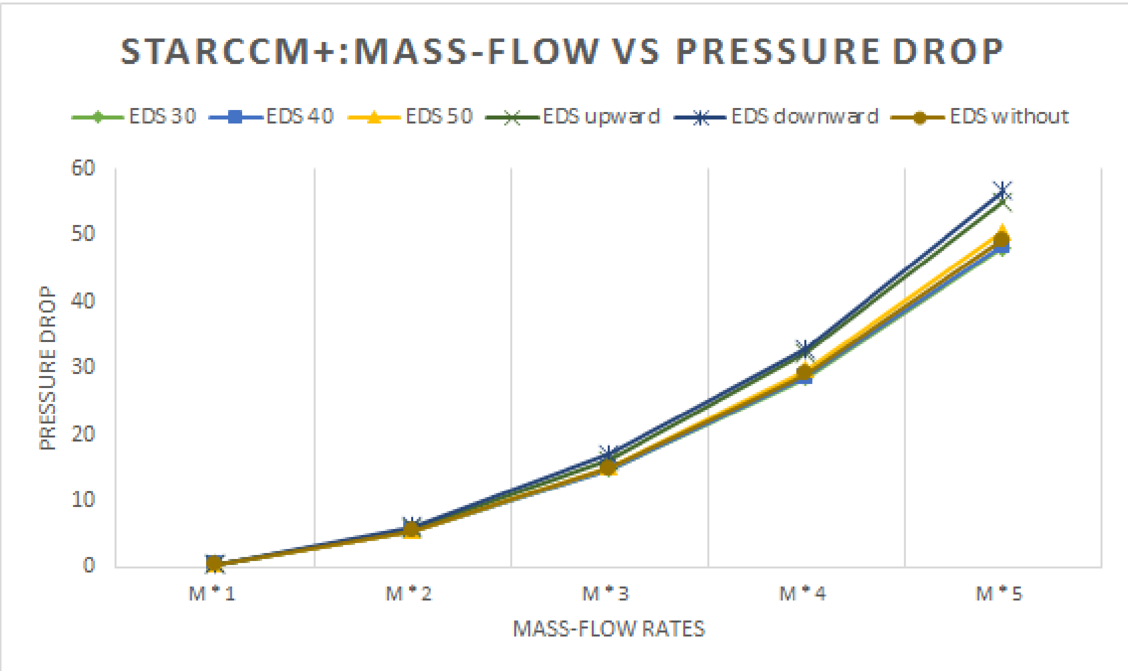

Figure 6.3: Graph plotted against mass-flow and pressure drop in StarCCM+ for different design

The results from different software for a single design variant (EDS diameter 30mm and 50mm) with different mass-flow and pressure drop were also compared in the two distinguishable graphs, as shown in figure 6.4 and figure6.5.

These graphs were generated to compare and visualize if the finalised software justify the currently practised StarCCM+ simulation software's accuracy and performance. It could be said that, the accuracy are higher for lower mass-flows and they deviate as the mass flow increases, but the deviations are not drastic and they vary with just couple of pascals. This is due to the fact that, accuracy is compromised for the speed in the identified software. Hence it could be wrapped up, that the software performs sufficiently for analysing concept models from template.

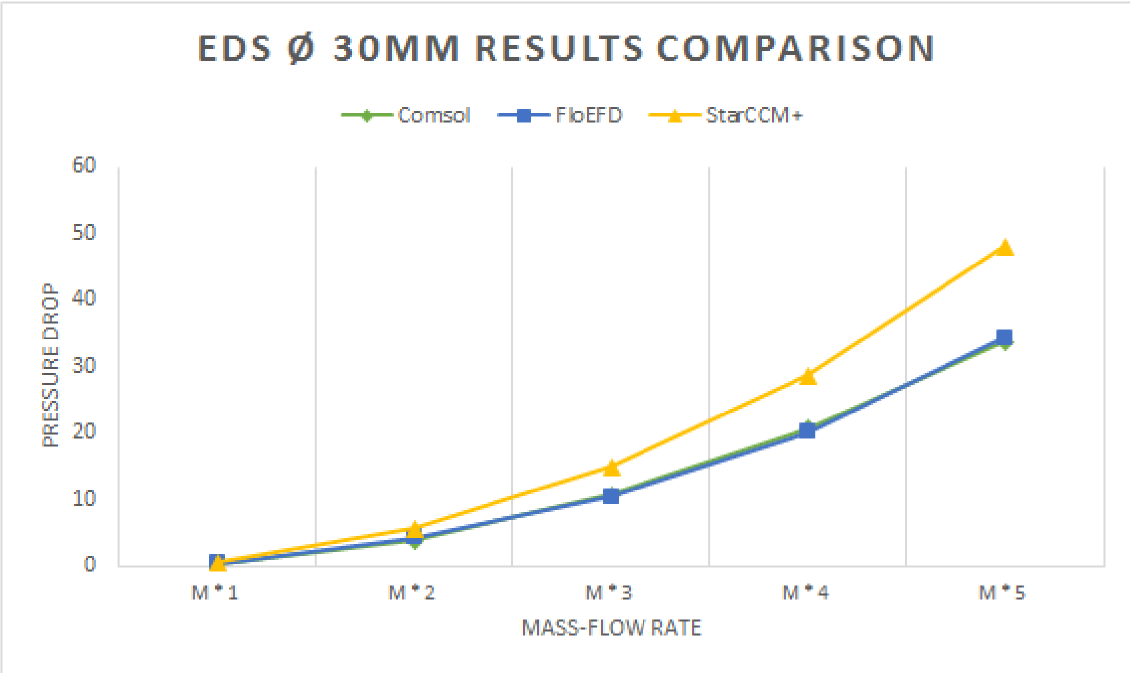

Figure 6.4: Graph plotted against mass-flow and pressure drop in different software for EDS diameter 30mm design variant

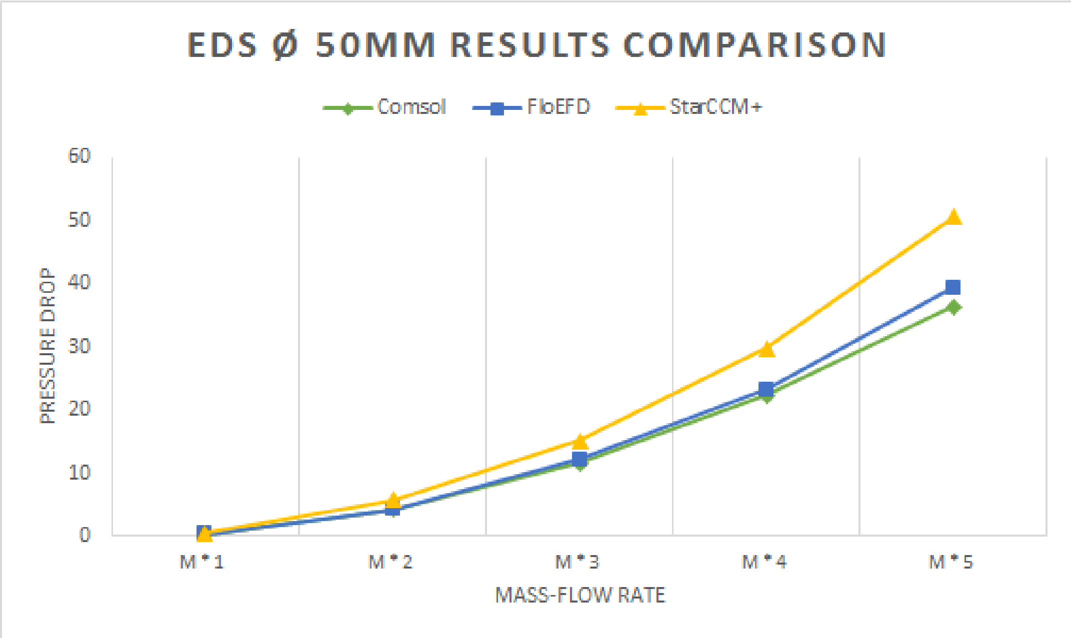

Figure 6.5: Graph plotted against mass-flow and pressure drop in different software for EDS diameter 50mm design variant

Efforts were put in to finalise only one of the competent two software, hence the time taken to complete one simulation from setting up till results obtained was observed. The time record is shown in the table below 6.1.

Software	Setting up time	Simulation time
FloEFD	10 - 15 min	Atmost 1 min
Comsol Multiphysics	2 min	10 - 12 min
StarCCM+	15 min	25 min

Table 6.1: Time record for running one simulation

The cumulative time for setting up, until obtaining results are almost the same for both the software. It is at most 15minutes to complete one simulation. Whereas generating a surface mesh takes 663 seconds, volume mesh 275 seconds and the simulation itself (solving flow equations) takes 1490 seconds in StarCCM+, which come around 40 minutes from setting up till obtaining the result. Both Comsol and FloEFD have almost same time record as shown in the table 6.1 and accuracy as shown in the graphs. When they are compared with StarCCM+, the accuracy is consistent and almost 30minutes is saved. Therefore, it could be concluded that, irrespective of any factors, both the identified software are nonpareil.
The software are very idiosyncratic to each other, henceforth it could also be concluded that a particular software can be exercised depending upon the need and preference of the end user. Comsol Multiphysics can be utilized, if the engineer does not want to spend much time on setting up the simulation, excluding building the application, or vice versa for FloEFD.

To answer the research question which were put forth in the beginning of the search of a suitable solution to integrate are acknowledged below,

- How is it feasible to integrate Computational Fluid Dynamics with Engineering Template in early product development phase?

Answer: The integration of CFD with Engineering template in early product development phase, after vigorous investigation, can be done through software such as the one discussed in the chapter 4. The software based integration meets all the requirements that were addressed. They run quick and accurate simulations with less CAD model data. The template model was also developed with regards to simulation based design and easy development of concepts using paramterization.

- How much does the integration methods, to perform short simulation loops, abridged the development lead time?

Answer: As discussed in table 6.1, in chapter 6. The total cumulative time from setting up till obtaining the results is around 15 minutes for both the software. However, the software currently used produces results from setting up is 40 minutes. Almost 30 minutes of the current simulation and development time is saved, through the current developed solution. This salvaged time is when the design engineer performs short simulation loops to front load. However, the time taken by the supplier to build the detailed model in order to forward it for actual CFD simulation is still long and non-compromised. Valuable time is lost by waiting for the model to be developed by the supplier.

- How much does the short simulation loop's results does deviates from the actual simulation results?

Answer: From the figure 6.4 and figure 6.5, it could be perceived that the results, from Comsol and FloEFD, do not deviate much from the reference results from StarCCM+. Although, as the mass-flow increases the deviation intensifies, the deviation between them is not drastic and they vary within few pascals. Considering the fact, that huge amount of time is salvaged, compromising accuracy to such level is tolerable.

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A

Appendix

A.1 FloEFD Results

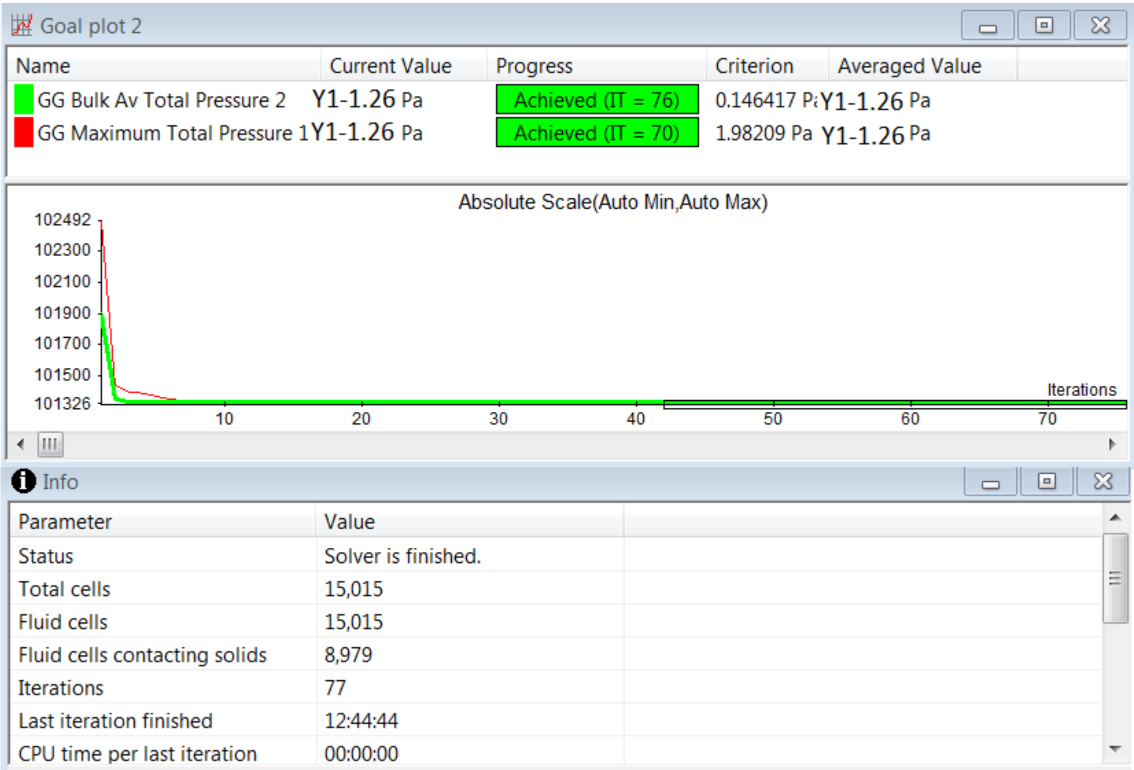

Figure A.1: FloEFD result for airduct with EDS intersection diameter 30mm and mass-flow m_2^*

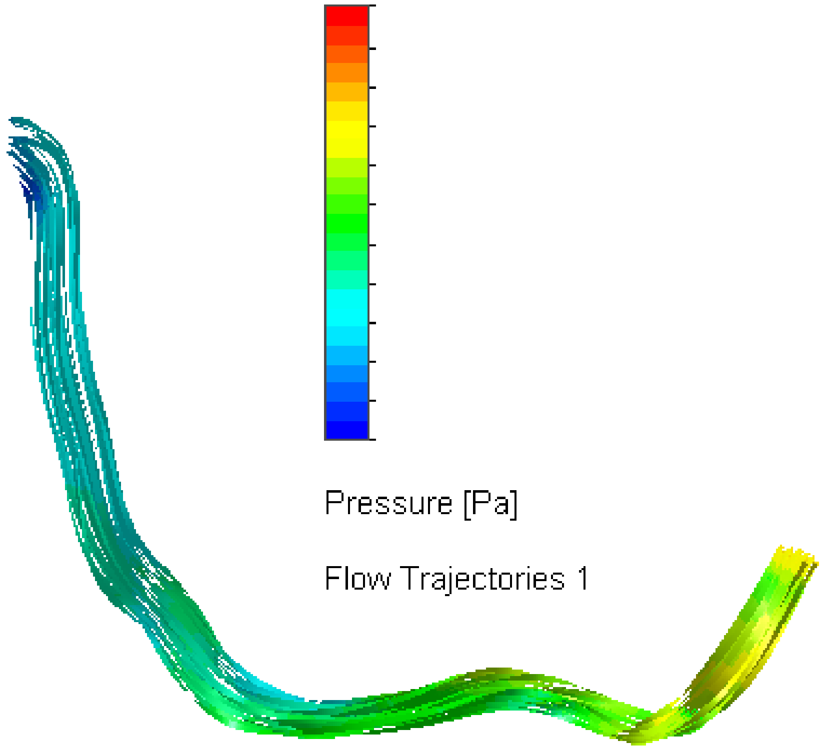

Figure A.2: FloEFD flow trajectories for airduct with EDS intersection diameter 30mm and mass-flow m_2^*

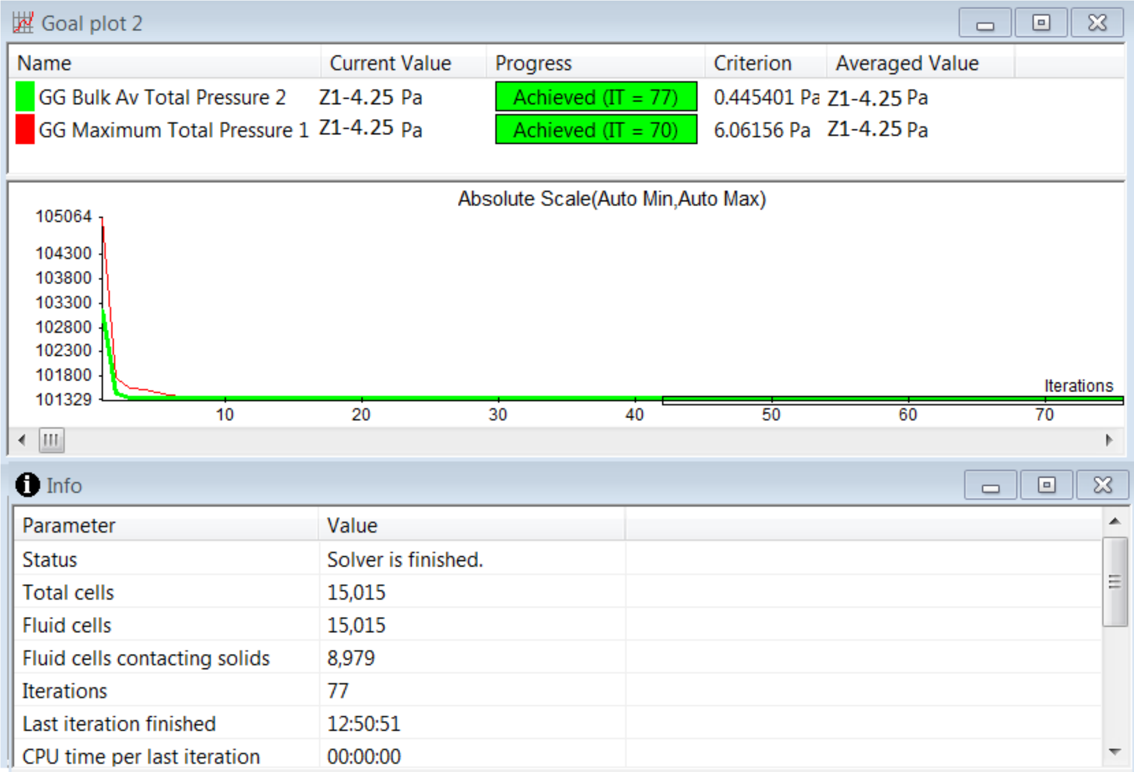

Figure A.3: FloEFD result for airduct with EDS intersection diameter 30mm and mass-flow m_3^*

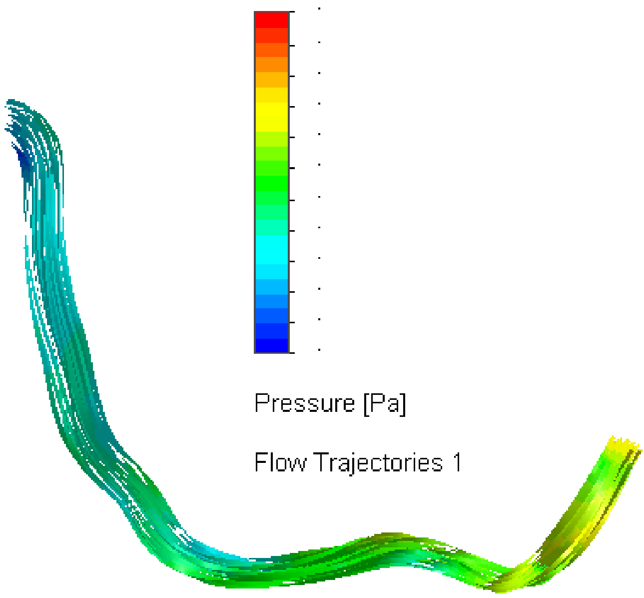

Figure A.4: FloEFD flow trajectories for airduct with EDS intersection diameter 30mm and mass-flow m_3^*

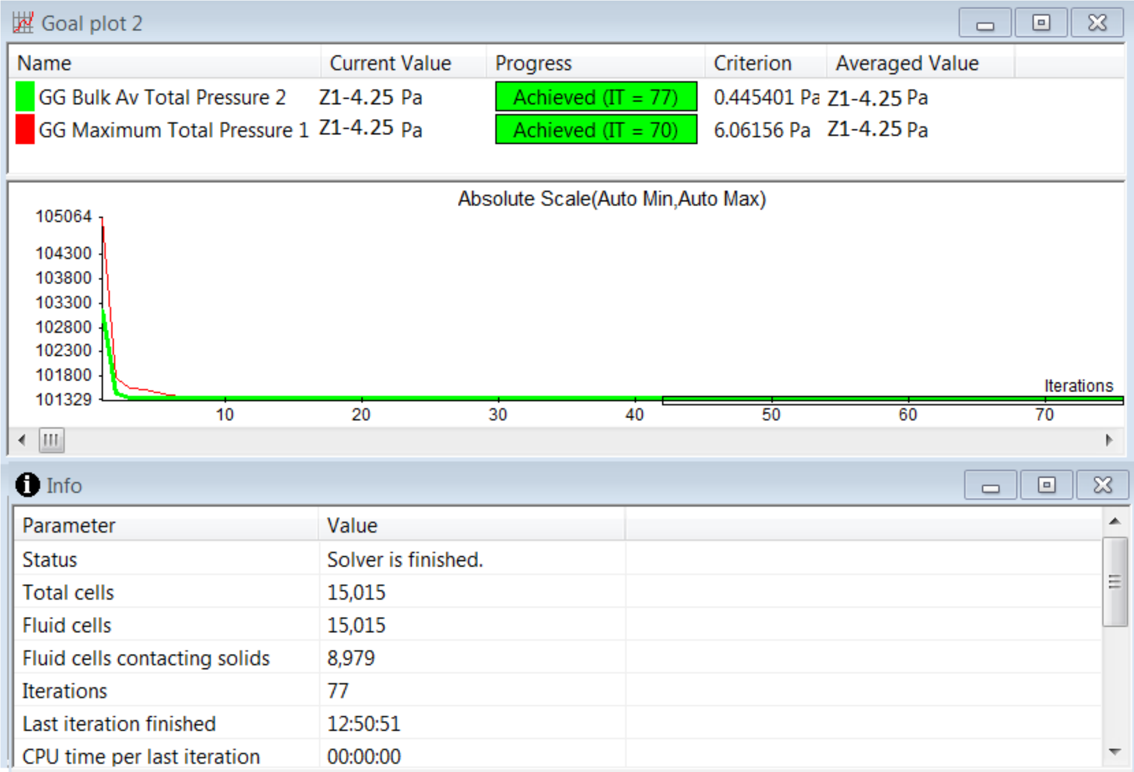

Figure A.5: FloEFD result for airduct with EDS intersection diameter 30mm and mass-flow m_3^*

