

DESIGN REFINEMENT BY ITERATIVE VIRTUAL EXPERIMENTATION (DRIVE):  
A METHODOLOGY TO SOLVING ENGINEERING DESIGN PROBLEMS

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A Thesis

Presented to

the Faculty of the College of Science & Technology

Morehead State University

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In Partial Fulfillment

of the Requirements for the Degree

Master of Science

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by

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April 25, 2015

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DESIGN REFINEMENT BY ITERATIVE VIRTUAL EXPERIMENTATION (D.R.I.V.E):  
A METHODOLOGY TO SOLVING ENGINEERING DESIGN PROBLEMS

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Engineering Design is an iterative process by nature. In traditional methods, analysis is performed as a validation tool at the end of the design cycle. This leads to delayed feedback on required change to the design and adds time to the overall design cycle. Another problem is that this extended cycle time will hamper the generation of alternatives to the design problem. This research proposes an integrated DRIVE (*Design Refinement by Iterative Virtual Experimentation*) approach to design, analyze and develop industrial equipment componentry. Experimental designs have been set up by targeting specific design factors and studying their impact on carefully selected system response variables. With CFD and FEA simulations performed on three dimensional CAD model iterations representative of specific design factor combinations, unique airflow and stress diagrams can be generated to analyze component performance. CAD design software has been utilized to create the various three dimensional geometry required for experimentation. CFD simulation software was utilized to perform and

solve the computational fluid dynamics simulations. The built-in analysis module within the CAD software was also utilized to perform and solve the finite element analysis simulations. Finally, statistical software was utilized for performing the factorial design calculations and generating the appropriate response charts. The application of the methodology is demonstrated by using two real life case studies from a construction equipment manufacturing company. The first study involves configuring an HVAC component for use in on-highway industrial equipment that will result in the highest possible airflow velocity. The second study pertains to configuring a mounting bracket for a steering column for use in on-highway industrial equipment that will result in the lowest possible maximum observed stress in the component, for a given loading condition. An analysis of variance is utilized to determine the significant effects of various configurations of the components being studied and guides the final design to the optimal combination configuration from the given input configuration parameters. Such an integrated analysis approach requires minimal physical testing, thus minimizing the overall cost and time spent on the project. This not only develops solutions to the immediate problems, but also generates a methodology that can be utilized in CAD/CFD and CAD/FEA based scenarios.

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## ACKNOWLEDGEMENTS

This research represents the culmination of various research and analysis projects that have spanned the past four years of my professional and academic careers. During which time, it has generated two published papers, has led to several professional and academic presentations that have discussed the various findings, and is one of my greatest achievements. The research contained within this thesis has been the winner of the 2012 Association of Technology, Management, and Applied Engineering (ATMAE) Graduate Student Research Competition. Also, there have been two published ATMAE conference proceedings papers (2012 & 2013), of which the 2012 paper entitled “*Integrated CAD/CFD Analysis of HVAC Fresh Air Intake System Design of an On-Highway Crane*” was designated as the top paper in the Graphics track and also reviewed and selected as the “Best ATMAE 2012 Conference Proceedings Paper”. Coupled with these awards, this research has also helped me to earn the 2012 ATMAE Early Career Achievement Award, which is given in recognition of outstanding achievement in the private sector by a recent Technology, Technology Management, or Applied Engineering graduate who has demonstrated leadership and superior performance in business and industry. Ultimately, all of these accomplishments have led to the development of the DRIVE methodology, of which can be used to steer various analysis-led design activities.

I would like to take this opportunity to thank everyone who has helped me along the way to completing this research.

First and foremost, I want to thank my family at home, especially my wife Julie, and our children, Grace and Jason. It has been through their continual love, support and motivation that I am able to be here at this moment in my life and it is to them that I wish to dedicate my work.

Second, I wish to give a special thanks to my friends and mentors, AZ (Dr. Ahmad Zargari) and Dr. Nilesh Joshi. It has been through their continued encouragement and support that I have been able to persevere not only in my undergraduate studies, but also in my graduate studies. Among the others who I wish to mention are my friends and colleagues at Morehead State University: Dr. Hans Chapman, Dr. Yuqiu You, Dr. Ni Wang, Dr. William Grise, Mr. Sam Mason, Mr. Jason Stepp, Ms. Kelli Cornett, and a former AET faculty, Dr. Rajeev Nair. It is with the utmost respect and admiration that I express my many thanks to you all. You will always be a part of my family in the Applied Engineering and Technology Department at Morehead State University.

Last, and certainly not least, I wish to convey heartfelt gratitude and respect to my friends, co-workers, and mentors at Link-Belt Construction Equipment Co.: Mr. Richard Shultz (to whom I owe special thanks for encouraging me to undertake a part of this topic of study as my undergraduate capstone project), Mr. LeRoy Williams, and Mr. Hoyt Gamble. It has been through their continual support, understanding, and friendship that I have been able to pursue my academic career during full-time employment, and have been able to realize two life-long dreams of mine – earning my bachelor’s and master’s degrees.

It has been a combined effort of support from all those who have been mentioned, and countless others that have not. All of you have afforded me a part of this opportunity in some way, and to each and every one, I humbly say to you: “Thank you.”

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# **Chapter 1 – Introduction**

## **1.1 General Area of Concern**

In designing componentry for industrial equipment, it is often necessary to theorize and design many versions of a system and/or components. By combining experimental design methods with commonly used analysis and design tools such as CAD (Computer-Aided Design), FEA (Finite Element Analysis) and CFD (Computational Fluid Dynamics), designers can develop powerful statistical models and utilize graphics visualization to analyze various design iterations. Such an integrated approach can result in a more robust and optimized system design. Not only does this help improve overall system performance but also has the potential to significantly reduce the cumulative time and cost spent on designing the system.

Prior to the usage of current engineering (Computer-Aided Engineering or CAE) tools such as FEA & CFD, designers would have to limit their exploration into design possibilities and produce a limited number of physical models that would then be tested either in the field or during a controlled experimental run. This left many possibilities off of the table for consideration and thus severely limited the total system improvements that could be tested and possibly implemented. With the usage of CAE, we find that we are able to digitally simulate significantly more ideas and designs. This ultimately results in higher quality test scenarios whereby the physical tests are made up of the top percentage of the digital simulations that have shown promise.