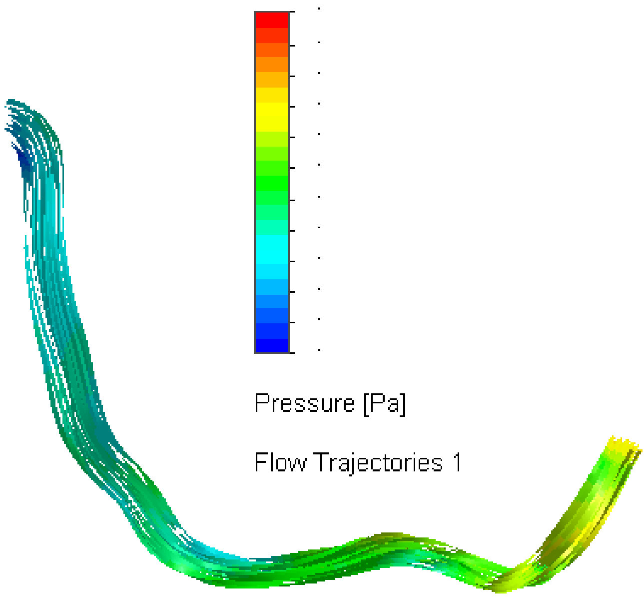

Figure A.6: FloEFD flow trajectories for airduct with EDS intersection diameter 30mm and mass-flow m_3^*

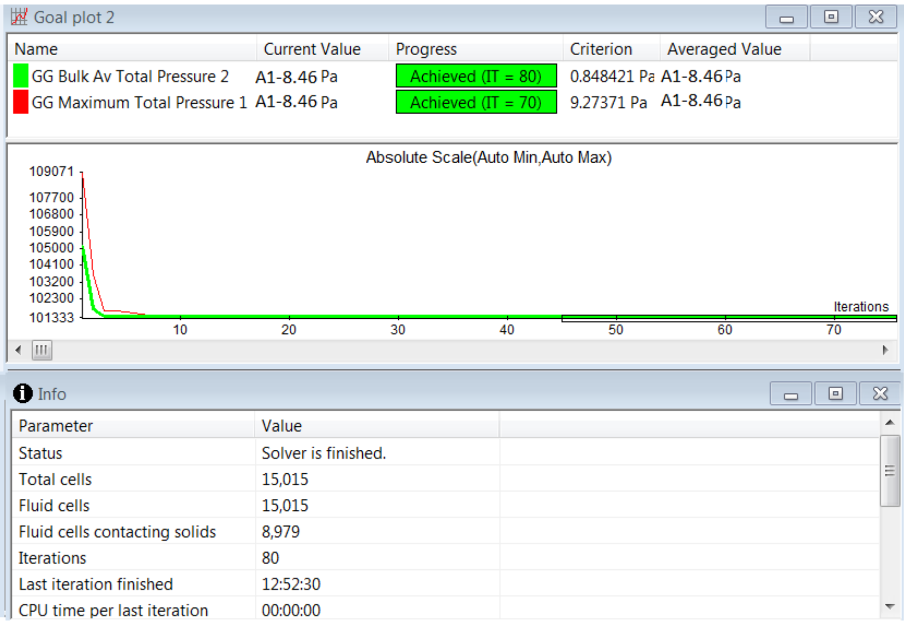

Figure A.7: FloEFD result for airduct with EDS intersection diameter 30mm and mass-flow m_4^*

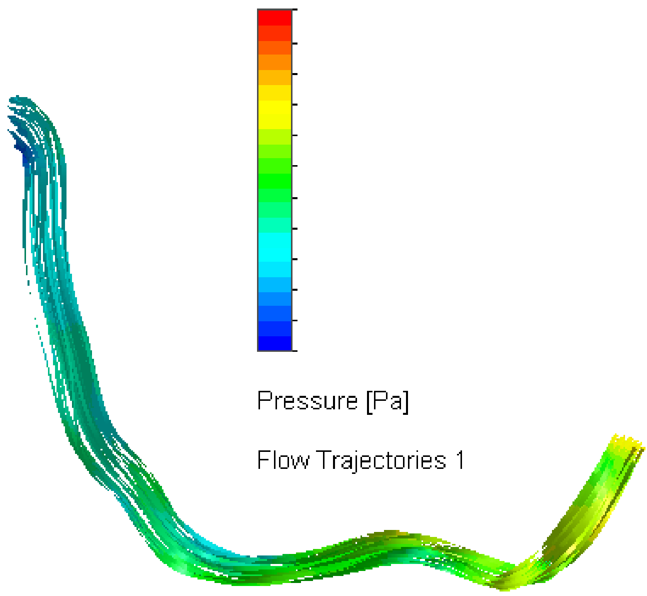

Figure A.8: FloEFD flow trajectories for airduct with EDS intersection diameter 30mm and mass-flow m_4^*

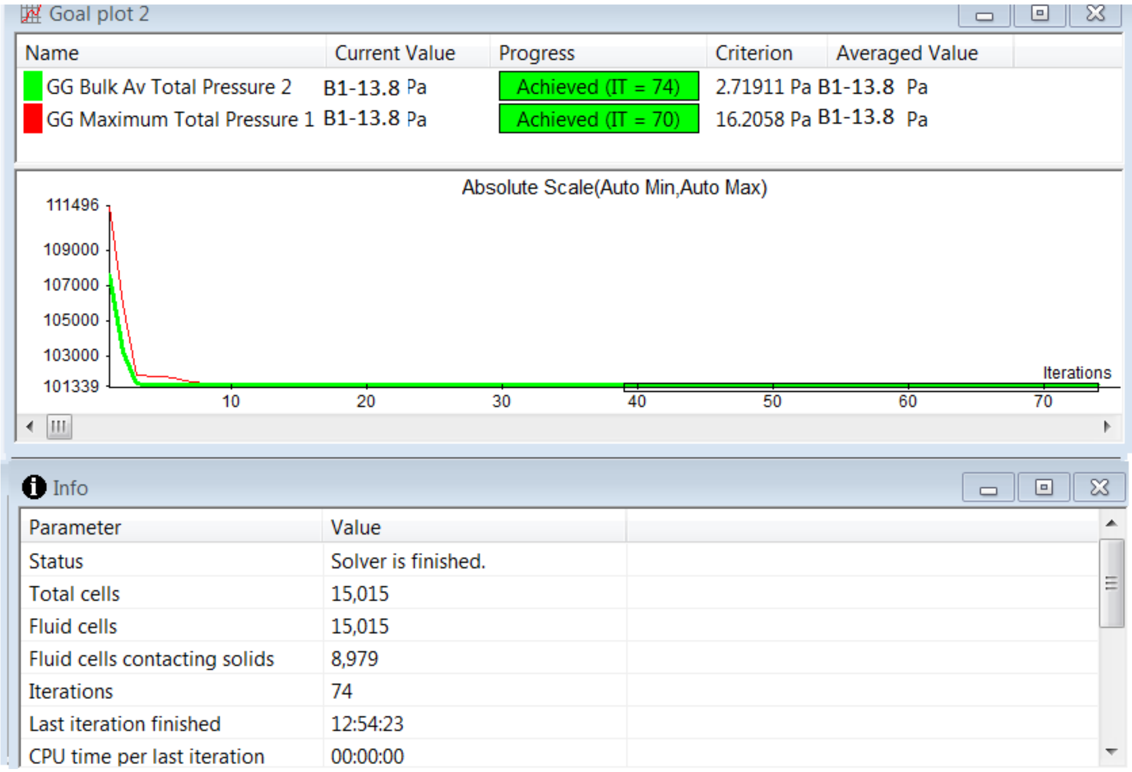

Figure A.9: FloEFD result for airduct with EDS intersection diameter 30mm and mass-flow m_5^*

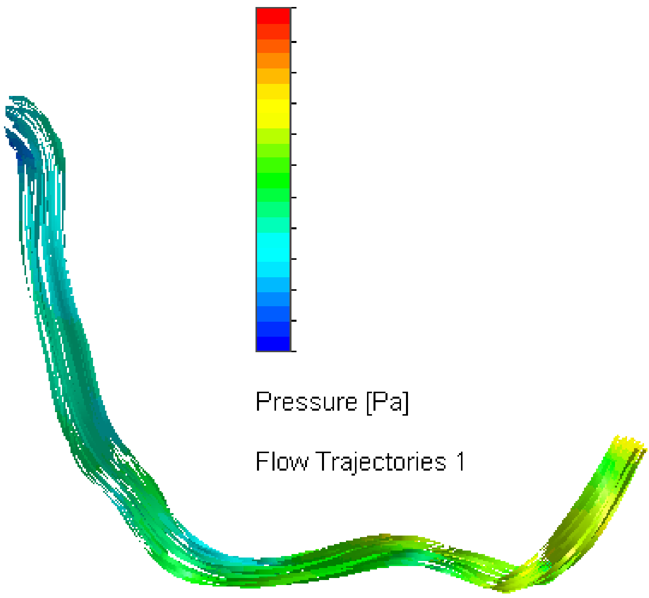

Figure A.10: FloEFD flow trajectories for airduct with EDS intersection diameter 30mm and mass-flow m_5^*

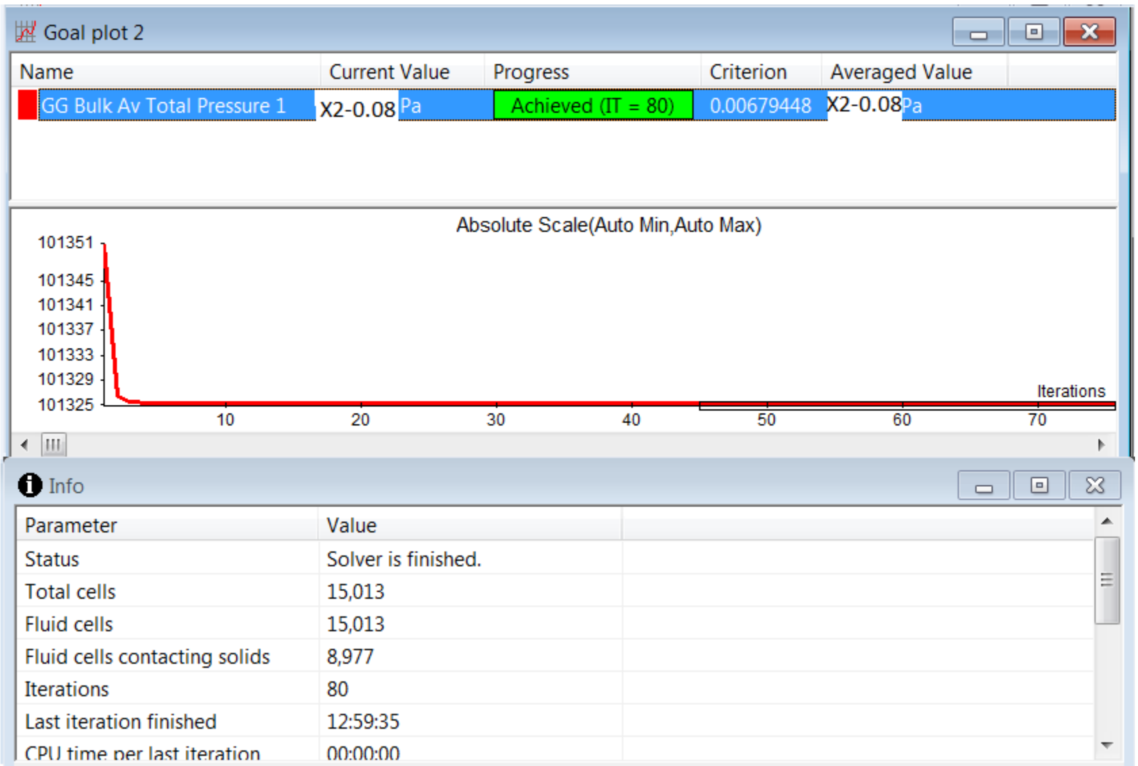

Figure A.11: FloEFD result for airduct with EDS intersection diameter 40mm and mass-flow m_1^*

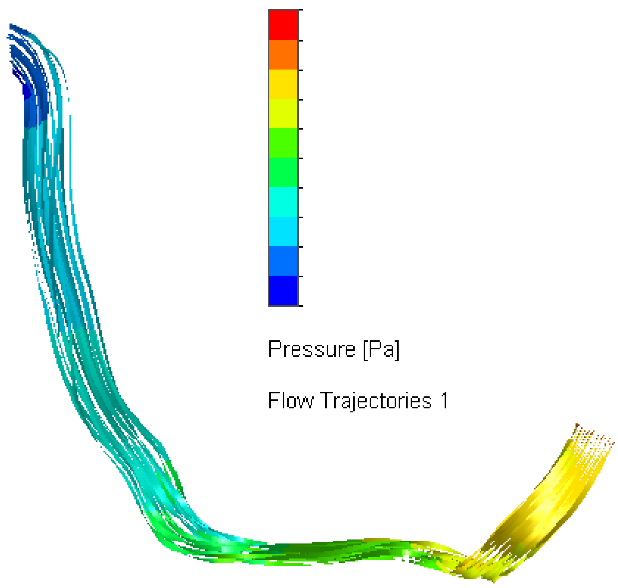

Figure A.12: FloEFD flow trajectories for airduct with EDS intersection diameter 40mm and mass-flow m_1^*

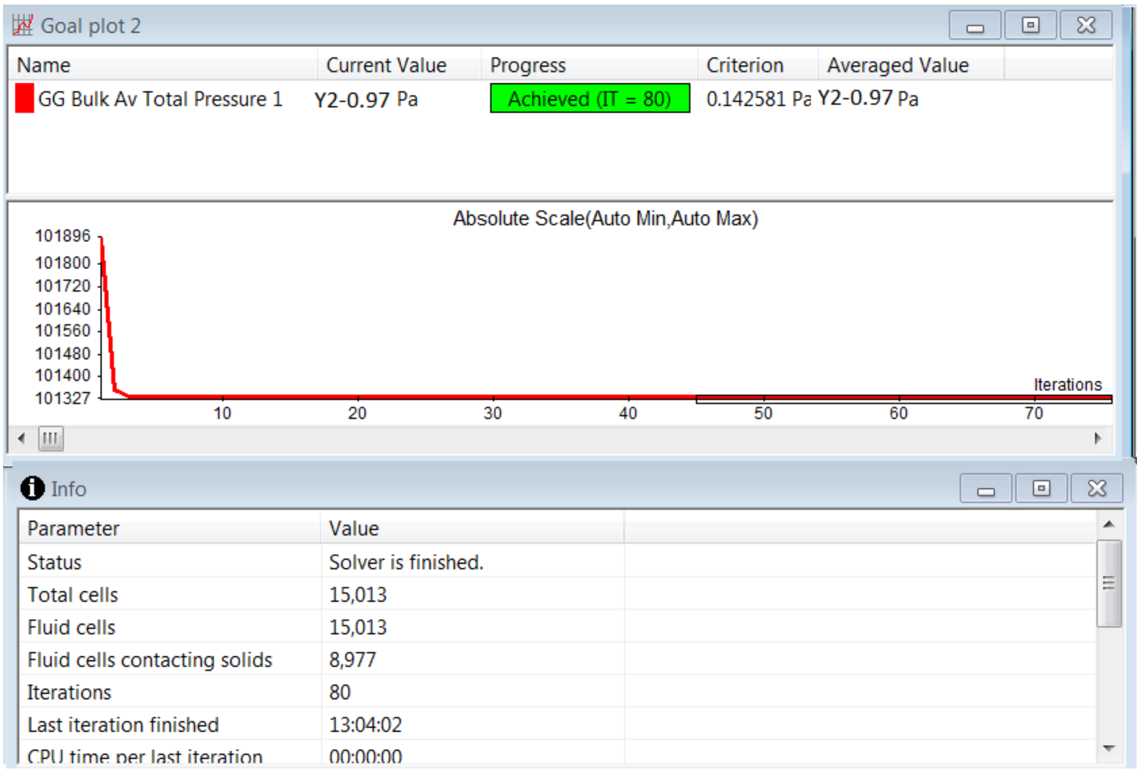

Figure A.13: FloEFD result for airduct with EDS intersection diameter 40mm and mass-flow m_2^*

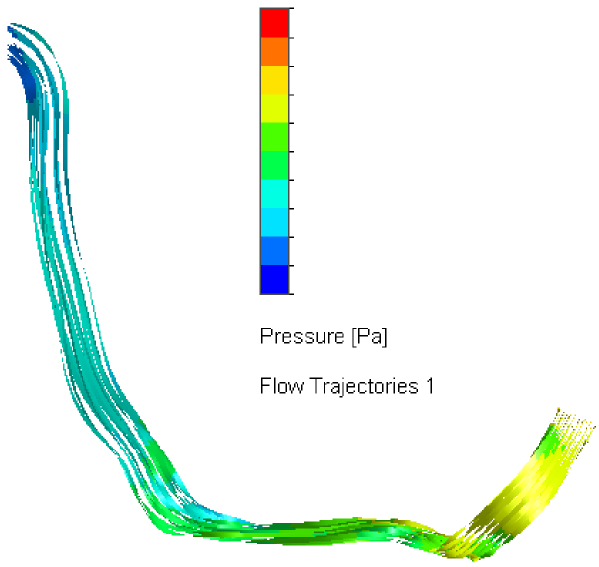

Figure A.14: FloEFD flow trajectories for airduct with EDS intersection diameter 40mm and mass-flow m_2^*

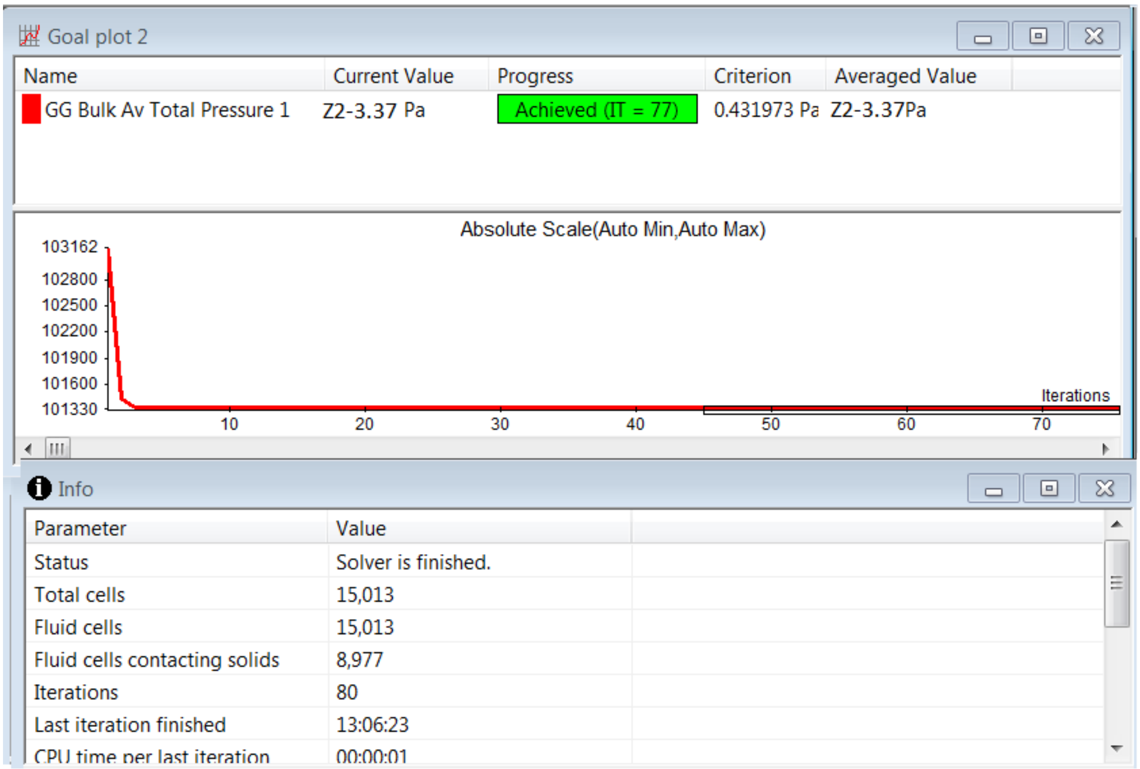

Figure A.15: FloEFD result for airduct with EDS intersection diameter 40mm and mass-flow m_3^*

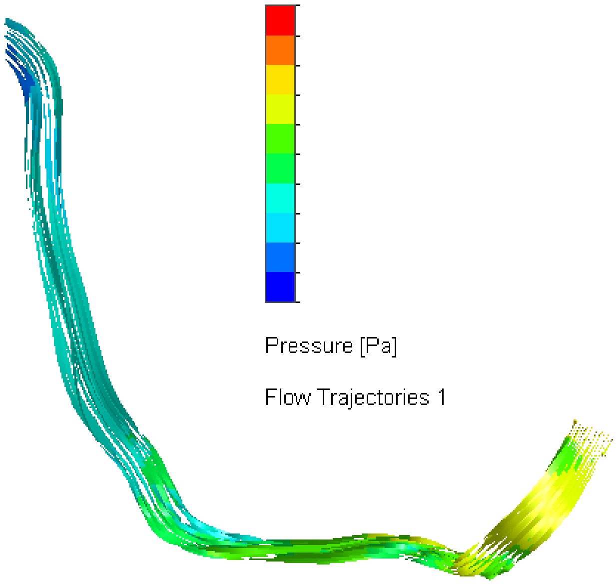

Figure A.16: FloEFD flow trajectories for airduct with EDS intersection diameter 40mm and mass-flow m_3^*

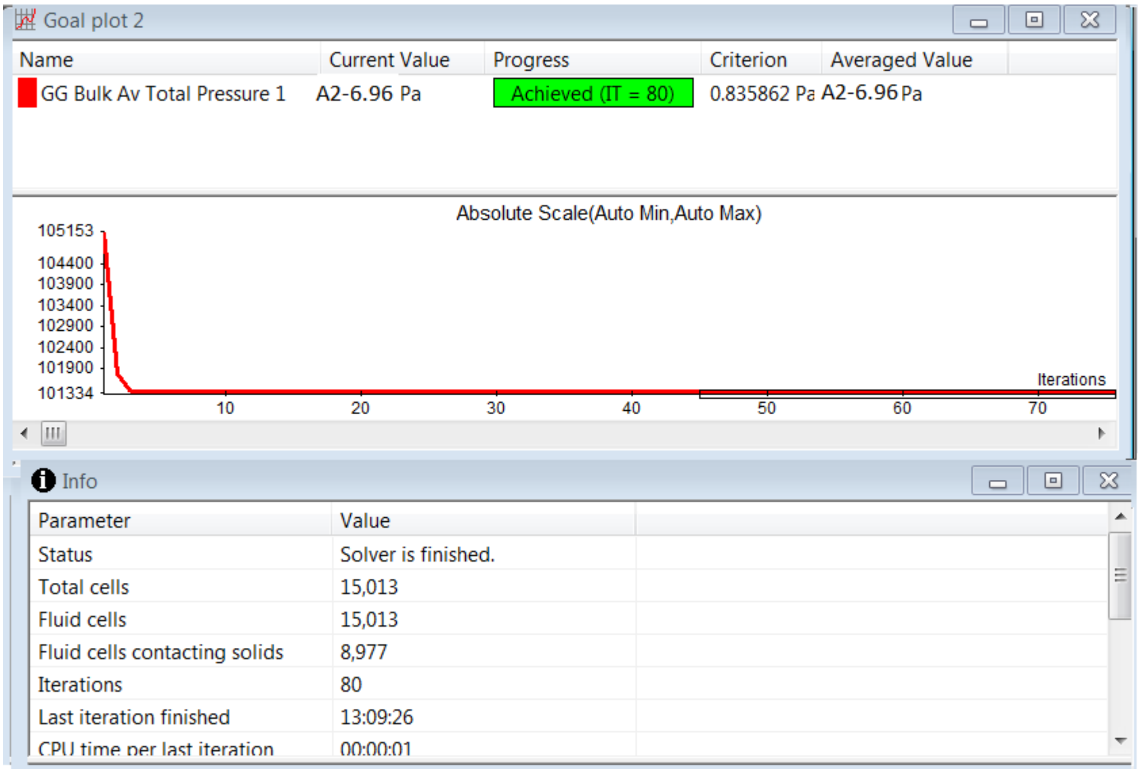

Figure A.17: FloEFD result for airduct with EDS intersection diameter 40mm and mass-flow m_4^*

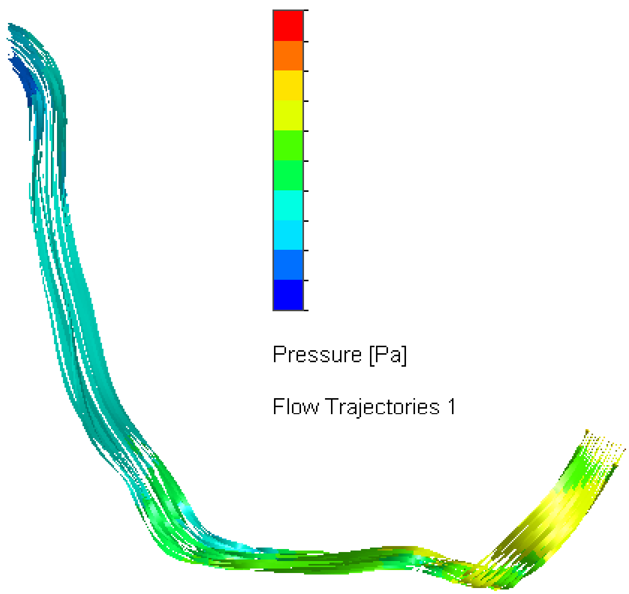

Figure A.18: FloEFD flow trajectories for airduct with EDS intersection diameter 40mm and mass-flow m_4^*

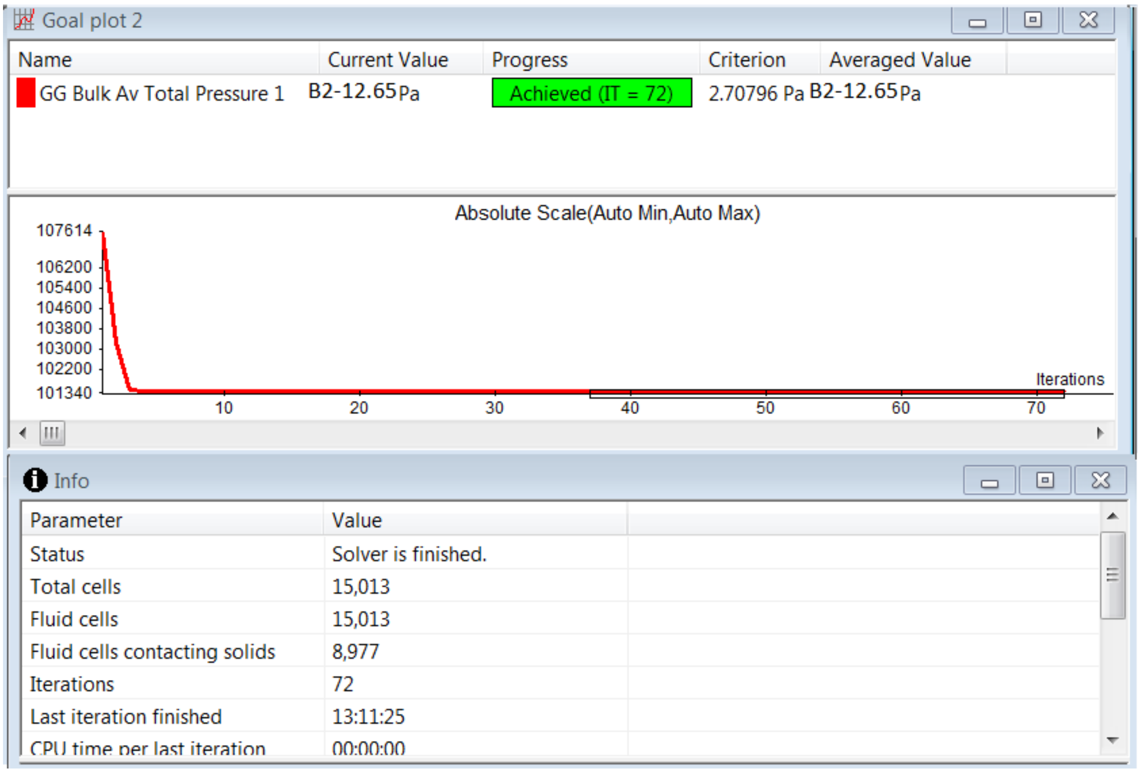

Figure A.19: FloEFD result for airduct with EDS intersection diameter 40mm and mass-flow m_5^*

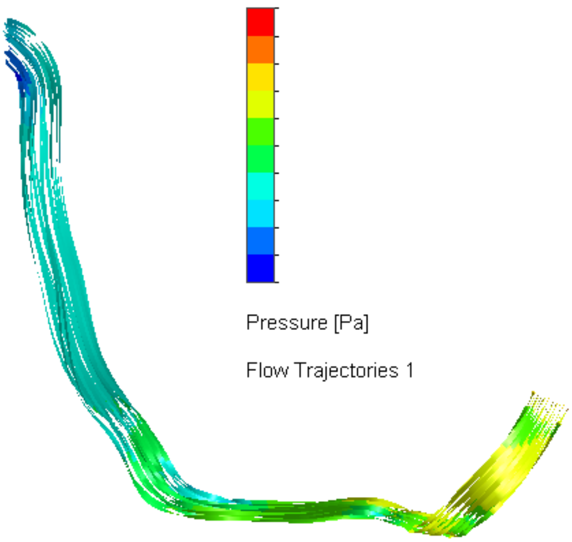

Figure A.20: FloEFD flow trajectories for airduct with EDS intersection diameter 40mm and mass-flow m_5^*

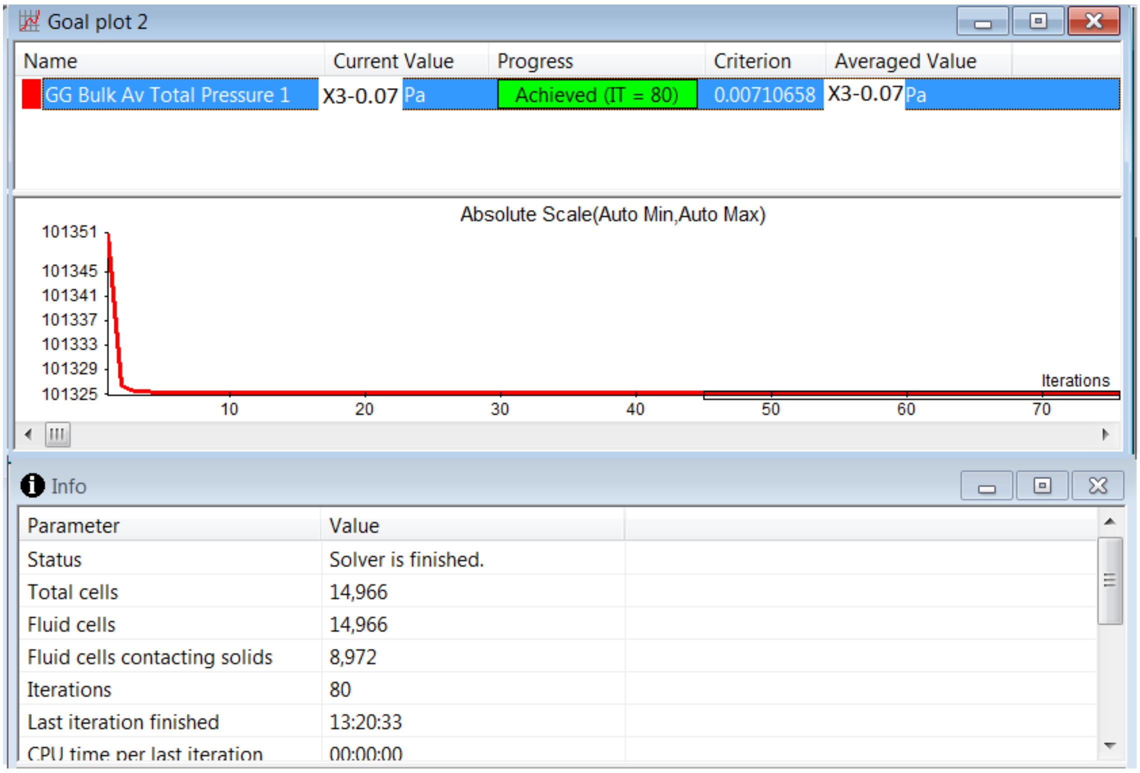

Figure A.21: FloEFD result for airduct with EDS intersection diameter 50mm and mass-flow m_1^*

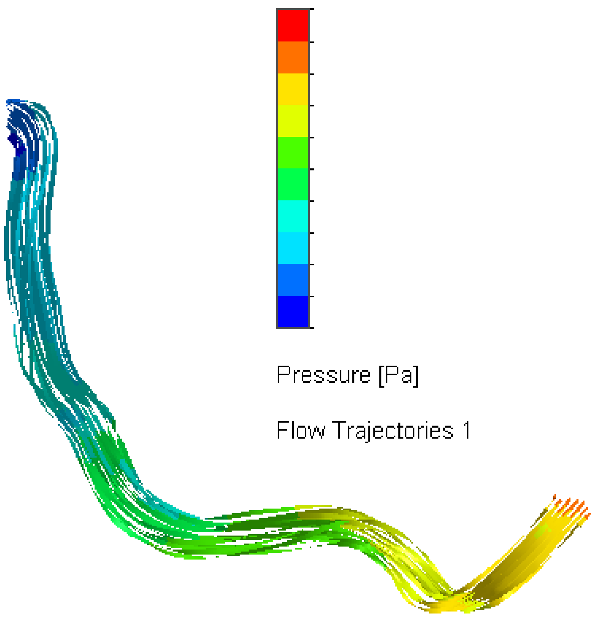

Figure A.22: FloEFD flow trajectories for airduct with EDS intersection diameter 50mm and mass-flow m_1^*

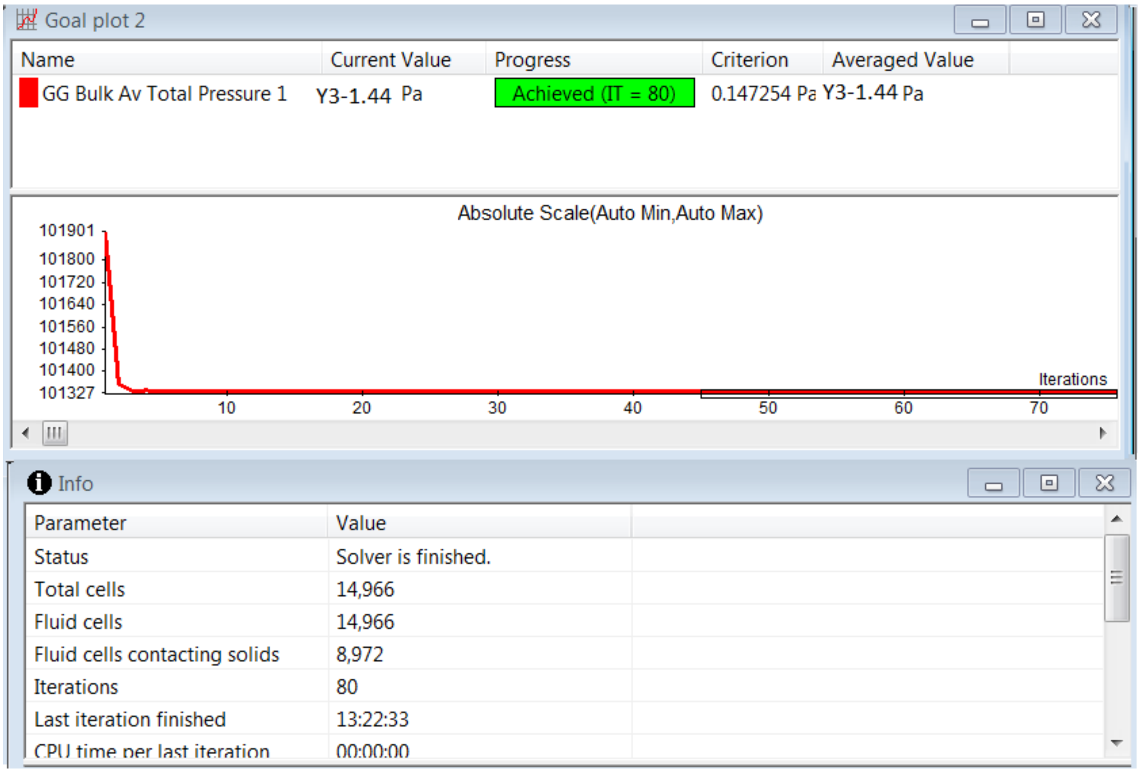

Figure A.23: FloEFD result for airduct with EDS intersection diameter 50mm and mass-flow m_2^*

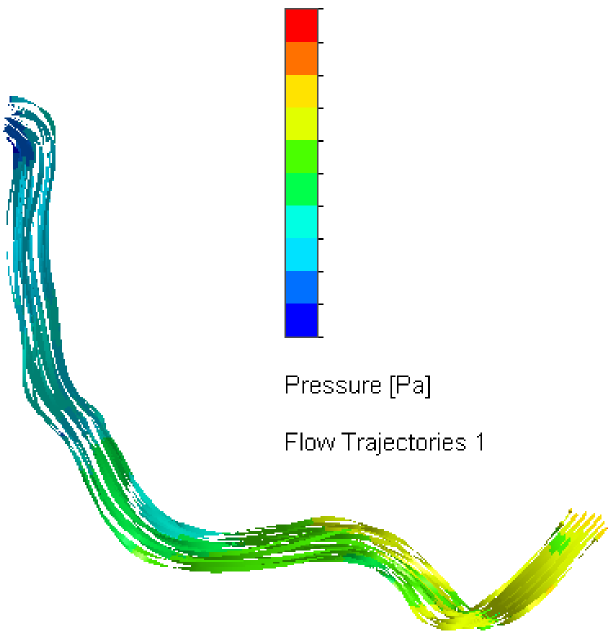

Figure A.24: FloEFD flow trajectories for airduct with EDS intersection diameter 50mm and mass-flow m_2^*

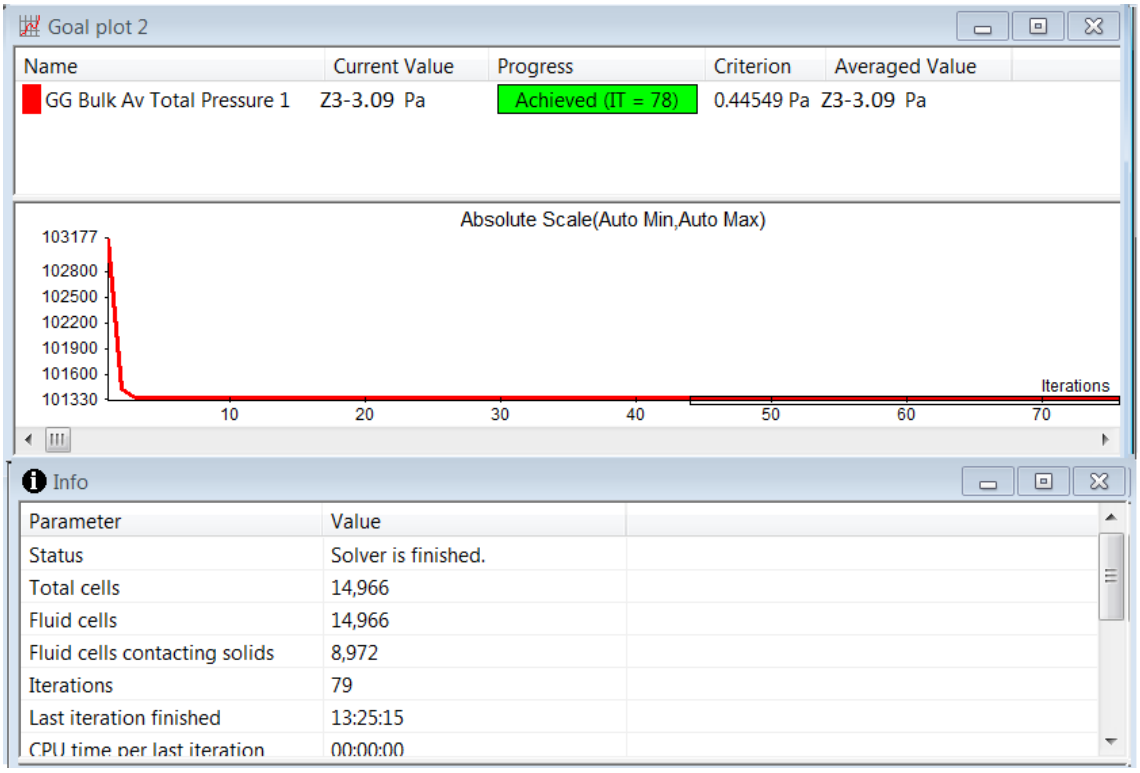

Figure A.25: FloEFD result for airduct with EDS intersection diameter 50mm and mass-flow m_3^*

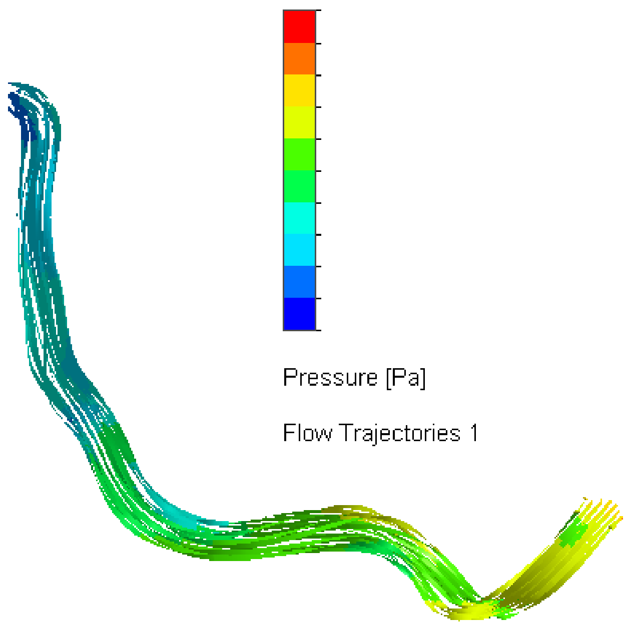

Figure A.26: FloEFD flow trajectories for airduct with EDS intersection diameter 50mm and mass-flow m_3^*

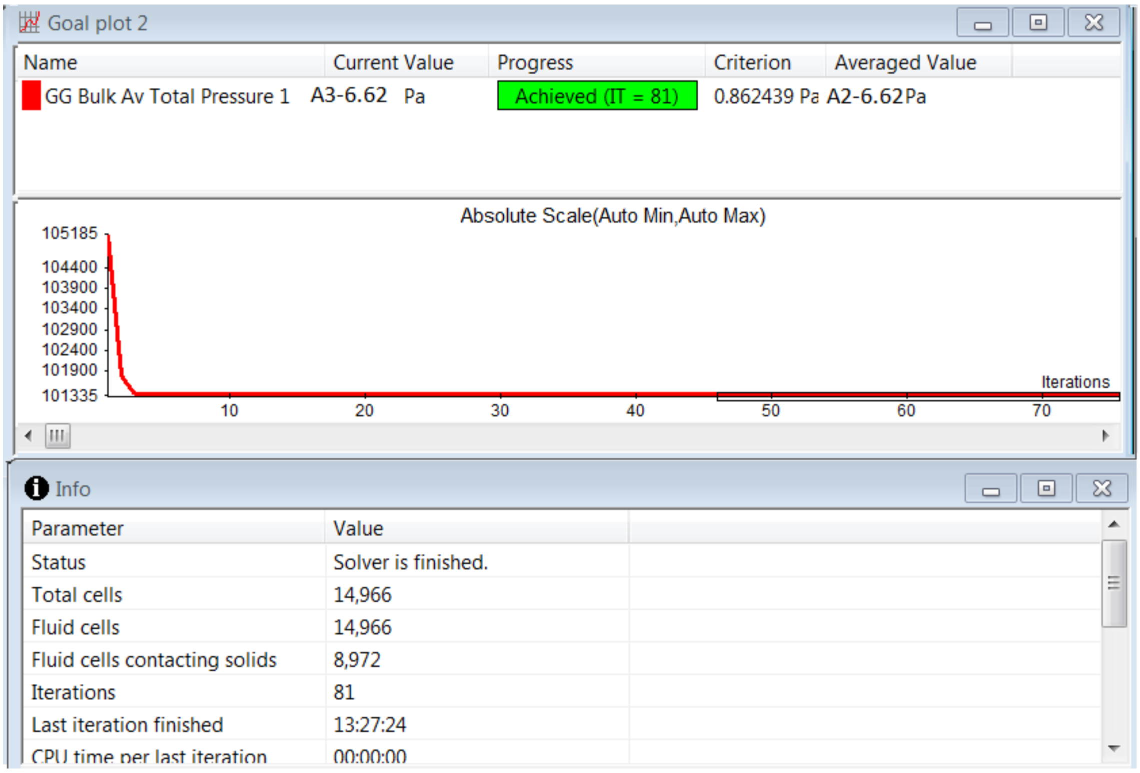

Figure A.27: FloEFD result for airduct with EDS intersection diameter 50mm and mass-flow m_4^*

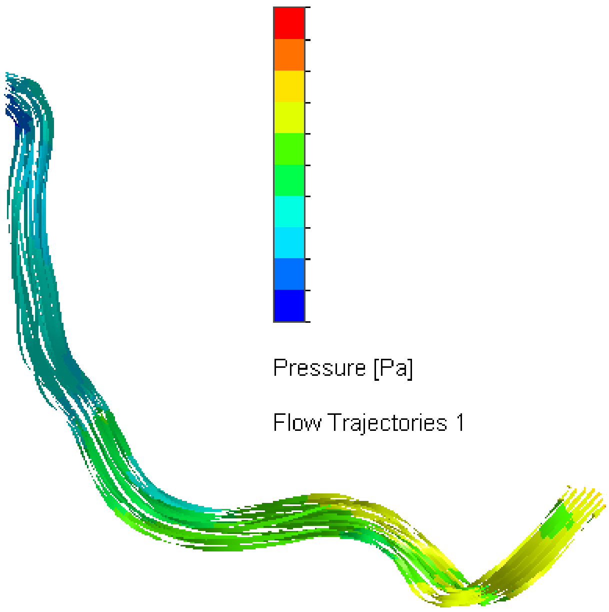

Figure A.28: FloEFD flow trajectories for airduct with EDS intersection diameter 50mm and mass-flow m_4^*