## **1.2 Significance and Importance of the Study**

While there exist applications where Finite Element Analysis (FEA) is utilized along with Computer-Aided Design (CAD) to produce design optimizations, there are very few applications where Computational Fluid Dynamics (CFD) is utilized along with Computer-Aided Design (CAD) for this purpose. Further, there exist even fewer applications where CFD and CAD are

combined with experimental design (DOE). The same can be said for applications where FEA and CAD are combined with DOE. The main focus of this research is to show how these tools can be utilized to optimize final designs of various components while maintaining an absolute minimal requirement for prototype manufacturing or to negate the requirement altogether. With the utilization of these tools in a concurrent manner (CAD/CFD/DOE or CAD/FEA/DOE), we can find that the total number of design possibilities to be initially explored will increase significantly and, thus, lead to an overall more robust and functional design. Another main focus of this project is to demonstrate the use of CAD/CFD/DOE and CAD/FEA/DOE to solve real-world engineering design problems and how the integrated approach can help save countless hours of physical modeling, mock-ups and prototype manufacturing as well as eliminating unnecessary waste and scrap materials that would be associated with the testing of prototype components.

### **1.3 Assumptions and Limitations**

It will be assumed for the sake of this research that there are no inherent design flaws within the components under investigation that will undermine the efforts of the research. Further, it is assumed that the components will be manufactured correctly and within specified manufacturing tolerances. The effects of surface irregularities and surface roughness are assumed to be zero. While this is not a likely situation to encounter in real life, this assumption will decrease the amount of factors that are required to be input into the software and will also subsequently decrease the total computation time required to solve the flow and stress situations.

Case Study 1 of this research directly emulates a component of an HVAC system as found on heavy duty industrial equipment and there are variables that are not taken into account for the sake of simplicity. Among these factors are: changes in atmospheric pressure, overall efficiency of the HVAC blower, flow loss due to gaps and incomplete system sealing, and flow



around internal cabin components. While most industrial equipment operates within a reasonable deviation of normal atmospheric pressure, there are some areas where this pressure is reduced, due to high elevation. This factor is neither simulated nor taken into account for the purpose of this study. Additionally, the maximum air flow as listed by the blower's manufacturer was utilized and no efficiency losses were accounted for. Further, errors and workmanship play a major role in any manufactured product. As such, any minor deviations from nominal such as gaps or incomplete sealed components in the system are not taken into consideration. Lastly, we will be examining the maximum observed air flow in the component. While it is understood that moving the air either too quickly or too slowly through the HVAC core is detrimental to system performance, this will be disregarded for the sake of simplicity in the course of this research.

While the processes described herein for Case Study 1 will be referred to as concurrent CFD, the software utilized for generating CAD models and the software used for CFD were two independent, stand-alone products. In an ideal environment, both functions would be provided by single software and there would be no need to export CAD geometry and then import that geometry into the CFD software, thus eliminating additional preparation time.

Case Study 2 of this research directly emulates a component as found on heavy duty industrial equipment and there are variables that are not taken into account for the sake of simplicity. Among these factors are: variations in material composition from those specified, overall duty cycle of the component, and strength loss due to gaps and incomplete joining. Further, errors and workmanship play a major role in any manufactured product. As such, any minor deviations from nominal such as gaps or incomplete welds will not be taken into consideration.

The processes described herein for Case Study 2 will be referred to as concurrent FEA. In this instance, both the CAD software and FEA module were integrated into the same program, thus eliminating the need to export geometry from one software and import into another, such as was done in Case Study 1. This eliminated the additional preparation time that would have otherwise been encountered.

#### **1.4 Application Background**

For Case Study 1, we are studying a generic HVAC return air and fresh air intake duct as would be used on heavy duty on-highway construction equipment. The main focus upon the HVAC duct revolves around improving airflow within the driver's cabin on the vehicle. For this application, as we are interested in the ways in which air is able to enter the duct as well as the ways that air is channeled once it has been introduced to the duct interior.

The particular application of the component that is the subject of Case Study 2 lies within the driver's cab for an on-highway construction vehicle. A typical installation of a steering column sub-assembly contains several components that are installed as a complete unit within the driver's cabin. The main focus on the base bracket is centered on the premise that upon gaining entry to the driver's cabin, the driver will pull on the steering wheel to aid in entry to the cab. This results in a force and moment being encountered at the attachment point of the steering column and base bracket.

#### **1.5 Definition of Terms**

1. ALD

Analysis-Led Design, the process of allowing simulation and analysis to lead or direct the product design cycle.

2. CAD

Computer-Aided Design, a highly specialized form of engineering software, whose sole

purpose is to create digital representations of components and systems that are to be manufactured.

3. CAE

Computer-Aided Engineering, any form of computer software that assists the design engineer in completion of his or her duties in some fashion.

4. CFD

Computational Fluid Dynamics, a process of replacing equations of fluid flow with numbers and advancing them through space and time.

5. DOE

Design of Experiments. Also known as Experimental Design, a technique for statistically testing different combinations and levels of variables on the overall outcome of an experiment.

6. FEA

Finite Element Analysis, a technique, numerical in nature, often used to solve stress/strain problems in the engineering design field.

7. Fresh air intake

The point on the machinery where fresh, outside ambient air is introduced into the HVAC system.

8. HVAC

Heating, Ventilating, and Air Conditioning, the main environmental control system found within most industrial equipment that contains an enclosed cabin.

9. Mesh

A representative model of an element within CAE software that comprises of many nodal

elements such as tetrahedra that are utilized to solve the complex calculations within the program.

10. PLM

Product Lifecycle Management, the process of managing the complete lifecycle of a product from its conception, through design and manufacture and to service and disposal.