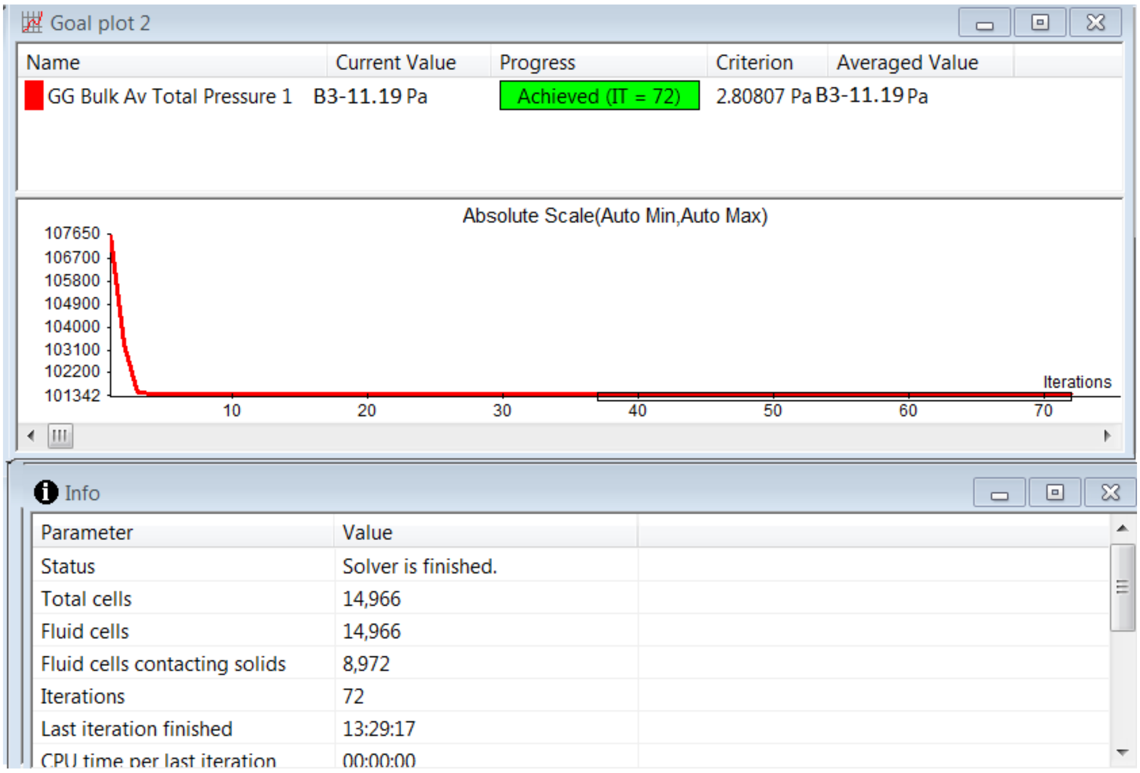

Figure A.29: FloEFD result for airduct with EDS intersection diameter 50mm and mass-flow m_5^*

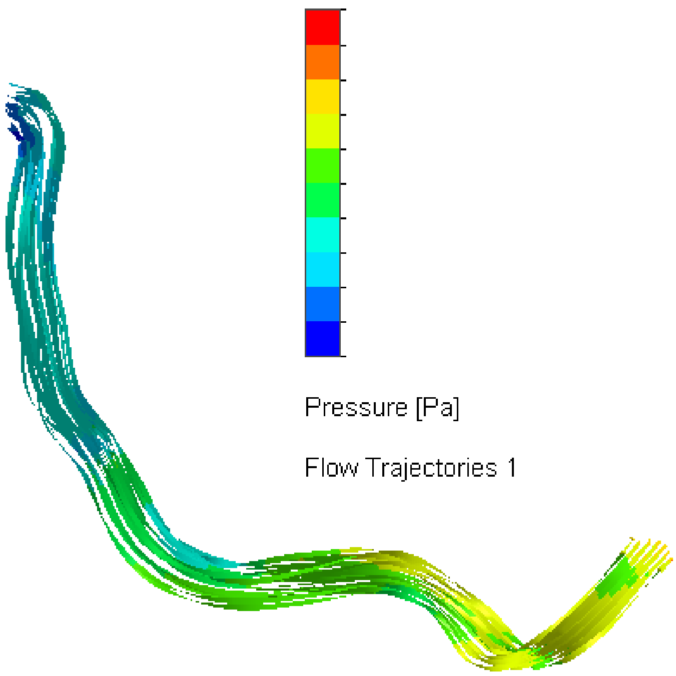

Figure A.30: FloEFD flow trajectories for airduct with EDS intersection diameter 50mm and mass-flow m_5^*

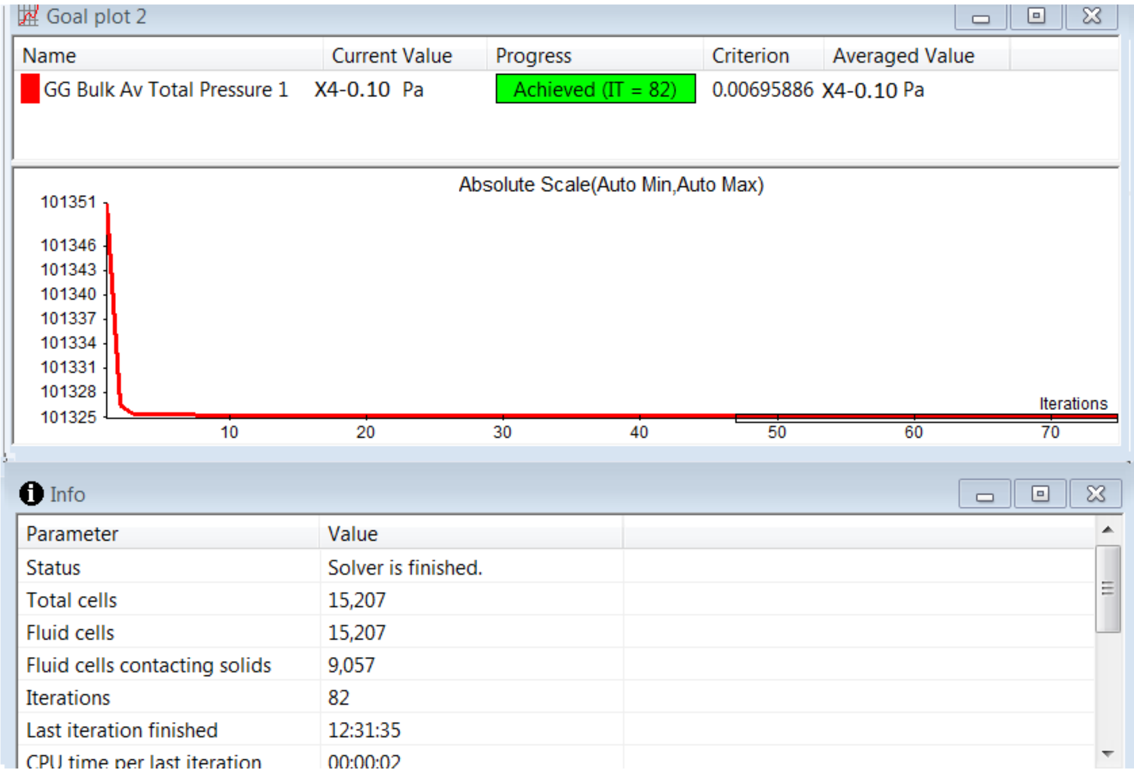

Figure A.31: FloEFD result for airduct with EDS intersection diameter upward and mass-flow m_1^*

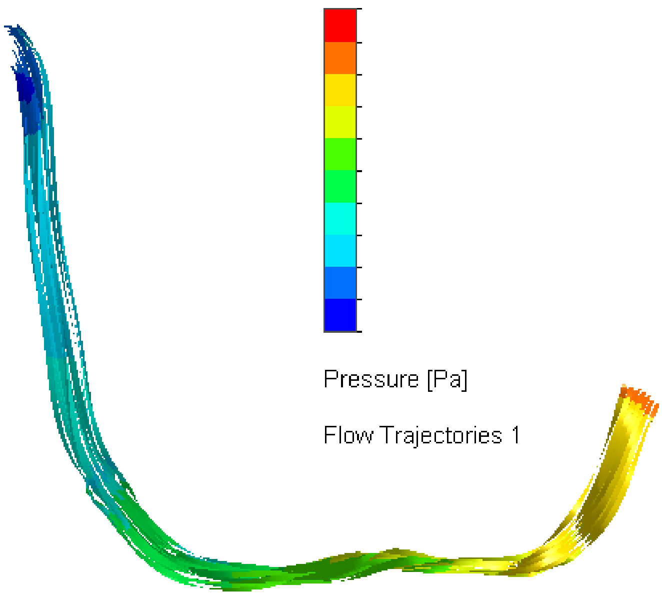

Figure A.32: FloEFD flow trajectories for airduct with EDS intersection diameter upward and mass-flow m_1^*

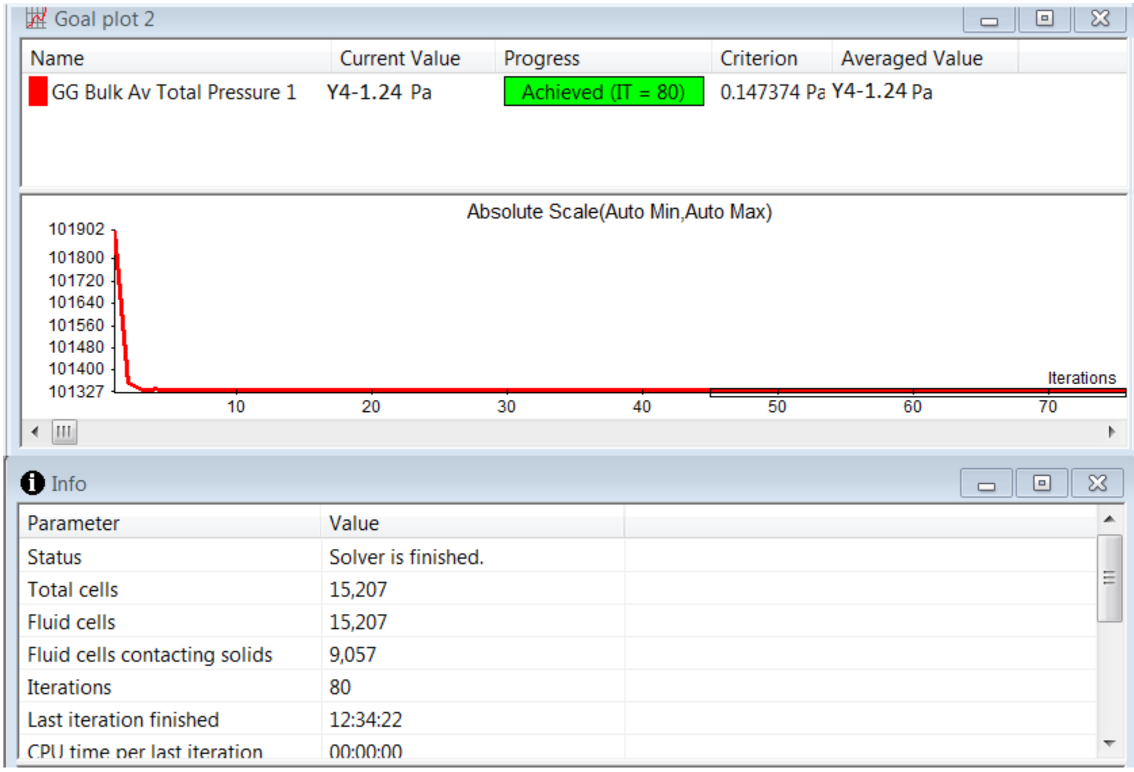

Figure A.33: FloEFD result for airduct with EDS intersection diameter upward and mass-flow m_2^*

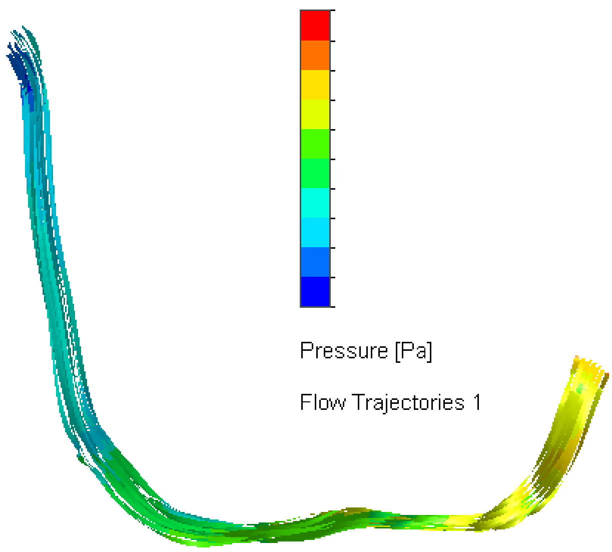

Figure A.34: FloEFD flow trajectories for airduct with EDS intersection diameter upward and mass-flow m_2^*

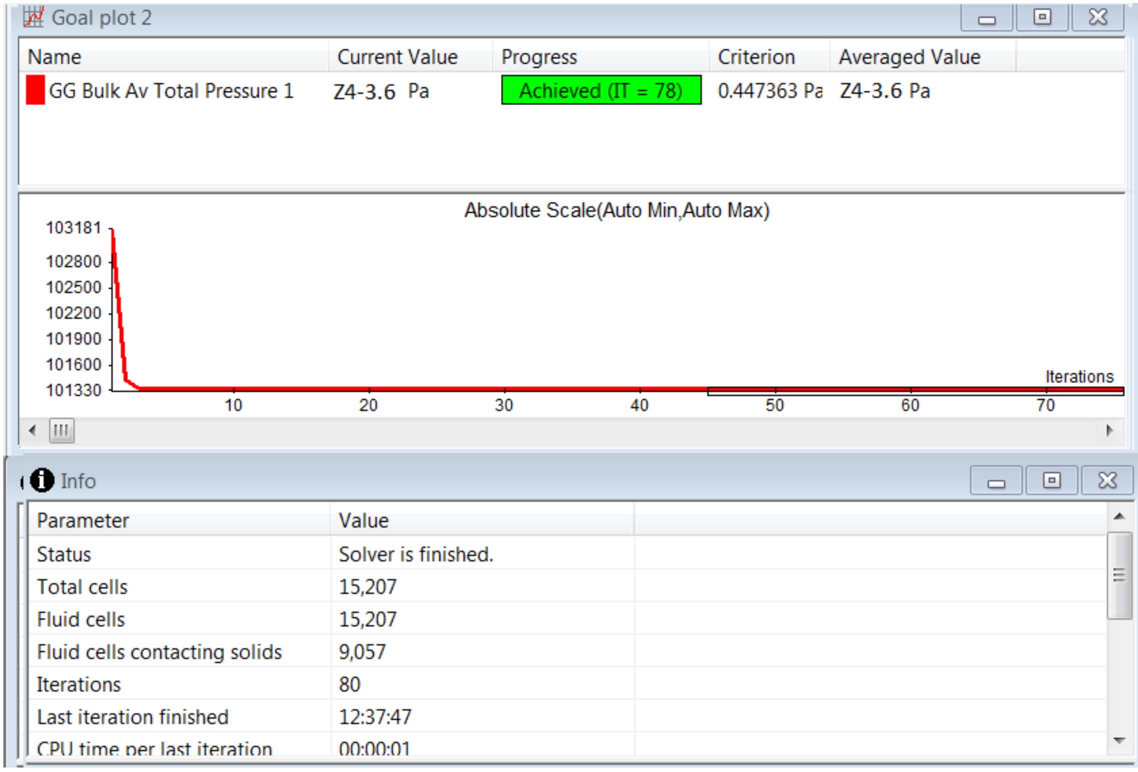

Figure A.35: FloEFD result for airduct with EDS intersection diameter upward and mass-flow m_3^*

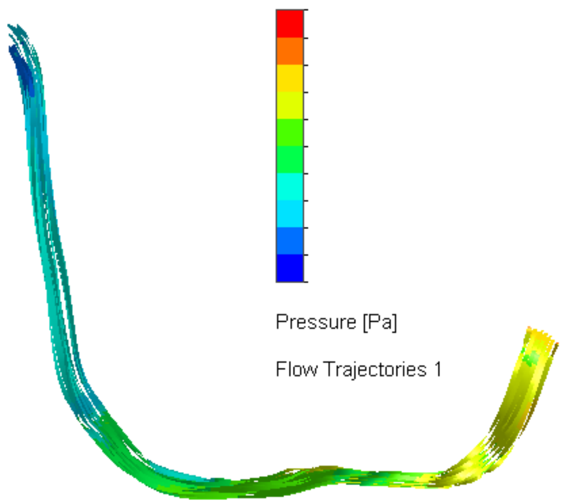

Figure A.36: FloEFD flow trajectories for airduct with EDS intersection diameter upward and mass-flow m_3^*

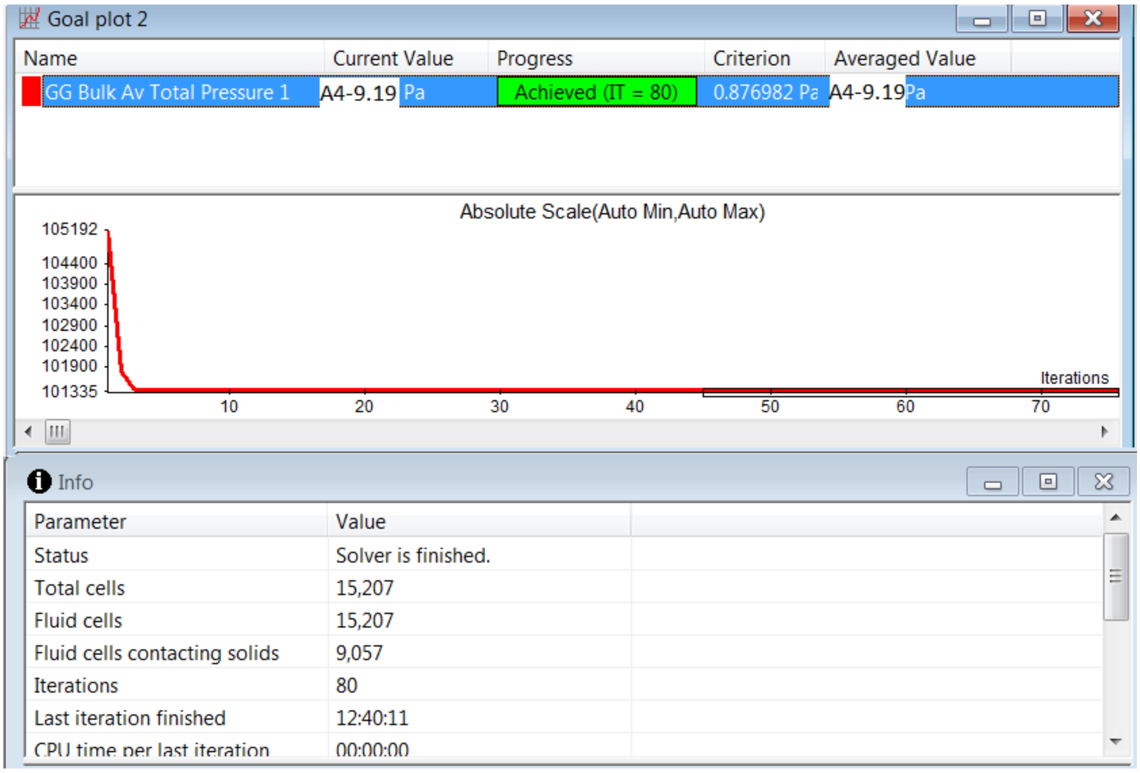

Figure A.37: FloEFD result for airduct with EDS intersection diameter upward and mass-flow m_4^*

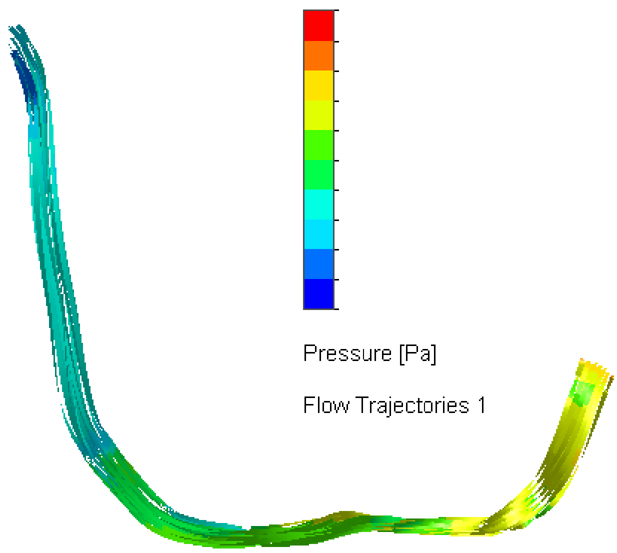

Figure A.38: FloEFD flow trajectories for airduct with EDS intersection diameter upward and mass-flow m_4^*

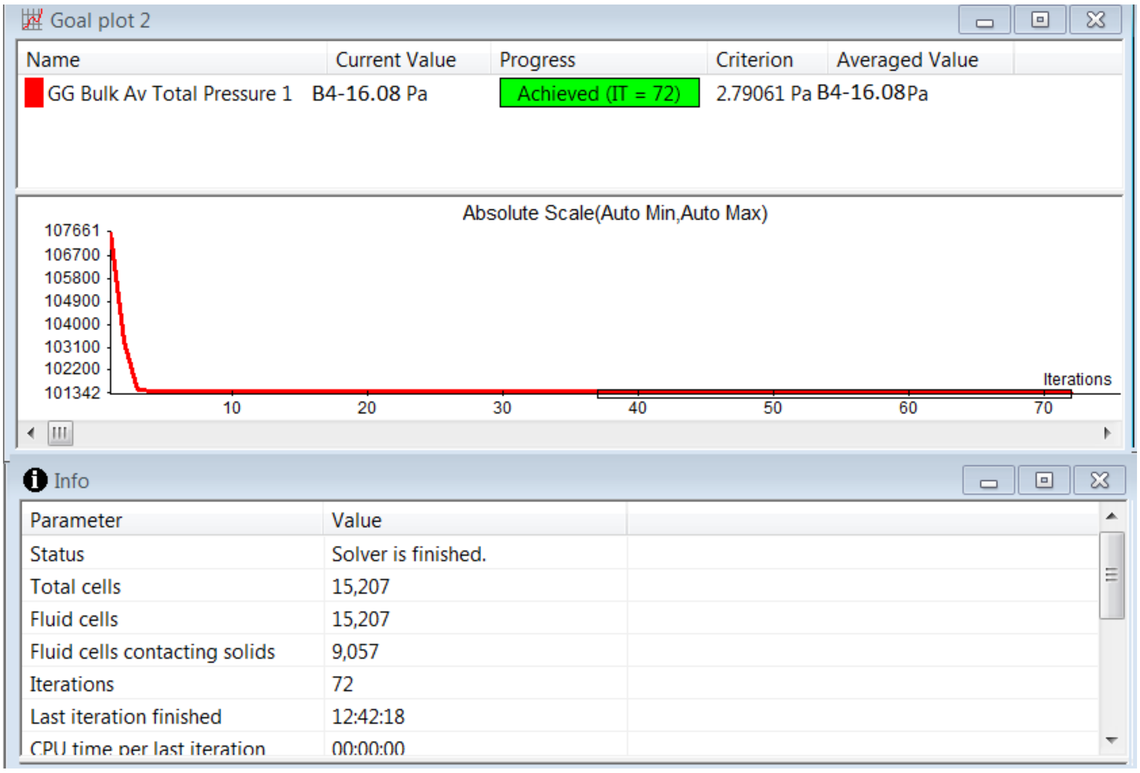

Figure A.39: FloEFD result for airduct with EDS intersection diameter upward and mass-flow m_5^*

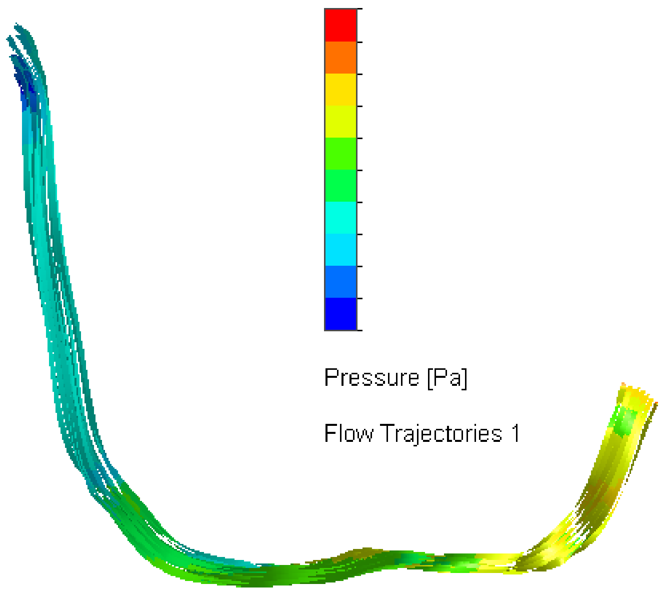

Figure A.40: FloEFD flow trajectories for airduct with EDS intersection diameter upward and mass-flow m_5^*

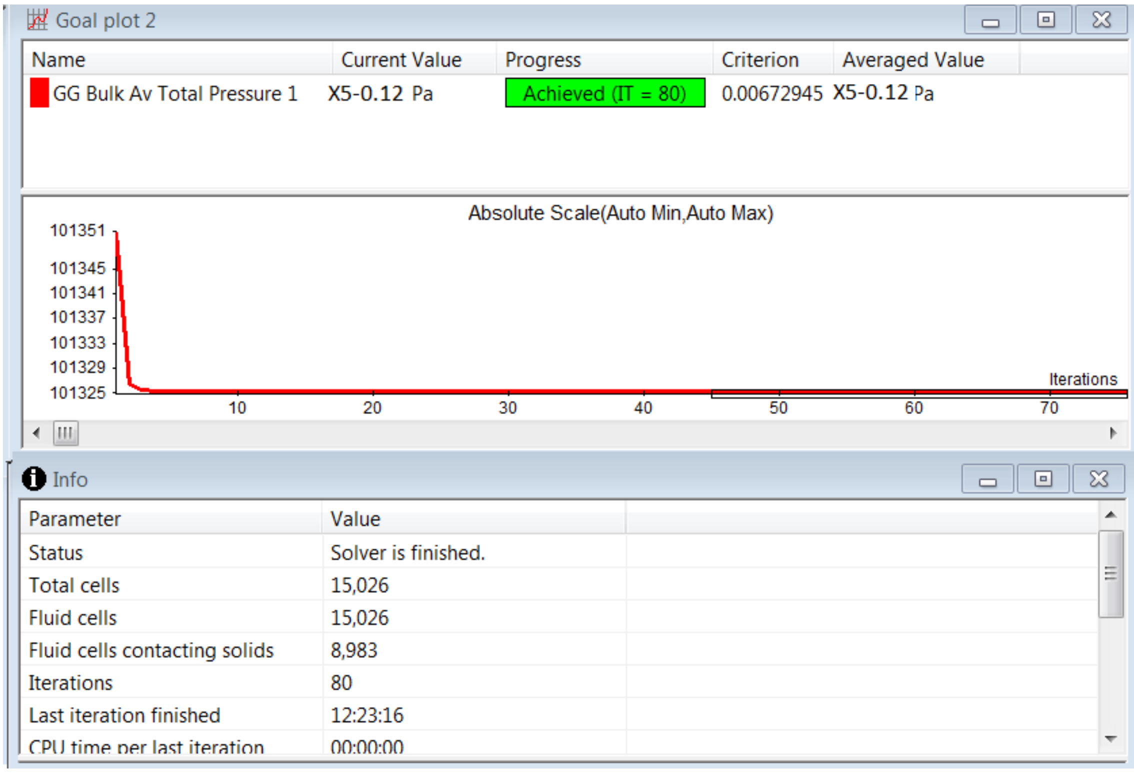

Figure A.41: FloEFD result for airduct with EDS intersection diameter downward and mass-flow m_1^*

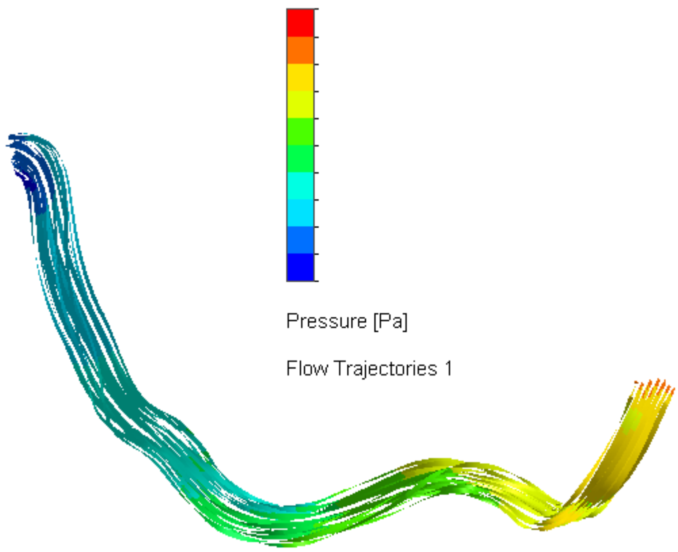

Figure A.42: FloEFD flow trajectories for airduct with EDS intersection diameter downward and mass-flow m_1^*

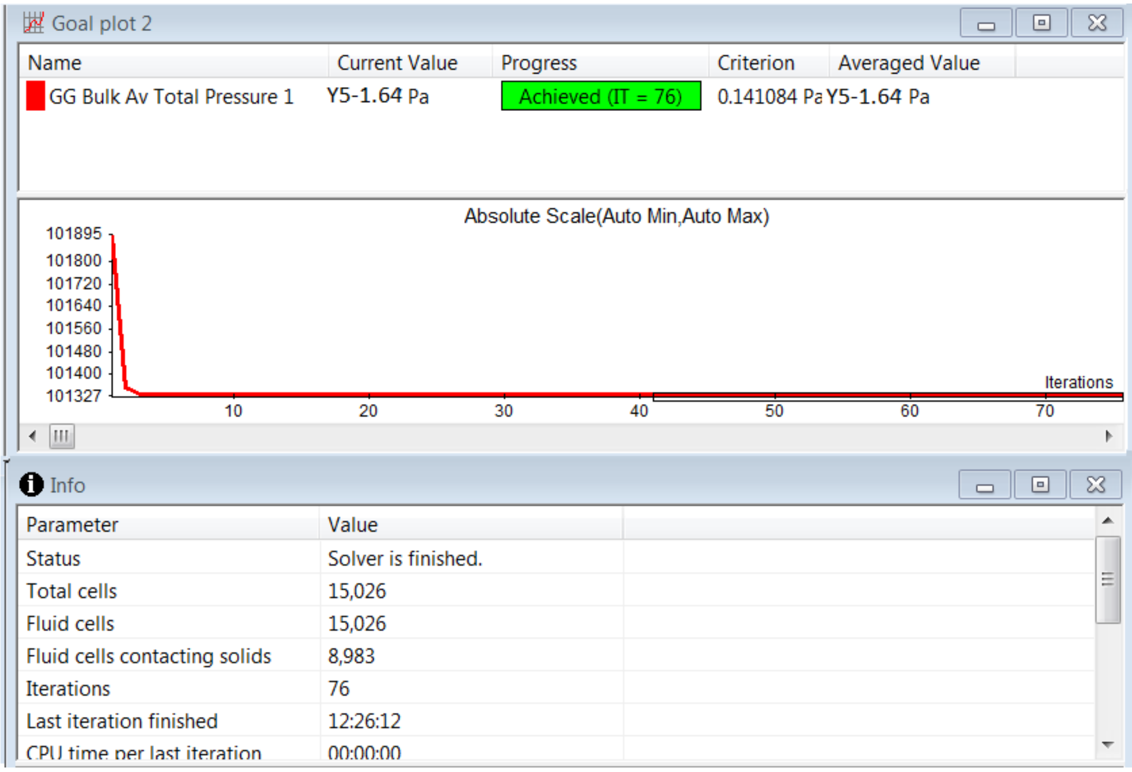

Figure A.43: FloEFD result for airduct with EDS intersection diameter downward and mass-flow m_2^*

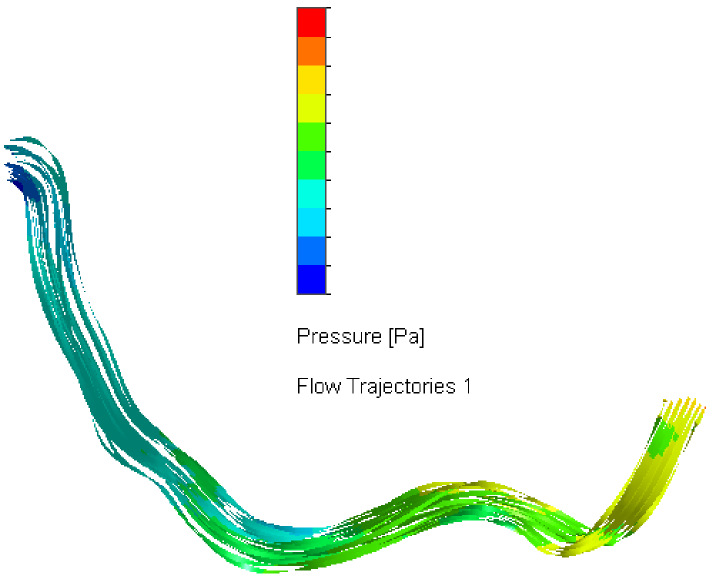

Figure A.44: FloEFD flow trajectories for airduct with EDS intersection diameter downward and mass-flow m_2^*

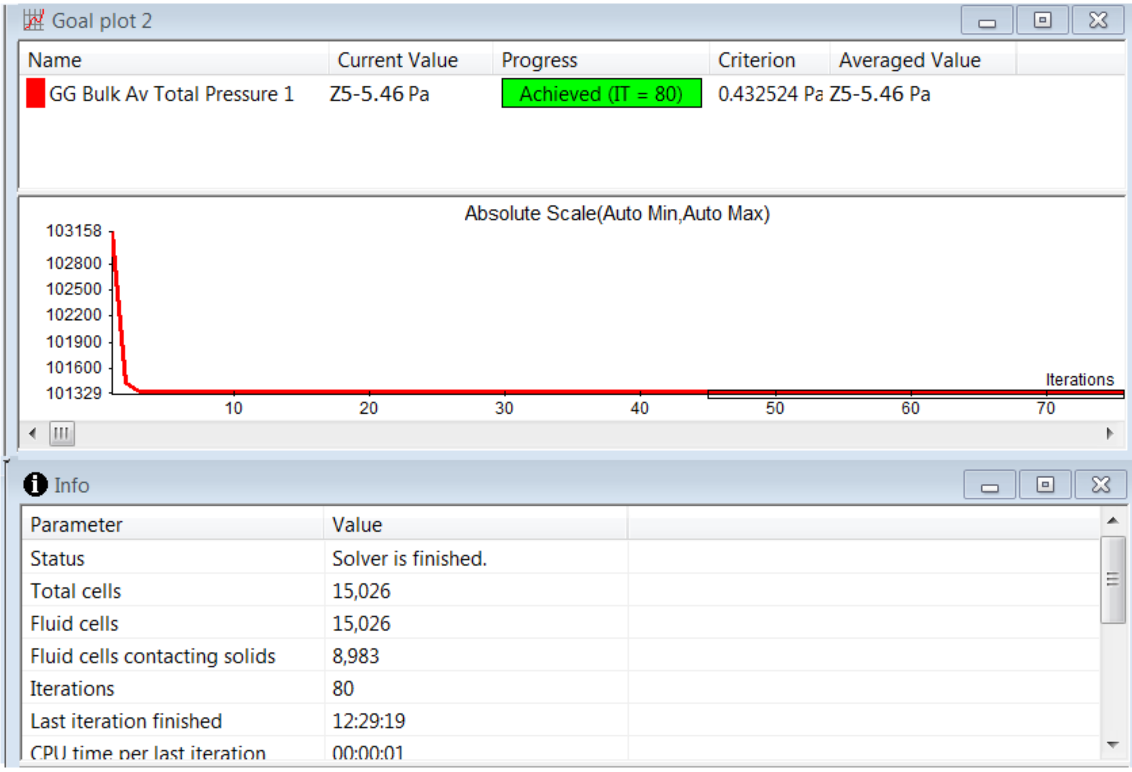

Figure A.45: FloEFD result for airduct with EDS intersection diameter downward and mass-flow m_3^*

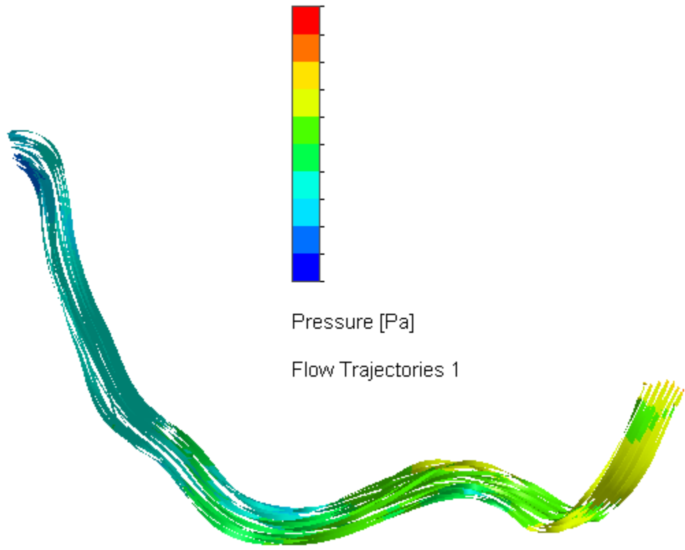

Figure A.46: FloEFD flow trajectories for airduct with EDS intersection diameter downward and mass-flow m_3^*

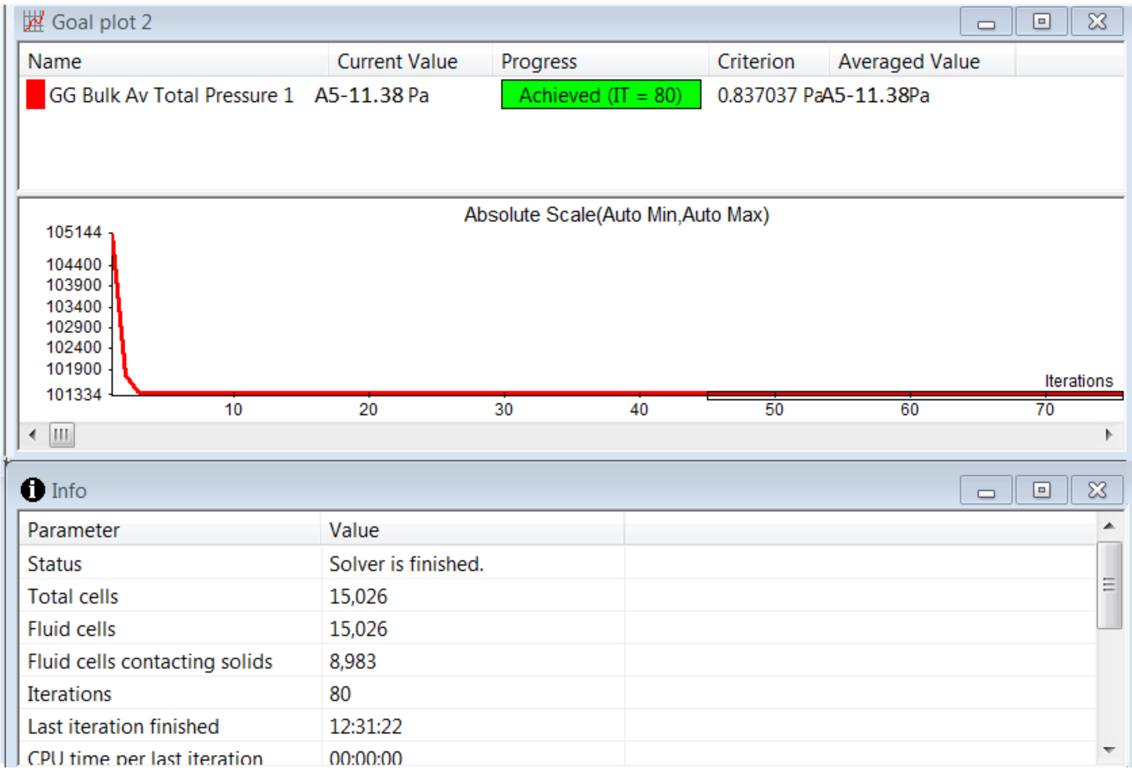

Figure A.47: FloEFD result for airduct with EDS intersection diameter downward and mass-flow m_4^*

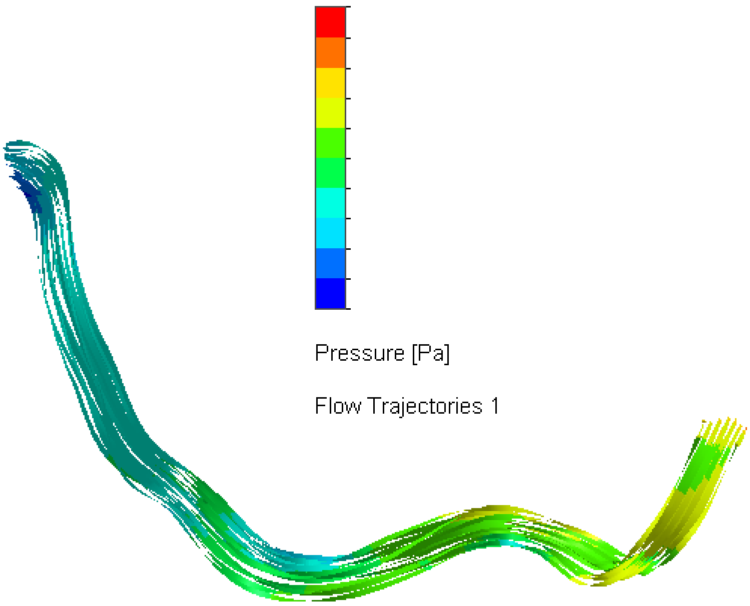

Figure A.48: FloEFD flow trajectories for airduct with EDS intersection diameter downward and mass-flow m_4^*

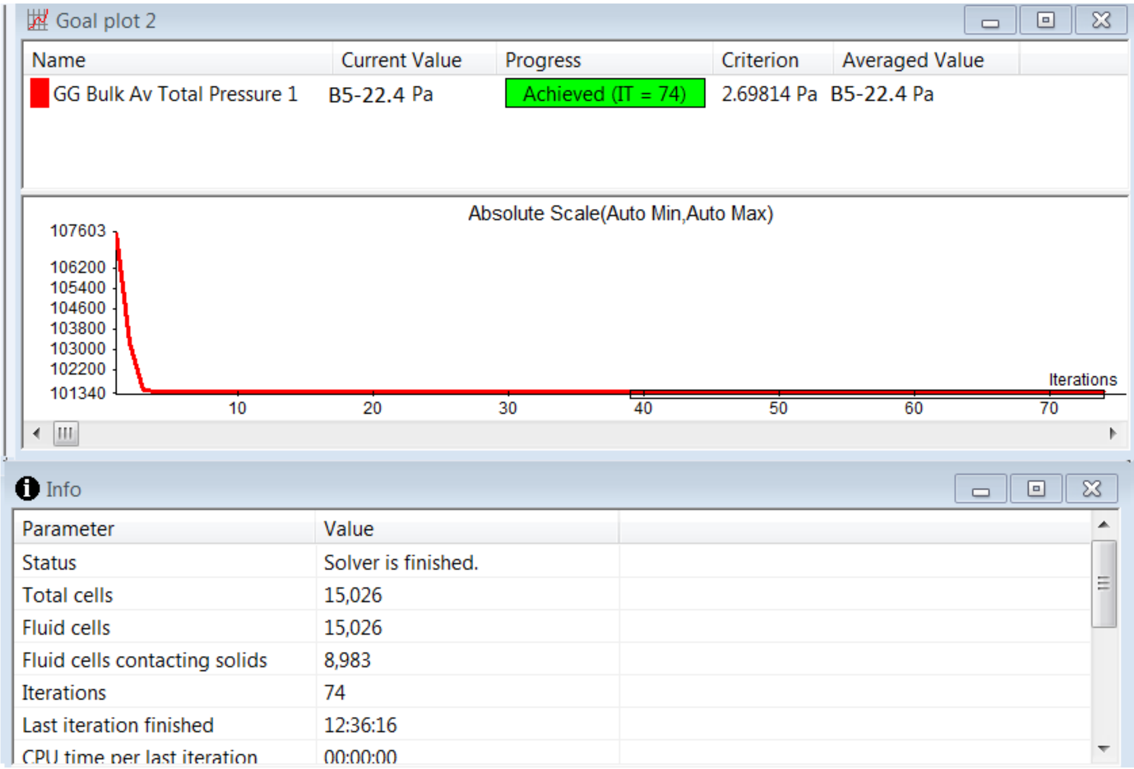

Figure A.49: FloEFD result for airduct with EDS intersection diameter downward and mass-flow m_5^*