## **Chapter 2 – Review of the Literature**

### **2.1 Background**

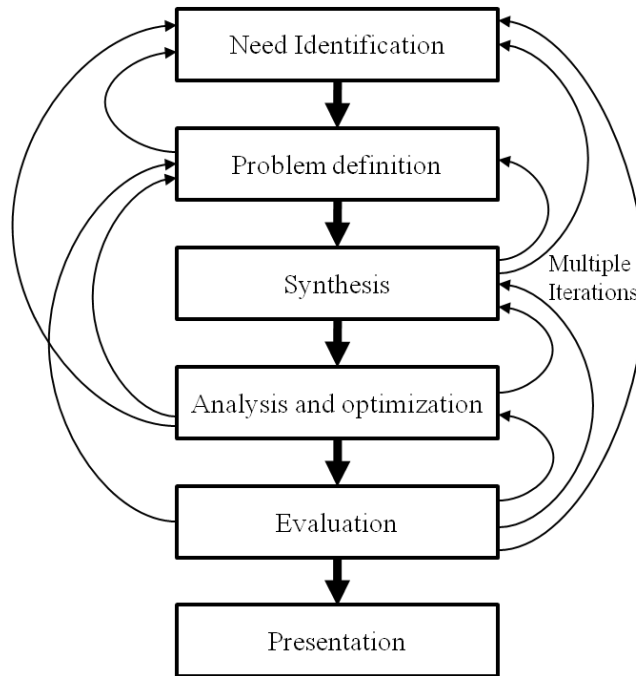
To effectively understand how CFD and FEA play a role in product development and design, let us first look at what comprises mechanical engineering design. Design is not simply something that happens. Rather, it is an iterative process that requires many different and interactive phases. There are many resources that exist that can aid the designer, of which there are many sources of information and guidance as well as an ample supply of computational design tools (Budynas, Nisbett, & Shigley, 2008, p. 10).

#### **2.1.1 The Fundamentals of Design**

When we say that we design something, all that we are really saying is that we have either formulated a plan that satisfies a specific need or that we have simply solved a problem. If by some reason that this plan culminates in the creation of something that has physical presence, then we must ensure that certain criteria are met. The product must be above all else functional, as well as reliable, safe, usable, manufacturable and marketable, among other things. Design is iterative, as mentioned earlier, and innovative. We also find that design is a decision-making process. All too often engineering designers find themselves faced with decisions that must be made with either too little information, sometimes with just the correct amount of information, and sometimes with an abundance of information that partially contradicts itself. These decisions must sometimes be made tentatively, with a reservation to change at a later time as more information becomes available. The main idea is that the engineering designer must be comfortable with decision making and problem solving, at both a professional and a personal level. There are various disciplines, such as mathematics, statistics, computers, and graphics, which are combined to formulate a plan that yields a product that has the characteristics as listed previously: functional, reliable, safe, usable, manufacturable and marketable. These

characteristics must be present within the product regardless of who actually builds it (Budynas et al., 2008).

Design engineers will undoubtedly fall into the category of either an innovator or adaptor, or both. These two types of individuals possess a preferred way of approaching problem solving. In general, adaptors are looking at resolving problems in a way that is in-line with the current paradigm, whereas innovators will search for solutions that lie outside this realm. (Scott, 2007). These different styles of thinking are vital during the design process. The design process, as seen in Figure 2-1, starts with the identification of a particular need and then involves a decision of some sort in regards to what to do about the need. At the completion of numerous iterations, a presentation of a plan that will meet the needs is given. There may be several design phases that are repeated during the life of the product, based upon the complexity and nature of the design task. It is strongly emphasized that the design process consists of numerous iterations. We see ourselves progress through several steps and then evaluate the results we have obtained. Once this is complete, we return to an earlier part of this procedure, only to repeat what we have done. As the situation dictates, there may be a need to generate several components that when assembled make up an entire system. For each component, we synthesize, analyze and refine. Ultimately we determine what affect each synthesis has on the other component and the system as a whole (Budynas et al., 2008).



**Figure 2-1. Typical phases in design.**

### **2.1.2 Design Characteristics**

In addition to being an iterative process, there are many other considerations that make up a design. These design considerations are basically those characteristics that influence the design of the single component or even the entire system. More often than not, there are a lot of characteristics that must be considered and even prioritized for the specific design situation. Table 2-1 outlines some of the more important things to consider while designing. Keep in mind that these are not necessarily in order of importance.

**Table 2-1. Characteristics to be considered in a design.**

1	Functionality	14	Distortion/deflection/stiffness
2	Safety	15	Styling
3	Cost	16	Shape
4	Reliability	17	Size
5	Liability	18	Volume
6	Manufacturability	19	Friction
7	Maintenance	20	Noise
8	Weight	21	Control
9	Life	22	Thermal properties
10	Wear	23	Surface
11	Utility	24	Lubrication
12	Marketability	25	Corrosion
13	Strength/Stress	26	Recovery

### **2.1.3 Design Tools**

Engineers today have an assortment of computer-based tools at their disposal to help in the solution of design problems. Due to the relative inexpensive nature of computers and the wide availability of software, we find ourselves immersed in an environment that has vast capability to provide the design, analysis and simulation of components. Computer-Aided Design (CAD) software plays the vital role of helping to develop the three-dimensional representations of components from which we may extract two-dimensional orthographic views and all pertinent dimensioning. We can also generate the necessary tool paths for manufacturing processes directly from the three-dimensional geometry created from the CAD software.

When speaking of computer-aided engineering (CAE) we are usually referring to any and all computer software programs that are engineering related. From this definition we find that CAD can be regarded as a subset within the CAE realm. There exist some programs that will perform specific analyses or simulation tasks for the purpose of assisting the designer, however they are not considered as a creation tool such that CAD is regarded. This type of software fits into one of two categories which consist of: engineering-based and non-engineering specific. Some specific examples of engineering-based software include finite element analysis (FEA),



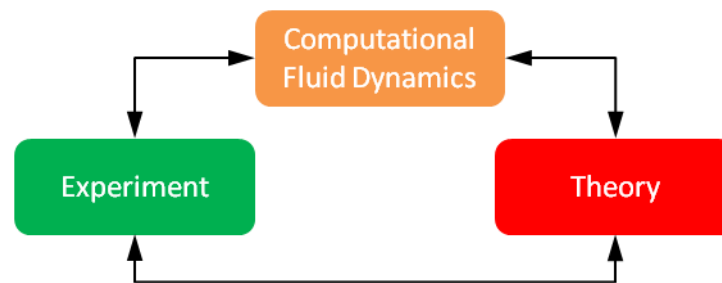
computational fluid dynamics (CFD) and programs for analysis of dynamic forces and motions in mechanisms. Conversely, non-engineering specific software includes types such as word processors, spreadsheet software, and mathematical solvers (Budynas et al., 2008).

#### **2.1.4 What is CFD?**

While we now have a working knowledge of what engineering design entails, we now turn our focus to CFD. The first thing that we need to understand is that the physical characteristics of fluid flow are governed by three fundamental principles. These principles are: 1) mass is always conserved, 2) force is equal to mass multiplied by acceleration, otherwise known as Newton's second law, and 3) energy is always conserved. Mathematical equations can be used to express these fundamental principles, which in a general state take on the form of partial differential equations. By definitions, computational fluid dynamics is the process of replacing these governing equations with numbers and advancing those numbers through space and time. This advancement through space and time produces the results which are in the form of a final numerical description of the fluid flow we are studying. Indeed, the final result of any CFD study is simply a collection of numbers (Anderson et al., 2009).

The impact that CFD has on engineering predictions is becoming stronger every day. Today, we see CFD emerging as a new third dimension in fluid dynamics, in addition to the other two dimensions of pure theory and pure experiment. The relationship can be viewed in Figure 2-2. Due to the innate ability to handle governing equations in their exact forms, CFD fast became a popular tool in engineering analyses. It is not only this ability to handle the "exact", but also its ability to function with the inclusion of detailed physical phenomena such as finite-rate chemical reactions that has boosted its popularity. We see that CFD not only supports both the pure theory as well as the pure experiment but also it compliments their presence as well. The current way that things are unfolding, it would appear that CFD is here to stay and will be sure to

remain the third part of fluid dynamics. CFD will remain equal in regards to stature and importance when compared to that of experiment and theory (Anderson et al., 2009).



**Figure 2-2. The Three Dimensions of Fluid Dynamics**

While CFD may be a very vital engineering tool in several different avenues of design, there remains one inherent drawback that will be present in any field of endeavor. The results that we obtain from CFD are only as valid as the physical models that we incorporate into the analysis. This covers aspects such as the governing equations and the boundary conditions. All aspects of the analysis are subject to error, and this is especially the case in regards to turbulent flow. The errors that we see due to truncation and/or round-off will combine and compromise the overall accuracy of the CFD model. However, despite these drawbacks, CFD remains a source of reasonably accurate results for a large number of applications (Anderson et al., 2009).

### **2.1.5 What is FEA?**

With a working knowledge of both engineering design and CFD, we now turn to finite element analysis (FEA). FEA, which is also known as the finite element method, is a procedure that is utilized in engineering as an approximation to the solutions of boundary value problems. When we speak of a boundary value problem, this refers to the mathematics involved whereby one or more variables will satisfy a differential equation within known boundaries. Depending on the problem that is being solved, these variables can include displacement, temperature or many others (Hutton, 2004). While we can analyze simple geometrically shaped components by using

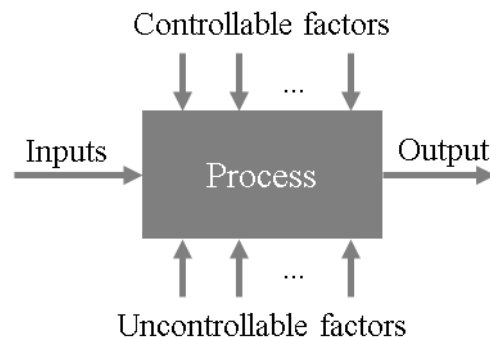
basic methods of mechanics, some of the more complex components are rarely able to be analyzed in such a way. The engineer is required to utilize methods of approximation that are less representative than their simple counterparts. The way that we solve this dilemma is simplified greatly when we account for the computing power that is available in this age. By dividing the structure of the component into small, finite elements, we are able to more closely approximate the true geometry of the component. When the number of elements increases as their corresponding size decreases, this allows for a better approximation of the actual component. As this is handled by more and more powerful software, with efficient and accurate solver routines, the computer brings a general ease to the preprocessing stage that includes the building of the model and creating the mesh. This also aids in the postprocessing stage of reviewing the calculated solution results (Budynas et al., 2008).

### **2.1.6 Experimental Design**

The last part of the engineering analysis assemblage in this research involves experimental design or design of experiments (DOE). We see that experiments are performed in nearly every field and are usually completed to discover some sort of information about a particular system or process. In its formal definition, an experiment is simply a test, or series of tests, in which deliberate changes are made to the inputs of a process or system for the express purpose of observing the effects that those changes make on the system and why they have occurred. It is apparent that experimentation plays a vital role in product realization, in which we find the activities of new product design and product improvement. Our ultimate objective in these activities is usually to develop a component or system that is robust and receives minimal influences from outside sources of variability (Montgomery, 2009).

In dealing with the scientific (or engineering) method, we find that experimentation plays a crucial role. The vast majority of problems that are encountered require some type of

observation of the system or component and a course of experimentation to understand how and why it works. It is within a well-designed experiment that we can often ascertain an empirical model for the system or component and can thus be utilized to predict future performance of said system or component. Generally speaking, we utilize an experiment to examine the performance and behavior of a system. As can be seen in Figure 2-3, a typical system is comprised of several different parts. The inputs into the system usually consist of some sort of material. The output of the system, also referred to as the response variable, is the result we are seeking. Other factors that will affect the system performance are the controllable and uncontrollable factors. While most experiments will usually involve a number of different factors, our main objective is to determine what effect, if any, that each factor or the subsequent interaction of these factors have on the output of the system being studied (Montgomery, 2009).



**Figure 2-3. Generic system or process model.**

There are experimental design methods seen in many different disciplines. Experimental design is a vital tool in the worlds of engineering and science for the purpose of improving the realization of various products. By utilizing the various aspects of experimental design, especially early in the design process, we can realize a number of positive outcomes. These are:

1. An overall reduction in cost.
2. An overall reduction in development time.

3. A reduction in variability which leads to closer attainment of targeted requirements.
4. An overall increase in the process yield.