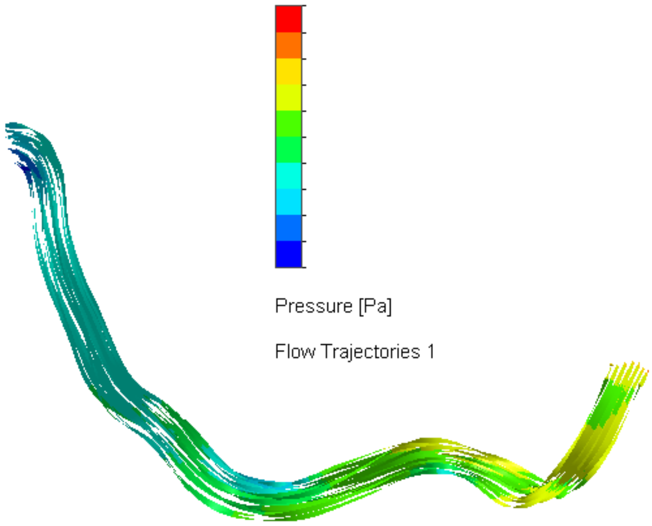

Figure A.50: FloEFD flow trajectories for airduct with EDS intersection diameter downward and mass-flow m_5^*

A.2 Comsol Multiphysics Results

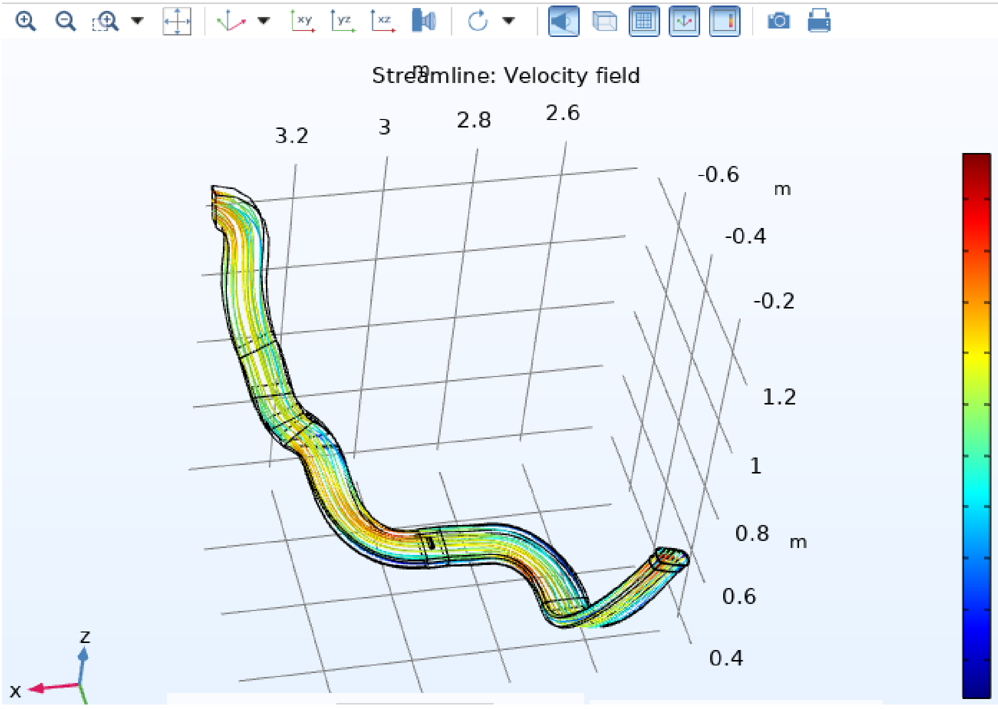

Figure A.51: Comsol Multiphysics result with trajectories for airduct, with EDS intersection diameter 30mm and mass-flow m_2^*

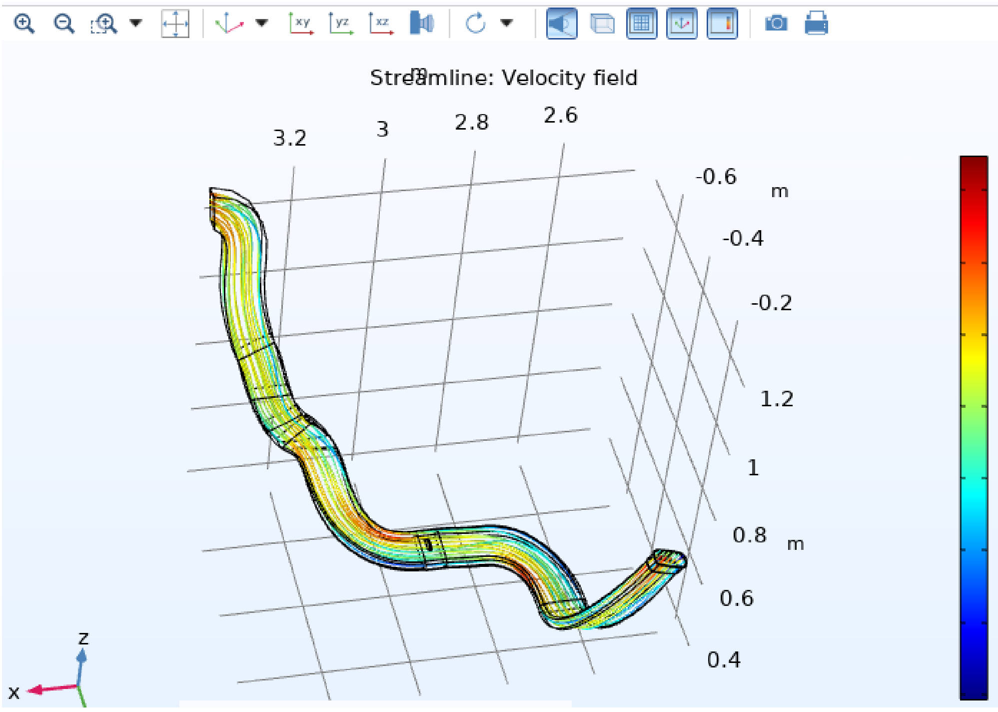

Figure A.52: Comsol Multiphysics result with trajectories for airduct, with EDS intersection diameter 30mm and mass-flow m_3^*

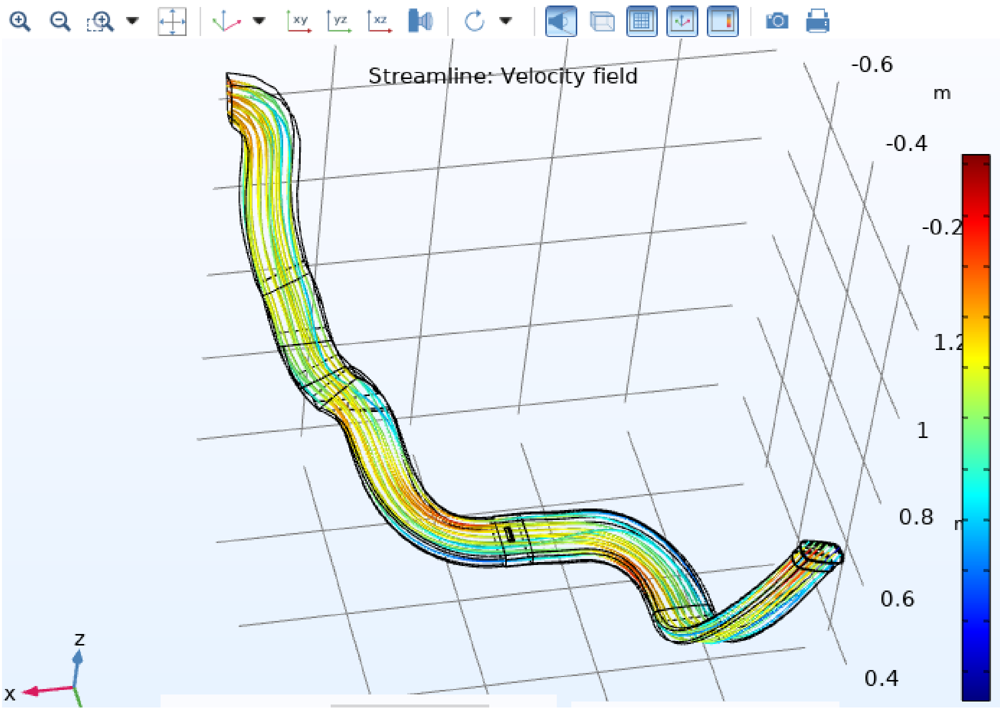

Figure A.53: Comsol Multiphysics result with trajectories for airduct, with EDS intersection diameter 30mm and mass-flow m_4^*

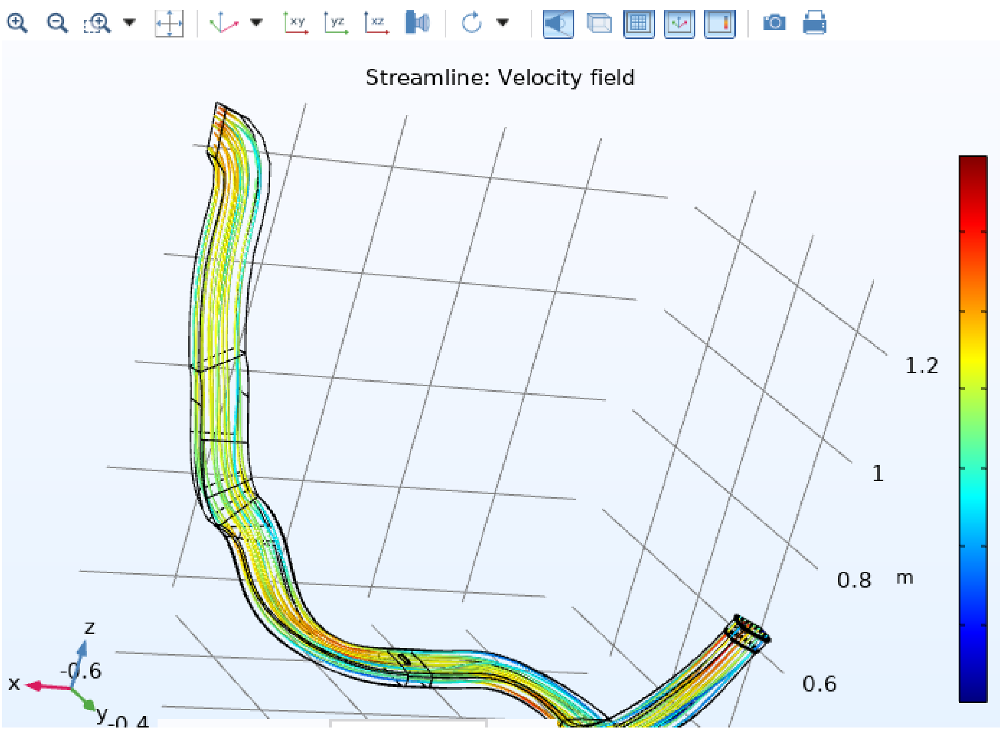

Figure A.54: Comsol Multiphysics result with trajectories for airduct, with EDS intersection diameter 30mm and mass-flow m_5^*

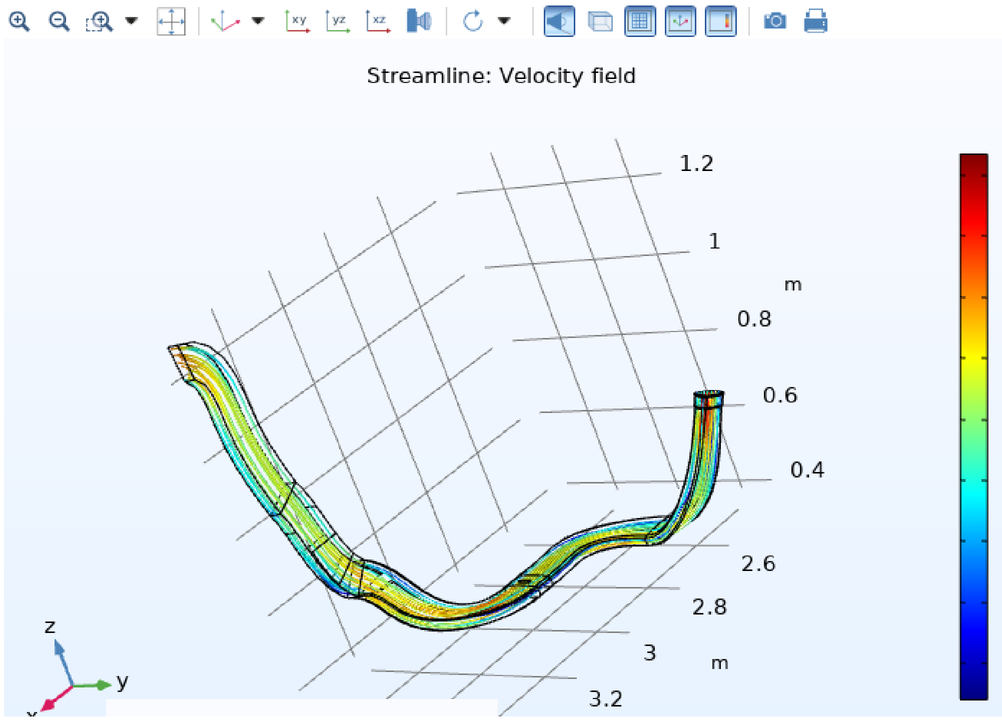

Figure A.55: Comsol Multiphysics result with trajectories for airduct, with EDS intersection diameter 40mm and mass-flow m_1^*

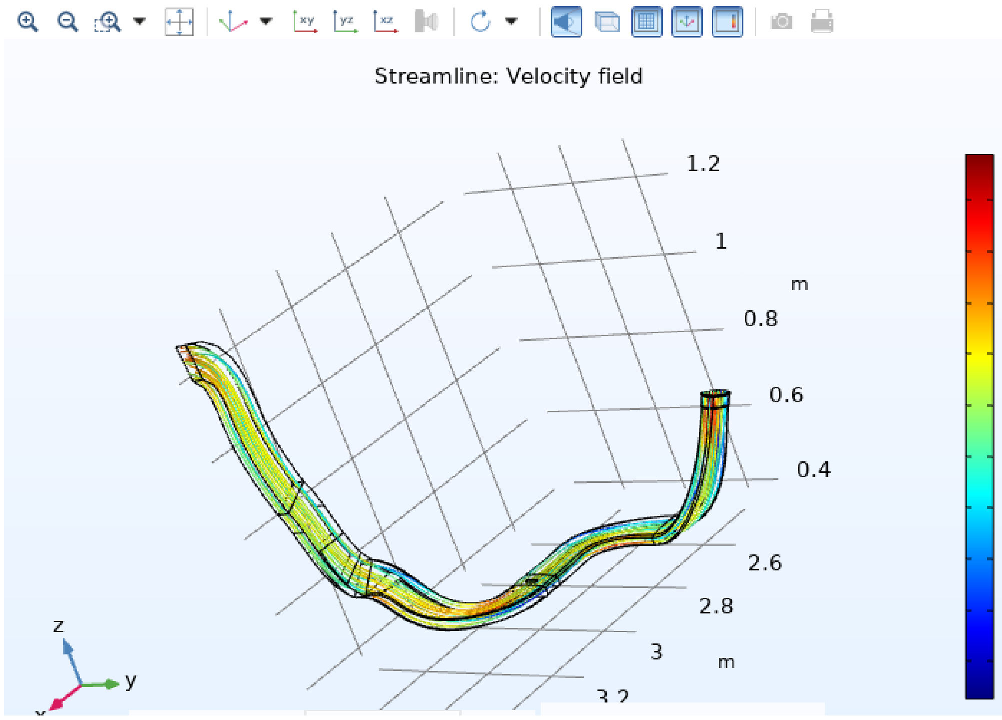

Figure A.56: Comsol Multiphysics result with trajectories for airduct, with EDS intersection diameter 40mm and mass-flow m_2^*

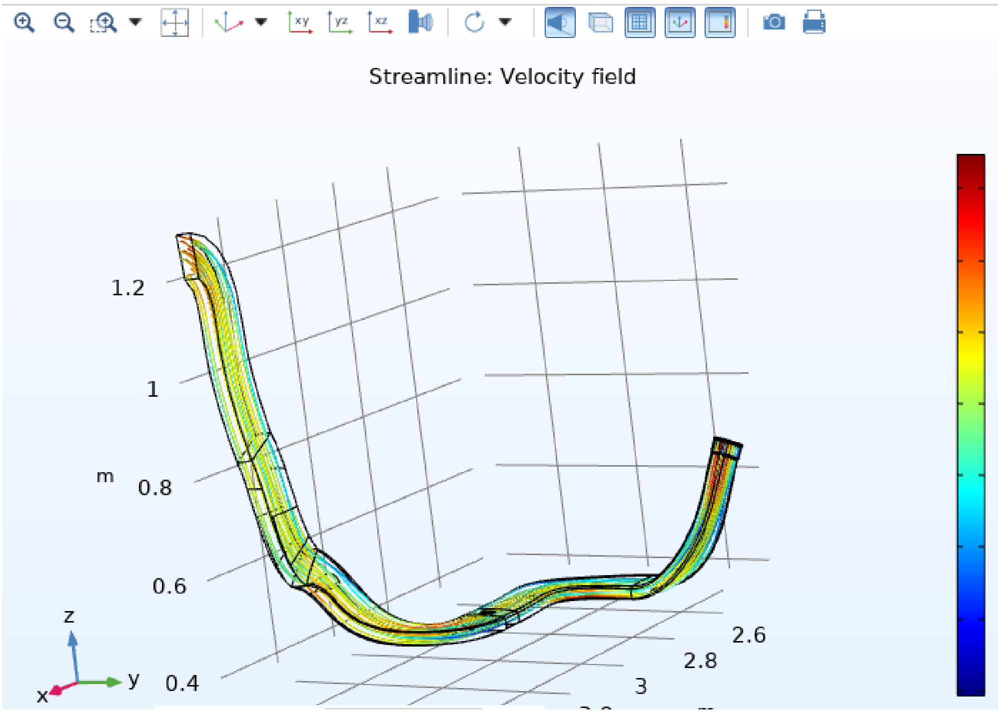

Figure A.57: Comsol Multiphysics result with trajectories for airduct, with EDS intersection diameter 40mm and mass-flow m_3^*

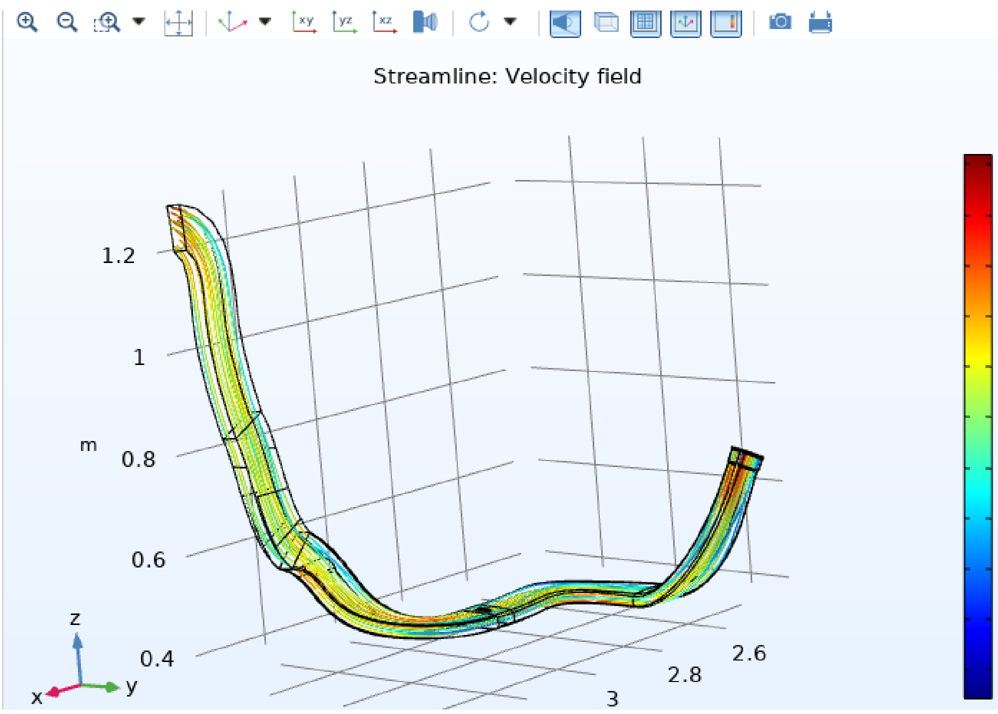

Figure A.58: Comsol Multiphysics result with trajectories for airduct, with EDS intersection diameter 40mm and mass-flow m_4^*

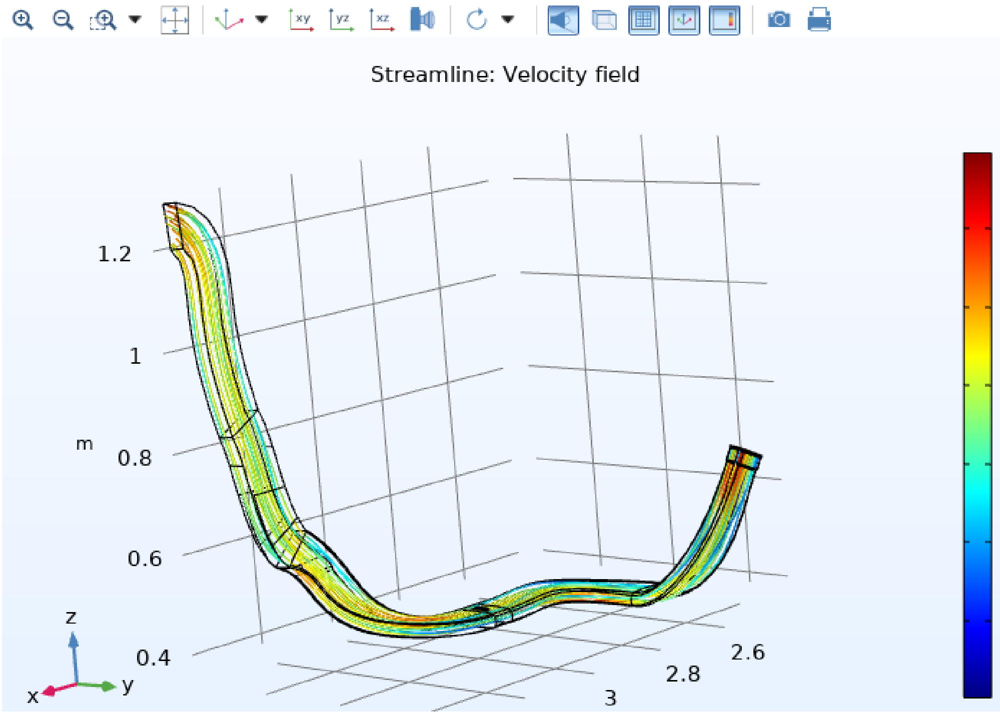

Figure A.59: Comsol Multiphysics result with trajectories for airduct, with EDS intersection diameter 40mm and mass-flow m_5^*