In a more specific manner, we can see that the experimental design methodologies can be of great value to the engineering design process as well. Here we are constantly developing new products and improving upon existing ones. Some of the more useful aspects of experimental design for this discipline are:

1. The creation of new products.
2. Validation of important product features that affect product performance.
3. Compare and evaluate multiple design configurations.
4. Determination of product features that yield robustness.
5. The evaluation of alternative materials.

Overall, with the use of experimental design, we can hope to obtain products that possess the following qualities: ease of manufacture, enhanced reliability and field performance, lower cost, and significantly less development and design time (Montgomery, 2009). Table 2-2 lists the common characteristics considered in experimental designs.

**Table 2-2. Characteristics to be considered in an experimental design.**

1.	Problem recognition and statement
2.	Picking of response variable*
3.	Selection of factors, levels, and ranges*
4.	Selection of experimental design
5.	Performing the experiments
6.	Statistical data analysis
7.	Conclusions/recommendations
* <i>These steps are often performed at the same time</i>	

### **2.1.6 Components in HVAC.**

The primary function of the HVAC system in an automotive application is not just concerned with temperature control. Some key elements to a successful design involve reducing

driver fatigue, ensuring good visibility and maintaining comfort. When a continual flow of air is circulated through the interior of the vehicle, the carbon dioxide levels are reduced, odors do not have a chance to build up and there is a bit of demisting that occurs. Carbon dioxide buildup within the cabin in a high enough concentration can render the driver less responsive than normal. In regards to the internal air volume of the cabin, there are recommendations on how often this volume of air needs to be replaced every hour, and in some countries the HVAC system performance is governed by legislation (Daly, 2006).

In the not too distant past, the only viable way to test and prove out the design of a new HVAC system was to first produce a prototype of the system and subsequently test that prototype in a laboratory environment. This method of testing proves to not only be costly in a monetary sense, but also requires a significant amount of time to complete. In addition to the amount of time and money this approach requires, we also find that the process provides little or no understanding of why the performance of a design happened in that particular fashion. We begin to see the limitations of physical testing, as they cannot detect areas of recirculation, turbulence or constrictions that impact the performance of the system in a negative fashion. Further, the HVAC system will likely need to be tested in multiple configurations while in multiple different operation modes. This is further compounded by testing at a number of different temperature controls (Daly, 2006).

## **2.2 Real World Examples**

There are several examples in various industries that exist today that illustrate the versatility and usefulness of CFD. The following real world examples show how each specific industry has harnessed the power of CFD and incorporated it into one or more of their design processes. This trend seems to be on the rise and appears that it will continue for the foreseeable future.

### **2.2.1 Golf**

Adams Golf uses an integrated CFD solution which helps its design team members visualize how specific geometric features and changes will affect the driver drag and subsequent speed of the ball. After using this software over their last couple of products, Scott Burnett, director of advanced product development, says that “It’s pretty much an integral part of the design process for driver heads now.” Adams’ Speedline driver was the first driver developed utilizing their old process of making a prototype, whereby they made numerous guesses about the aerodynamics and make many tradeoffs. The new software allowed them to implement things in the next generation driver like getting the face size back up, which was a direct result of many expansion iterations through the CAD and CFD software. In addition to increasing the face size, they were also able to reduce the drag back to the benchmark of their Speedline series. Adams, having applied this newfound knowledge to their product development, has had their driver named the *Golf Digest* 2009 Gold Winner, and has also been fortunate enough to be a part of several tour victories. Others comment that Adams appears to have discovered something that has been overlooked by others (Siemens PLM Software, 2011).

### **2.2.2 Medical**

When dealing with components in the medical field, it requires software that is finely tuned to enable engineers to understand the basic flow of air, blood and even chemicals that are used in medical applications. In this field, the margins for design safety are extremely tight. We are seeing that CFD is fast becoming a tool for designers in all fields since the software can accommodate the internal and external flow of air, water and even blood while also accounting for heat transfer. In particular, one design is for elderly people: an oxygen mask worn somewhat away from the face. The main idea of the design is to enable the patient to be able to speak yet retain enough proximity to the mouth that they receive the proper percentage of oxygen. One

particular firm has been able to successfully simulate the mixing of the air and oxygen around the face. This particular type of situation is found to be extremely difficult in reality. Yet in another application, CFD is enabling designers understand how the airflow in the operating room is behaving versus the theoretical flow. This application of CFD has allowed designers to effectively optimize the system to minimize turbulent flow and provide better control for air direction (Waterman, 2013).

### **2.2.3 Automotive**

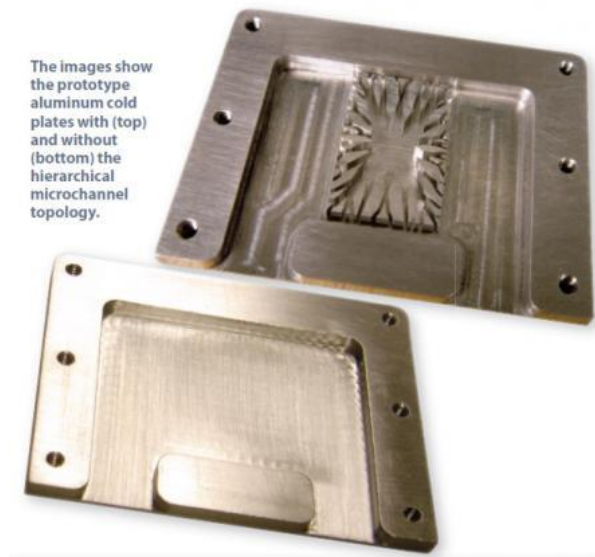
With over 150 test cells spread across the globe, a well-known engine manufacturer, Cummins, is moving in the direction towards analysis led design (ALD). This new strategy involves new tools and revised engineering processes which highly emphasize CAE testing in an early part of the development phase. At this point, it is significantly less costly and easier to change thinking and make changes. According to Bob Tickel, Cummins' director of structural and dynamic analysis, "Our goal is to reduce testing, reduce time-to-market, reduce cost, and get the design right the first time." In the traditional manner, the company's engineers would target a handful of best-case designs for their engines and would subsequently invest time and resources into building prototypes and subject those designs to rigorous testing. If the design were to fail, the team would begin anew and would add literally months to the already lengthy development cycle time. This is not only costly, but also it prevents the further exploration of other possible design options (Stackpole, Analysis-Led Design Gets It Right the First time, 2012).

The value of ALD and CAE are blatantly obvious. According to Tickel, "The physical testing process worked, but it was difficult to get an optimized design because you are limited in the number of permeations you can look at. In the virtual world, you can look at hundreds or thousands of alternatives. In a test cell, you can look at two or three." Now years into its ALD initiative, Cummins has been able to realize significant benefits. They have less dependency on



hardware testing and have seen significant reductions in the historically lengthy testing cycles, which has also significantly decreased the development cycle time. All of these things combine to allow Cummins to bring their new designs to market faster (Stackpole, Analysis-Led Design Gets It Right the First time, 2012).

In another automotive application, involving Toyota hybrid vehicles, engineers utilized multiphysics software to design and test possible prototypes for a more efficient heat sink used to regulate the thermal aspects of electronic components (See Figure 2-4). This was a discernible change from tradition where they would typically utilize analytical design methods coupled with trial and error prototyping. In prior designs, the cold plate was simple and featured an inlet on one side of a large cavity and an outlet on the other side. While providing adequate performance in regards to the associated heat transfer, this was at the price of a pressure drop across the entire plate. Upon initial observation, a designer would surmise that it should be reasonable to redesign the plate so that more coolant was allowed to pass through. However, this would ultimately lead to the requirement for a larger coolant pump and thus requiring more power and physical space, in a compartment that is already diminutive. Thus, the idea of a larger pump was not feasible. Using CAE software to optimize the configurations of the various channels in the heat sink, a final design was created and tested in the virtual environment (Dede, 2012).



**Figure 2-4. Original (lower) and prototype (upper) cold plates.**

(Image from Dede, E. (2012, November 22). Multiphysics Software builds a better heat sink. *Machine Design*, pp. 45-47.)

### **2.2.4 Heavy Equipment**

Caterpillar is another well-known company that is utilizing CFD to know and understand the complete system design prior to the cutting of any materials. They are able to analyze exactly how fluid flows through their hydraulic circuits and the designer is able to understand and visualize the expansion and losses as the fluid expands. This enables them to quantify the loss and make the appropriate changes such as changing the orifice size and the resulting fluid flow (Preshner, 2010). In addition to CFD, Caterpillar also employs virtual DOE where they are able to analyze a one thousand point experiment and they are not able to tell which is simulated and which is part of the test, in regards to the data received. This is thanks to their virtual product development, which is physics-based simulation based upon their existing machinery (Morey, 2012).

### **2.3 Rationale**

Fluid dynamics and Finite Element Analysis are two of the main engineering sciences that are utilized for the design of a multitude of different machines and mechanisms. As past

experience tells us, CFD was quite simple in that it used empirical formulas from engineering handbooks or some other means of simplified analysis techniques. As quick way to analyze the performance of a component and subsequently optimize that design, we come to parametric CFD and FEA analysis. This process for each analysis type comprises of five basic steps:

1. Problem definition
2. Dimensional reduction
3. Experimental design
4. Management of simulations
5. Metadata analysis

This type of analysis has been shown to serve a vital role in the design of devices that are dependent on fluid flow and stresses encountered. Were it not to be available for use, the alternative engineering methods would be very costly and time consuming and upon the completion of the project there very well could be an alternative way to use the device. An understanding of these five steps allows designers to better understand how a device functions over the course of its useful life and will generate far superior designs in a shorter timeframe (Imlay, 2012).

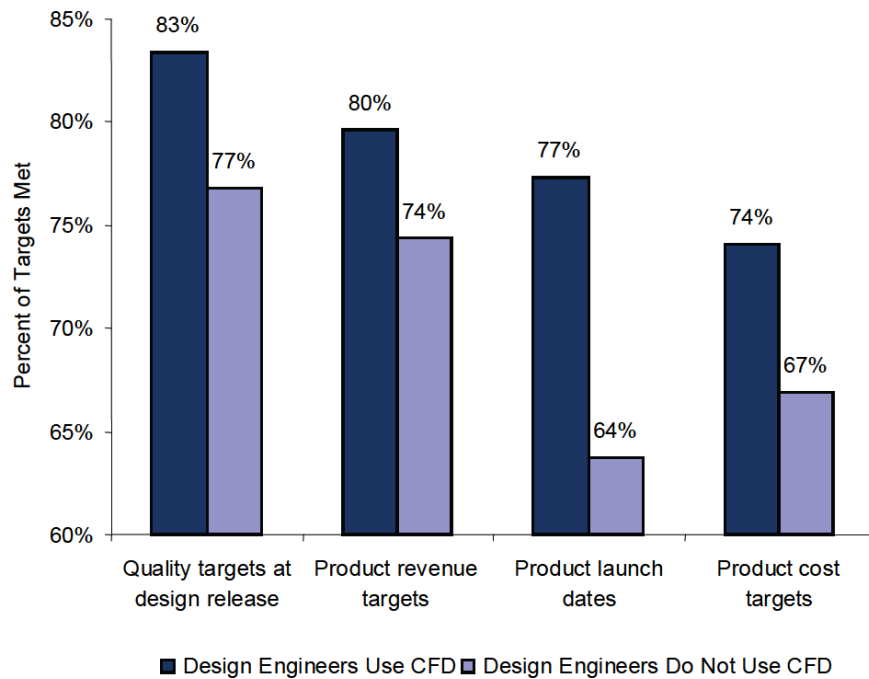
In the past 25 years, the utilization of CAD, analysis, and optimization methods have increased massively in such industries as aerospace, automotive, and electronics, among others. The added value of these types of tools is apparent, as they provide a virtual laboratory for the designers and engineers to test their various designs. They are able to assess the suitability of the structural strength or even the aerodynamic drag of components. Were this not available in the digital format, it would be far too costly and time consuming to actually conduct much, if any physical experimentation (Farouki, 1999).