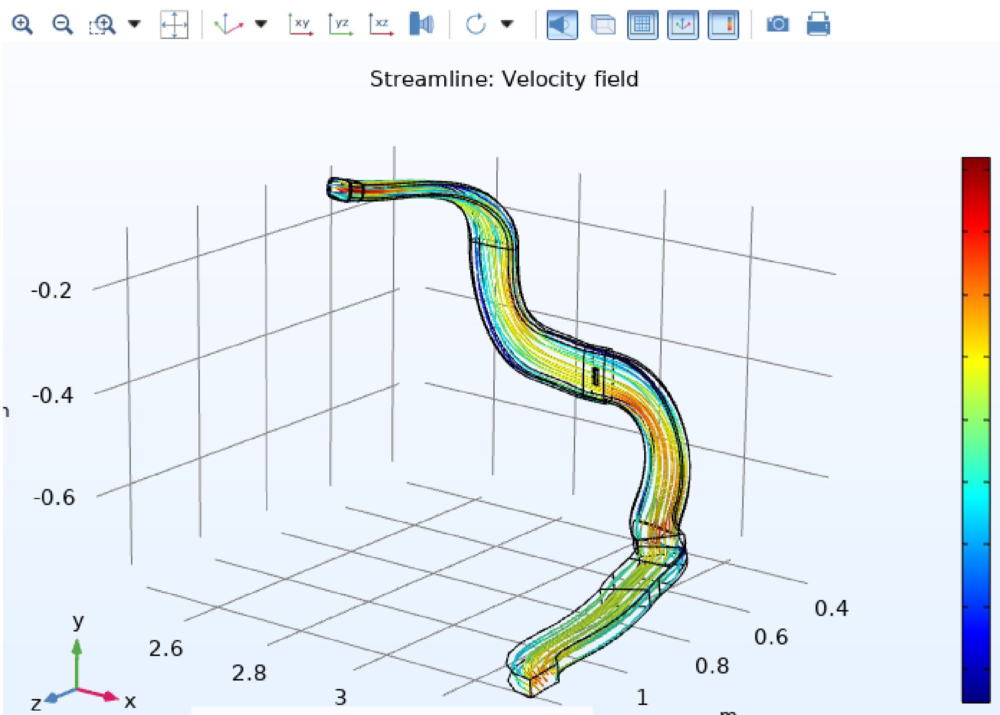

Figure A.60: Comsol Multiphysics result with trajectories for airduct, with EDS intersection diameter 50mm and mass-flow m_1^*

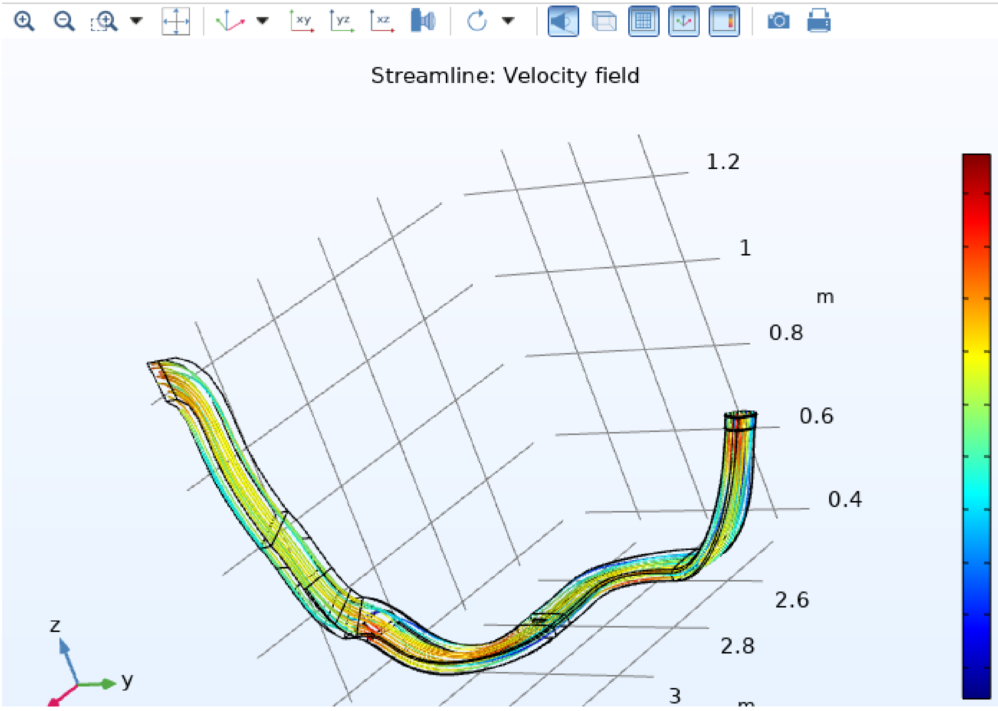

Figure A.61: Comsol Multiphysics result with trajectories for airduct, with EDS intersection diameter 50mm and mass-flow m_2^*

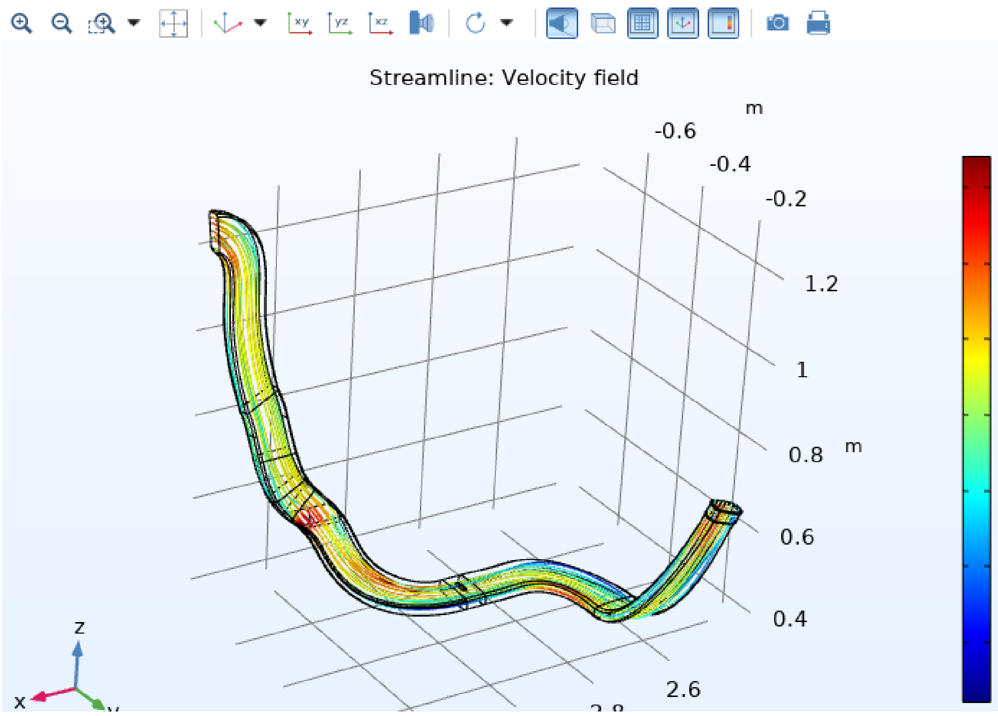

Figure A.62: Comsol Multiphysics result with trajectories for airduct, with EDS intersection diameter 50mm and mass-flow m_3^*

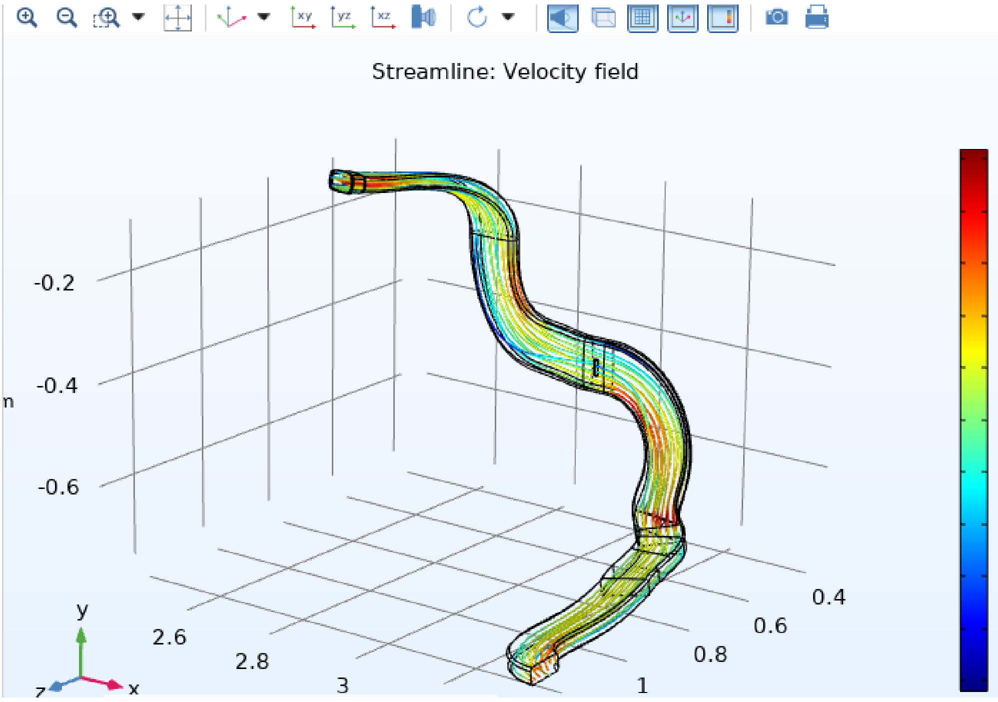

Figure A.63: Comsol Multiphysics result with trajectories for airduct, with EDS intersection diameter 50mm and mass-flow m_4^*

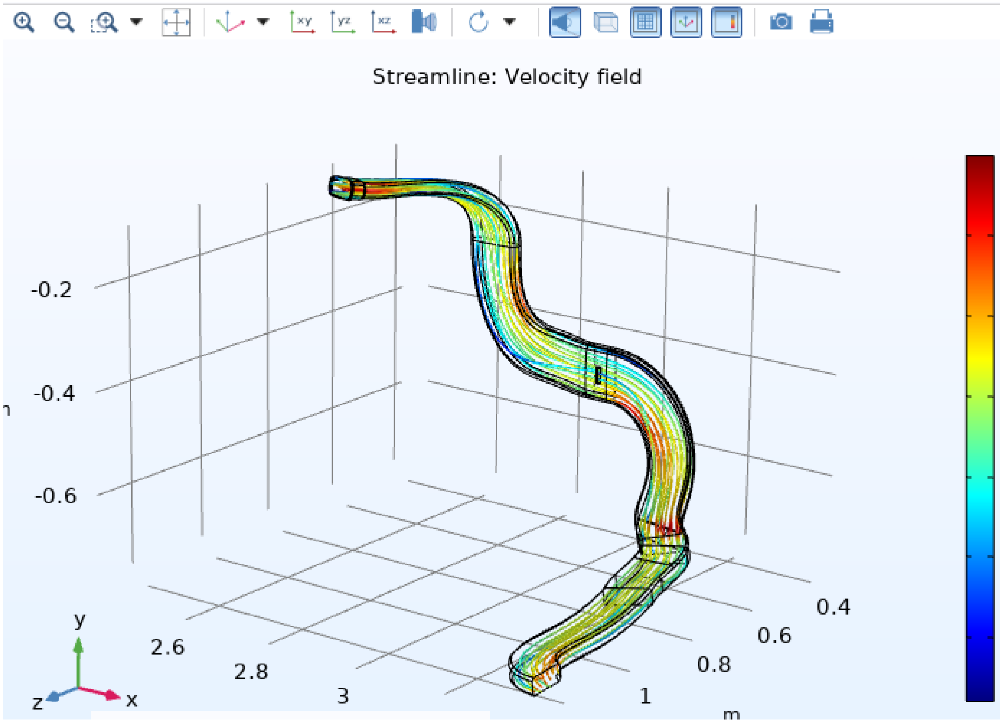

Figure A.64: Comsol Multiphysics result with trajectories for airduct, with EDS intersection diameter 50mm and mass-flow m_5^*

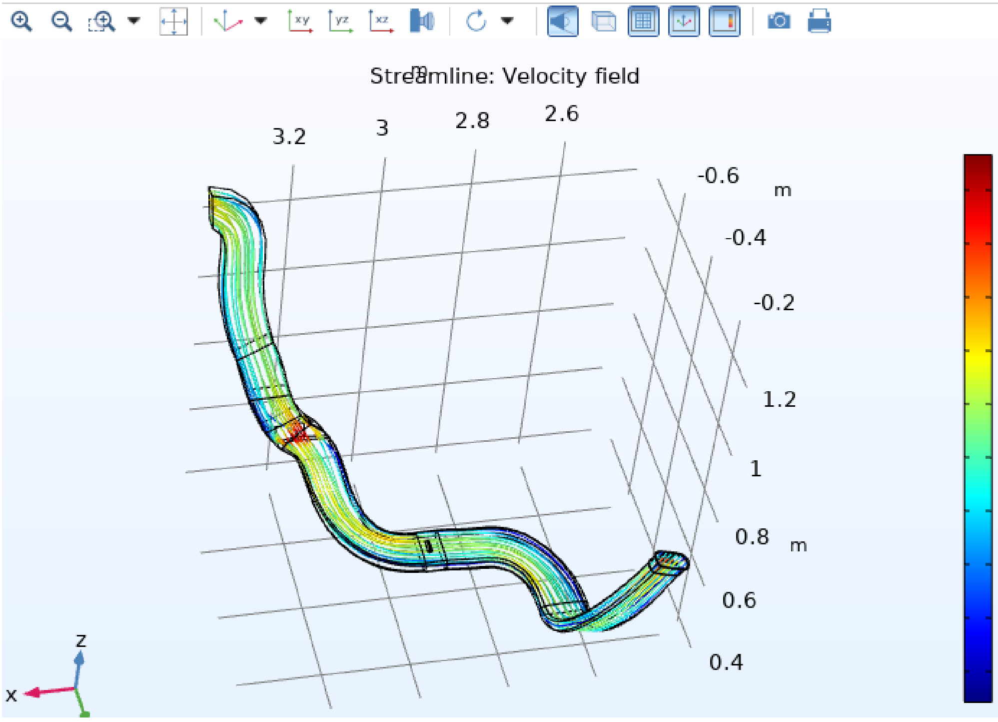

Figure A.65: Comsol Multiphysics result with trajectories for airduct, with EDS intersection upward and mass-flow m_1^*

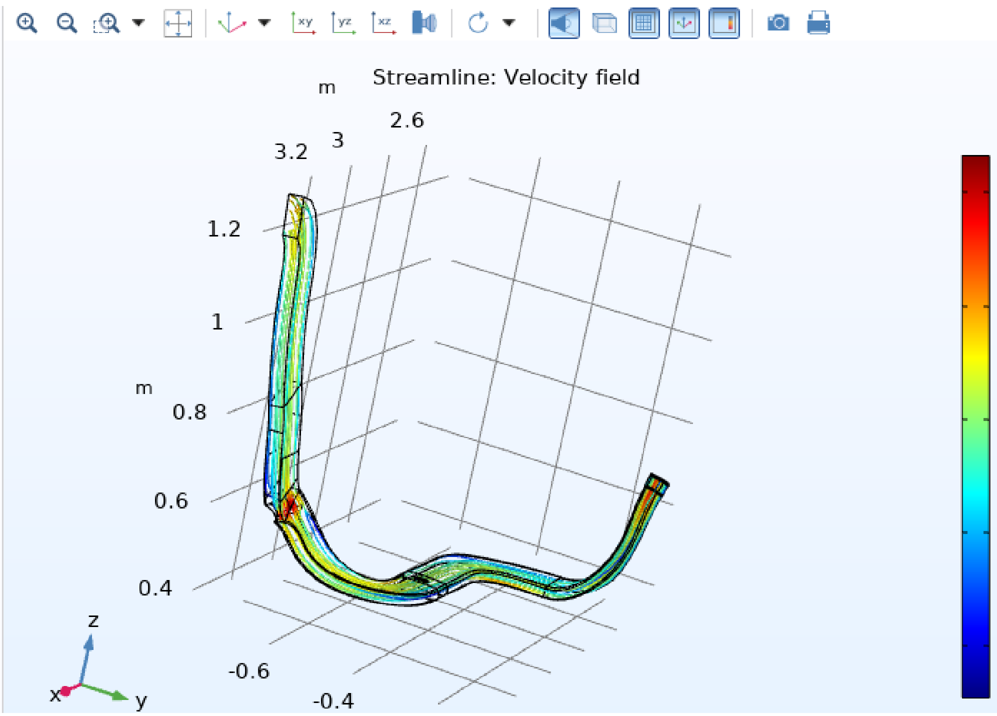

Figure A.66: Comsol Multiphysics result with trajectories for airduct, with EDS intersection upward and mass-flow m_2^*

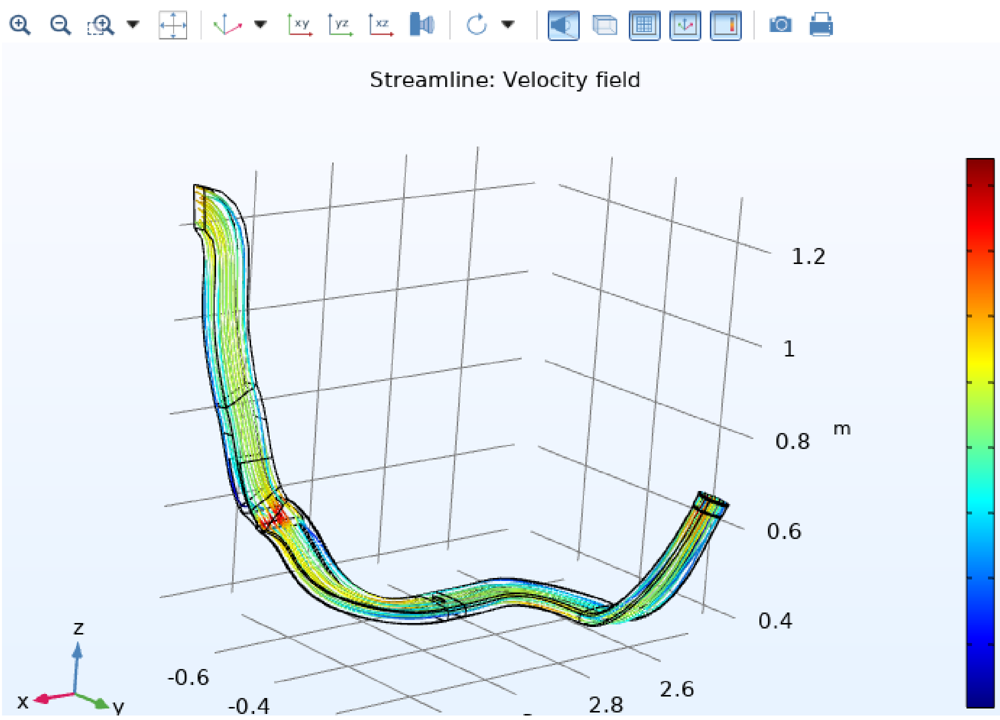

Figure A.67: Comsol Multiphysics result with trajectories for airduct, with EDS intersection upward and mass-flow m_3^*

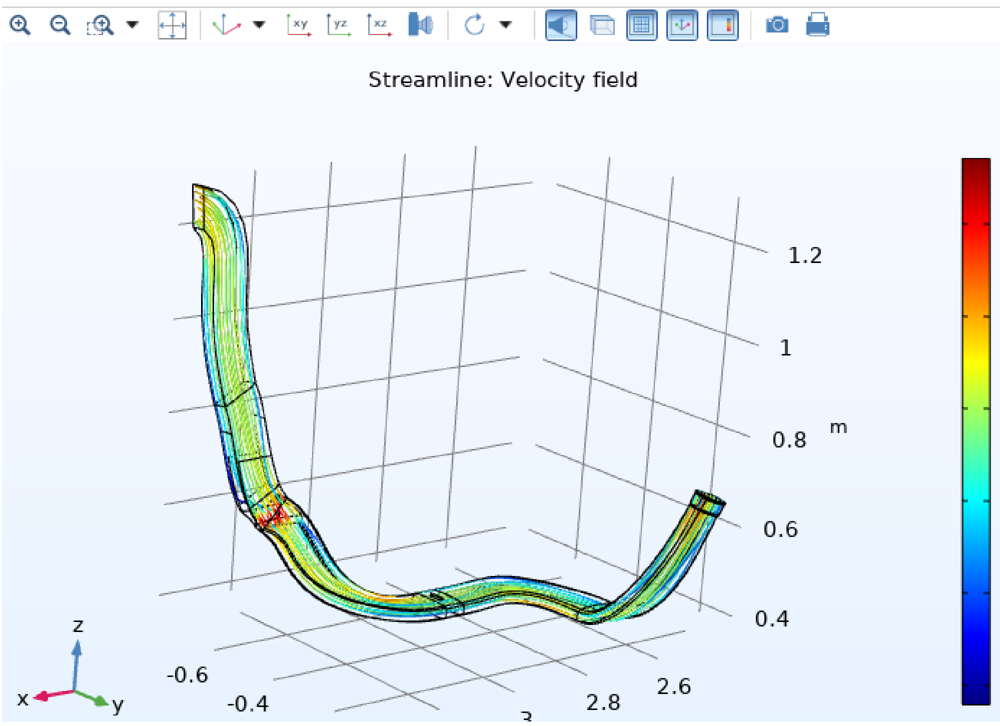

Figure A.68: Comsol Multiphysics result with trajectories for airduct, with EDS intersection upward and mass-flow m_4^*

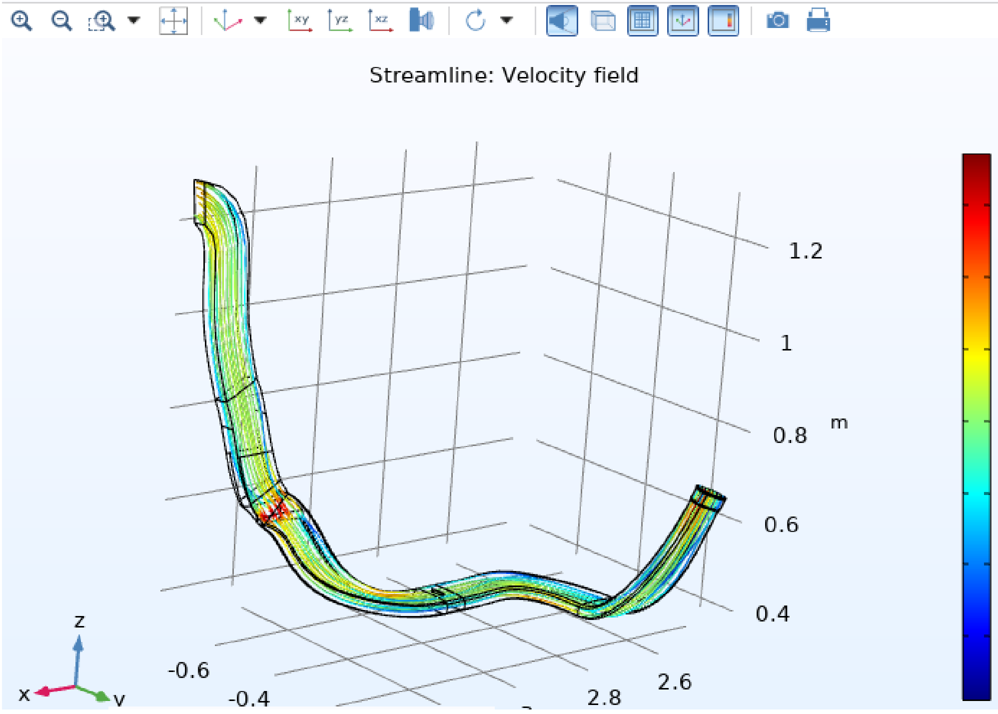

Figure A.69: Comsol Multiphysics result with trajectories for airduct, with EDS intersection upward and mass-flow m_5^*