Today, we find that most engineering designers will not give a second thought about running basic stress analyses, via FEA software, on their CAD models. Many of the more popular design software suites offer integrated FEA analysis tools embedded within the graphical interface. While this type of analysis was usually the realm of a specialized analyst, it is now commonplace for today's designers. It is the hope that we will see a trend towards performing analysis simulations earlier within the design phase. This is desired in order to transition towards a simulation-driven design mentality, which can be utilized in any field of design whether it is for a crane or a camera (Wong & Stackpole, 2013). In other areas, we see that optimization of components is already underway within the FEA realm. Altair's Product Design division, of which, its engineers have the reputation for being able to significantly reduce weight and mass in various products, has recently been involved with the design of a section of wing from the Airbus 380. The engineers were ultimately able to provide optimal topology and reduce the weight of the wing by 40% (Wong, 2013).

In regards to using simulation early on in the product development cycle, we are seeing an increasing trend of usage by engineers. Even though there is an increasing trend, this only accounts for approximately 3% engineers across the globe that utilize CFD for fluid flow simulations. With the ever increasing state of technology, we are now able to obtain near real-time results from CFD analyses so that simulation can now take on a more central role in the design process. Currently we see that mechanical and structural analysis is widely utilized in the early stages of design, and CFD lags far behind. However, it has long since been commonplace to see CFD utilized in design areas that rely heavily on fluid flow, such as the aviation and automobile industries (Watson C. , 2012). As we see an increase in the importance of the way that fluids flow and behave, there is certain to be an increased demand for the usage of CFD in

non-traditional fields of design and engineering. While the automotive and aviation industries have been utilizing these technologies for many years, the new developments in computing power will surely make this available to most other industries, which until now have seen CFD as unattractive (Ottitsch & Scarpinato, 2000). Usage of concurrent CFD methodologies has enabled designers and engineers, which have no specific training, to perform CFD analyses in approximately 80%-90% of all cases (Mentor Graphics Corporation, 2011).

Overall, the statistics will speak for themselves. According to statistics from the Aberdeen Group, engineers and designers who utilize CFD throughout the design cycle, have reported that they are able to manage the complexity of their product easier as well as they are able to identify problems earlier and make more efficient decisions (Boucher, 2011). Figure 2-5 depicts the return seen by engineers that utilize CFD.



**Figure 2-5. Return on Investment of Engineers Using CFD**

(Image from Boucher, M. (2011, June). *The ROI of Concurrent Design with CFD*. (White paper). p.4)

### **2.3.1 Misconceptions of CFD**

When we hear of someone speak of computational fluid dynamics, there may be a moment of cringing or grimacing in a returned expression. The truth of the matter is that CFD is often misunderstood and a great deference is given to those who routinely use the software. There are five basic misconceptions or myths that shroud the CFD realm in mystery and fear.

Myth #1: CFD is too difficult to be used in the design process.

Myth #2: CFD takes too long to use during the design process.

Myth #3: CFD is too expensive to be used by mechanical designers.

Myth #4: You can't directly use your CAD model to do CFD analysis.

Myth #5: Most products don't need CFD analysis.

(Weinhold, 2010)

Myths are exactly what we have just listed. Folklore, fable, legend, nothing more, nothing less. The truth of the situation is easier to grasp than one might think. To debunk these myths, let us go through them one by one.

Myth #1: Actually, the skill set that is required to operate CFD software is basically the same as that of the CAD environment as well as an understanding of the physics of the component. These are two crucial bits of knowledge that the designer already possesses.

Myth #2: We have been accustomed to seeing CFD utilized as an afterthought for a product that has already been through the design phase. This was primarily due to limitations of the software and hardware of the past. In the past, if a CFD analysis were to be run at the onset of the design cycle, it would have been rendered obsolete by a new design iteration before the calculations had adequate time to complete.

Myth #3: Traditionally, all engineering software is on the pricey side. However, when seeing a price tag in excess of \$25,000 for a one year lease, that would put the average

engineering company out of the picture. This, when coupled with the need for a supercomputer, left only the most hardcore aerospace and automotive engineering firms able to pay the hefty sum. With the price having fallen to \$25,000 for a perpetual license, while still a bit pricey, CFD is becoming more affordable for most mid-level companies.

Myth #4: While in the past, one was required to export and translate CAD geometry to the correct format for use in the CFD software, this is becoming a non-factor. Most modern CFD software packages will either operate directly within the CAD environment or will accept native CAD geometry as a direct import.

Myth #5: Again, as we look to the past we see that CFD has been restricted to the organizations that absolutely had to have it, like the automotive and aerospace industry. In actuality, fluid flow has a major impact on the performance of many products. Any product that deals with fluids or gases is a subject for analysis (Weinhold, 2010).

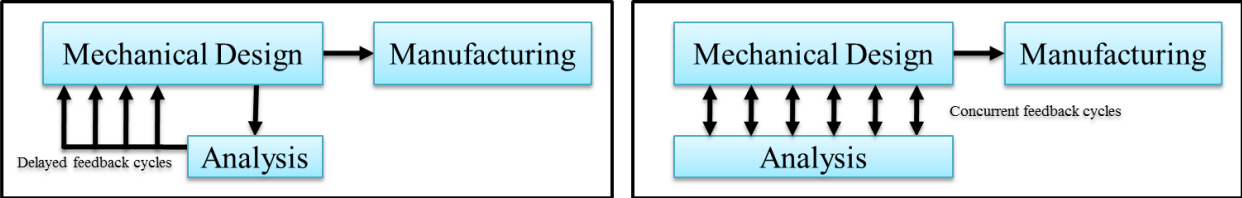
## **2.4 Value of Early Use**

Companies can benefit in numerous ways by utilizing FEA and CFD early and often within the product design cycle. Some of these benefits include:

1. Support faster design
2. Improve product design
3. Avoid rework
4. Improve quality
5. Reduce Prototypes
6. Faster time to production

Figure 2-6 illustrates how concurrent analysis can negate the ramifications of delayed feedback cycles due to analysis being placed at or near the end of the design cycle. By utilizing concurrent

analysis, designers are able to explore many more options and ultimately make better decisions based on analysis results rather than conjecture (CIMDATA, Inc., 2009).