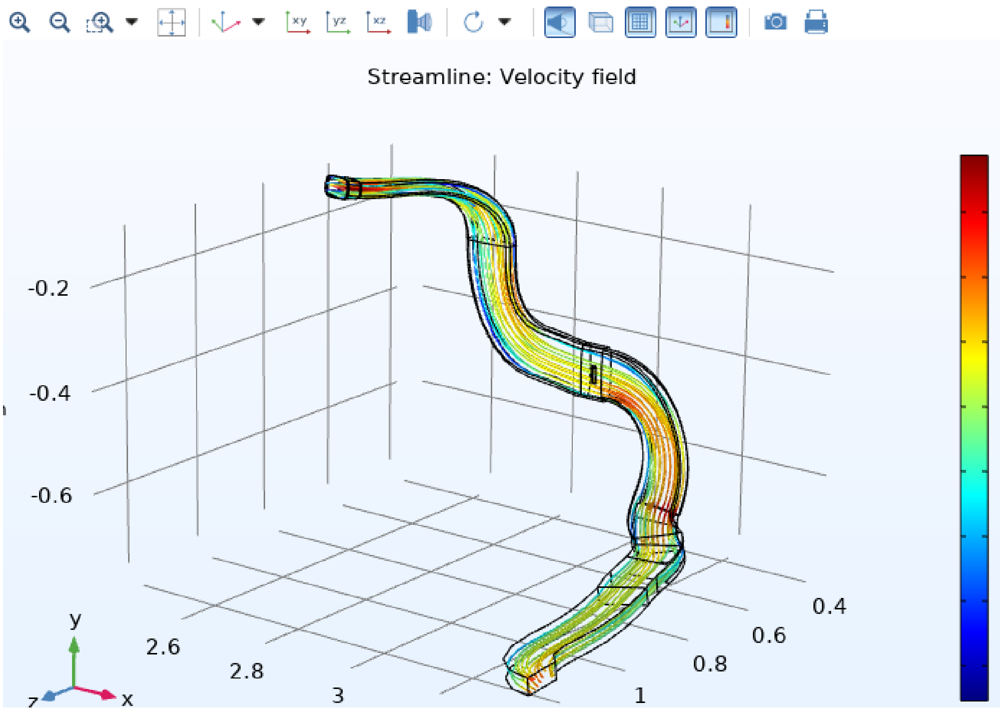

Figure A.70: Comsol Multiphysics result with trajectories for airduct, with EDS intersection downward and mass-flow m_1^*

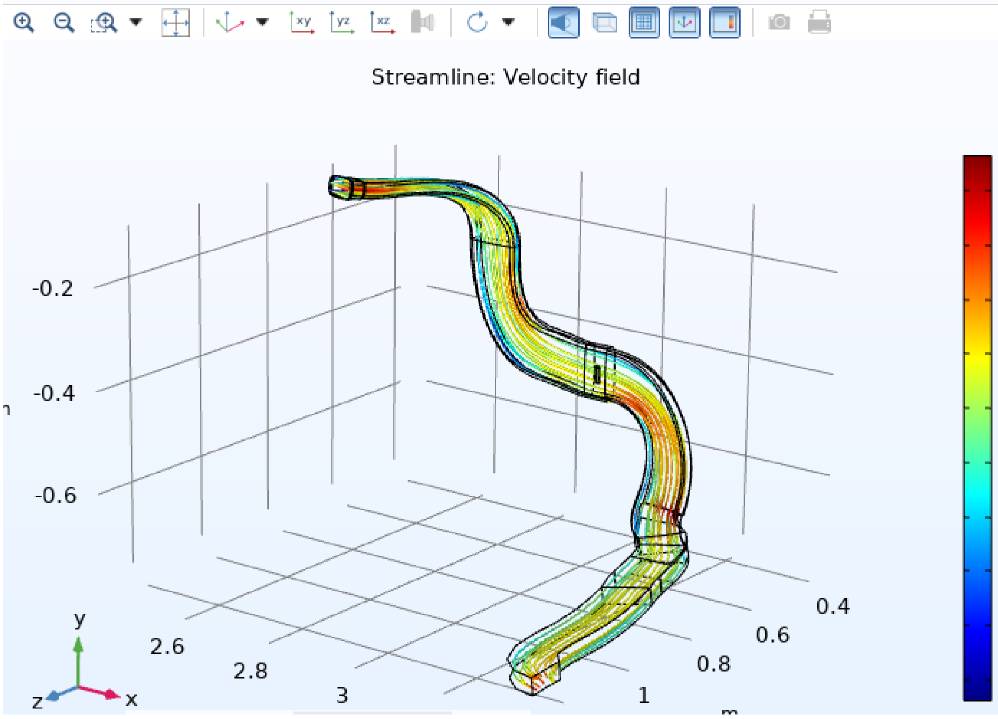

Figure A.71: Comsol Multiphysics result with trajectories for airduct, with EDS intersection downward and mass-flow m_2^*

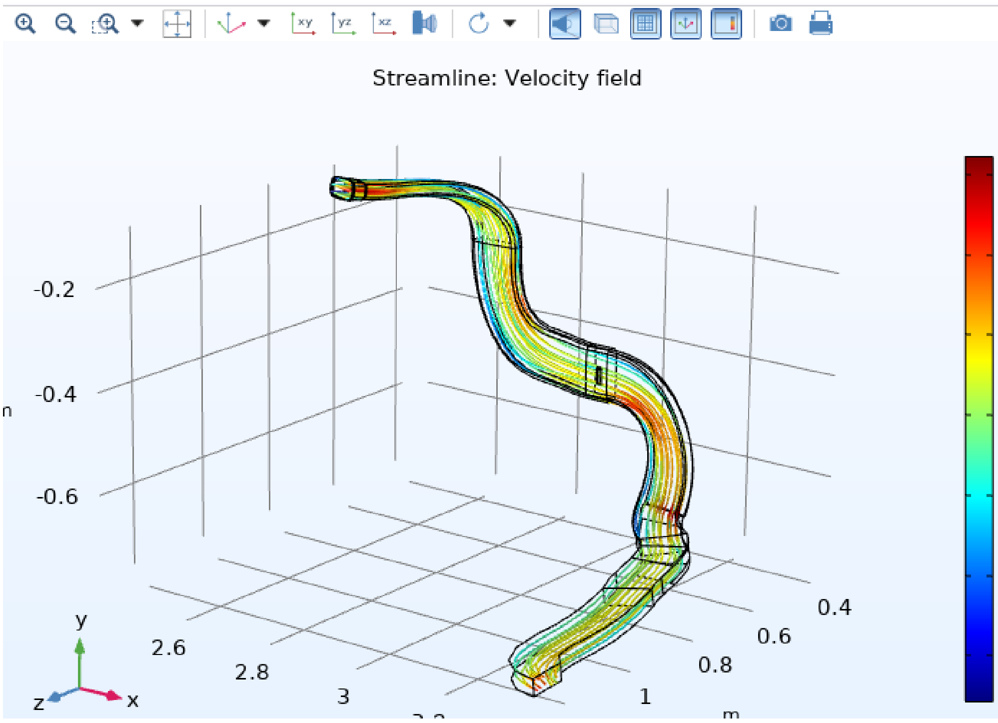

Figure A.72: Comsol Multiphysics result with trajectories for airduct, with EDS intersection downward and mass-flow m_3^*

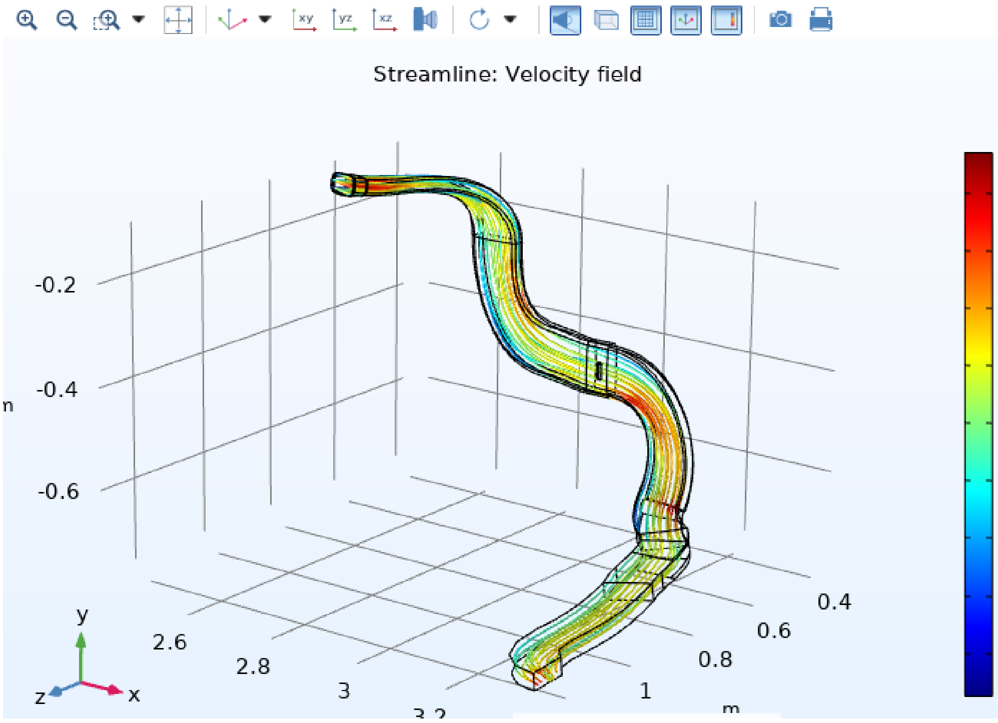

Figure A.73: Comsol Multiphysics result with trajectories for airduct, with EDS intersection downward and mass-flow m_4^*

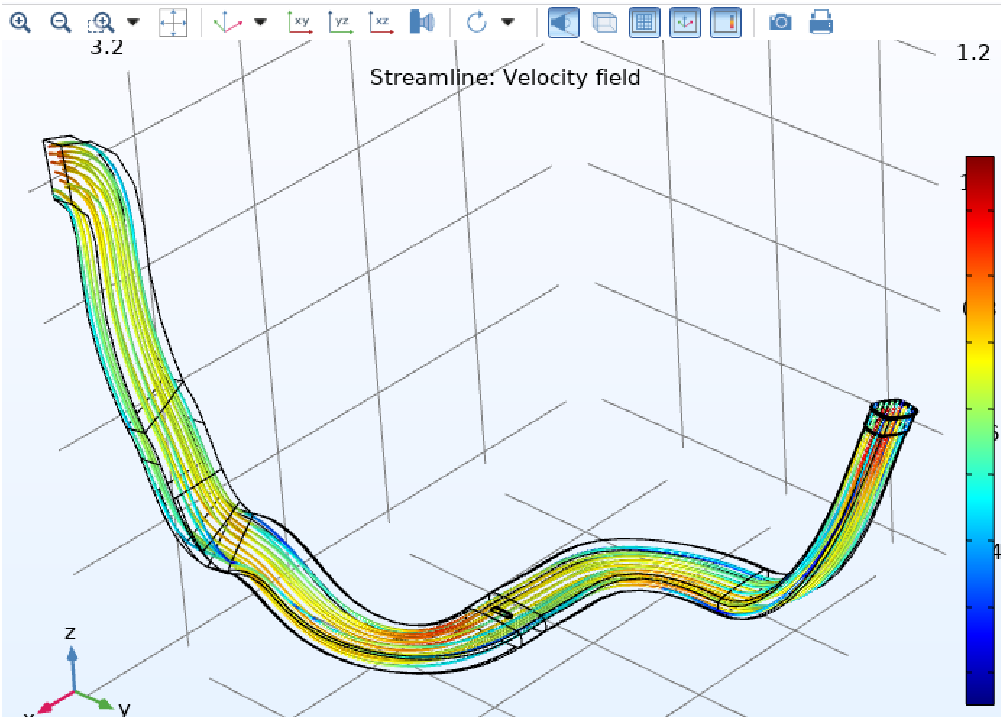

Figure A.74: Comsol Multiphysics result with trajectories for airduct, without EDS intersection and mass-flow m_1^*

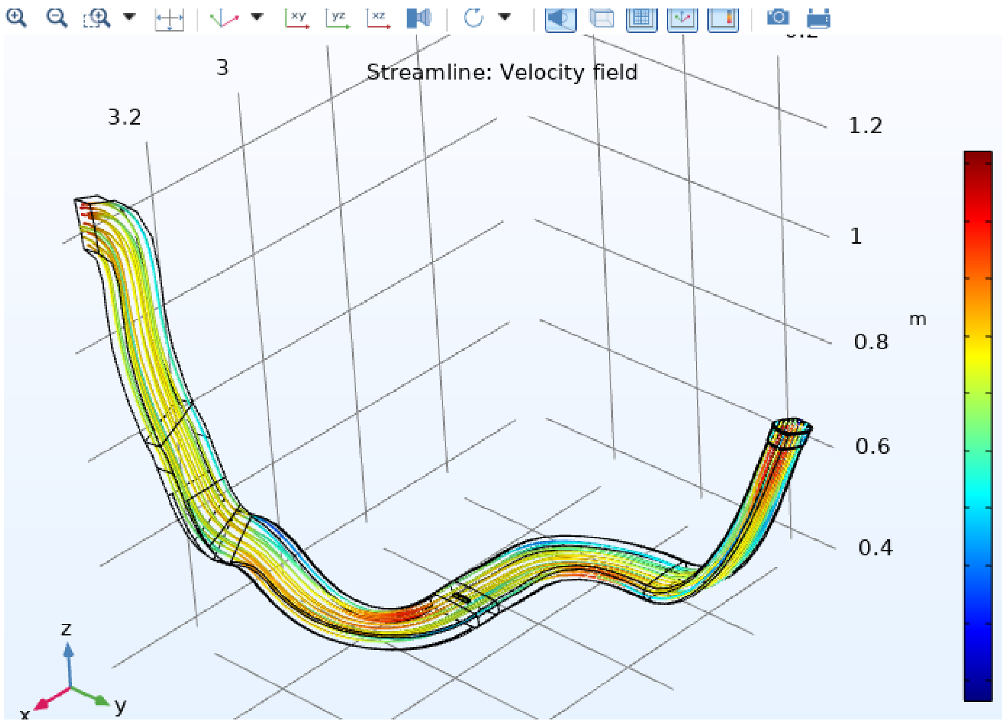

Figure A.75: Comsol Multiphysics result with trajectories for airduct, without EDS intersection and mass-flow m_2^*

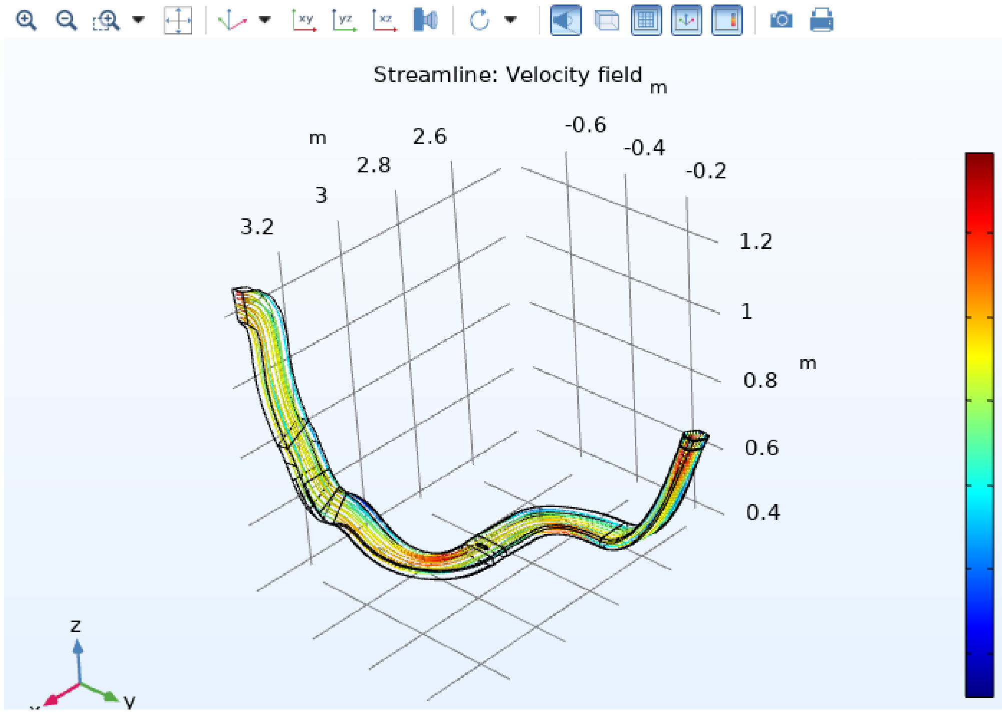

Figure A.76: Comsol Multiphysics result with trajectories for airduct, without EDS intersection and mass-flow m_3^*

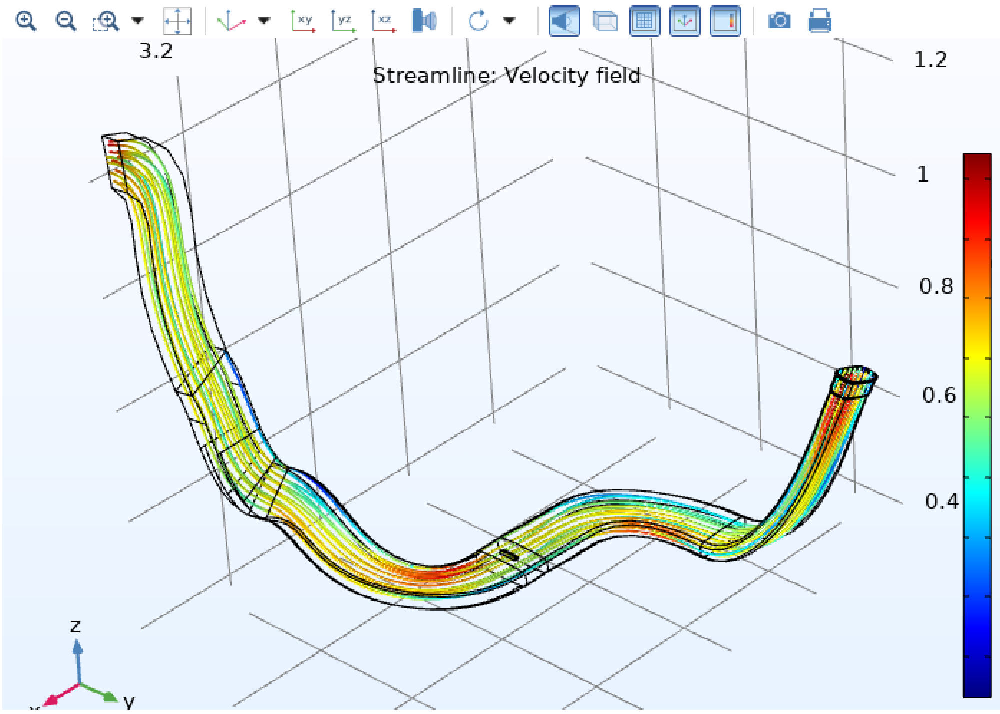

Figure A.77: Comsol Multiphysics result with trajectories for airduct, without EDS intersection and mass-flow m_4^*

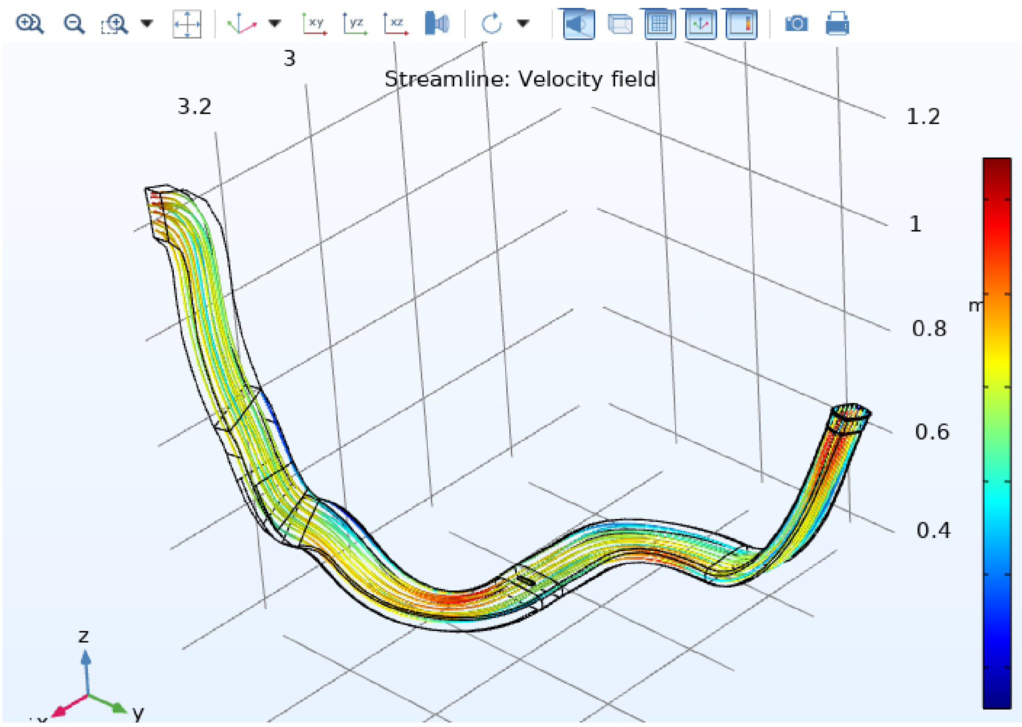

Figure A.78: Comsol Multiphysics result with trajectories for airduct, without EDS intersection and mass-flow m_5^*

A.3 Interview table

Role	Experience / View with template?	Current drawbacks?	Necessary improvements?
Climate Engineer	Really useful to develop models quickly to run simulations	No matured airduct template to build stable models	New parametrized template that could integrated with simulation loops
CAE Engineer	No experience and not sure how effectively could be integrated.	Simulations take too long and model updates are faster than simulation duration	Better simulation based design of concepts to avoid wastage of resources
Integration Engineer 1	Experience working with template, recent work with plenum template	Tedious and complicated to develop, but once developed would be beneficial	Paramterization required for quick model update and corrections
Integration Engineer 2	Experience with template, findsit to be time consuming	Slow update loops for input in template. requires constant update.	Needs to be updated easily with respect to surrounding component changes without affecting the simulation results

Table A.1: Interview of the various engineers and focus group at Volvo Cars