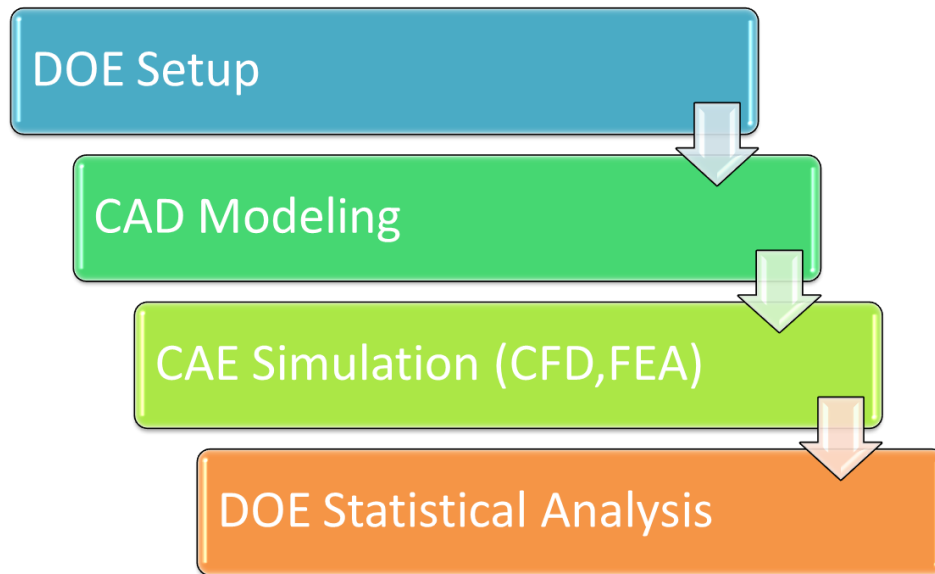
**Figure 2-6. Delayed feedback versus concurrent analysis**



## Chapter 3 – Methodology

### 3.1 DRIVE Methodology

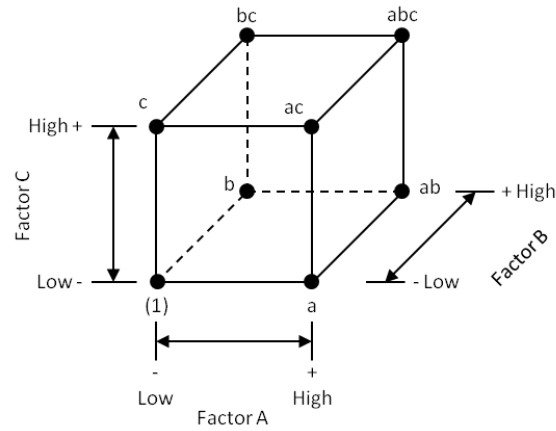
Figure 3-1 shows general outline of the DRIVE (Design Refinement by Iterative Virtual Experimentation) methodology.



**Figure 3-1. DRIVE Methodology**

### 3.2 Research Design

To deal with several design factors it is appropriate to conduct a factorial experiment, which is a process whereby all factors are varied together instead of one at a time (Montgomery, 2009). It is important to keep in mind that the DRIVE methodology is not intended as specific but more so as a generalization of the methods to be used. By this, we are not limited to the level of factorial design that we can use. For the sake of example, let us suppose that we are to conduct an experiment utilizing a  $2^3$  factorial design. From this type of experiment we have three factors each with two levels, using the '+' and '-' notation to represent the high and low levels of the factor. We find that there are eight treatment combinations and they can be expressed in a cubic notation as seen in Figure 3-2. The design matrix is shown in Table 3-1.



**Figure 3-2. Geometric view of 2<sup>3</sup> experiment.**  
(Adopted from Montgomery, 2009)

**Table 3-1. Design matrix of 2<sup>3</sup> experiment.**

Run	Factor			Treatment Combination
	A	B	C	
1	-	-	-	(1)
2	+	-	-	a
3	-	+	-	b
4	+	+	-	ab
5	-	-	+	c
6	+	-	+	ac
7	-	+	+	bc
8	+	+	+	abc

### 3.3 Factorial Design Governing Equations

Below we outline the formulation for estimating the main effects and interaction effects in a factorial design. This formulation is adopted from Montgomery (2009) and is specific to the  $2^3$  design with three factors designated as A, B, and C respectively. Each factor has two levels designated as low and high. Thus, the main effect of A is given by Equation 3.1 (Montgomery, 2009).

$$A = \frac{1}{4n} [a + ab + ac + abc - (1) - b - c - bc] \quad (3.1)$$

Where 'n' is the number of replicates for each treatment combination, 'a' is the average response received from treatment combination 'a', 'ab' is the average response received from treatment combination 'ab', and so forth. Each treatment combination can be seen in Table 3-1.

In very similar manners we can determine the main effects of both B and C, as seen in Equation 3.2 and Equation 3.3, respectively.

$$B = \frac{1}{4n} [b + ab + bc + abc - (1) - a - c - ac] \quad (3.2)$$

$$C = \frac{1}{4n} [c + ac + bc + abc - (1) - a - b - ab] \quad (3.3)$$

The two factor interactions are also computed. The AB interaction is basically the difference between the main effects of A at the two levels of B. This is shown in Equation 3.4.

$$AB = \frac{1}{4n} [(1) - a - b + ab + c - ac - bc + abc] \quad (3.4)$$

The interactions of AC and BC are also found to be similar to that of AB, as seen in Equation 3.5 and Equation 3.6.

$$AC = \frac{1}{4n} [(1) - a + b - ab - c + ac - bc + abc] \quad (3.5)$$

$$BC = \frac{1}{4n} [(1) + a - b - ab - c - ac + bc + abc] \quad (3.6)$$

Finally, the 3-way interaction among the three factors A, B and C is shown in Equation 3.7.

$$ABC = \frac{1}{4n} [abc - bc - ac + c - ab + b + a - (1)] \quad (3.7)$$

(Equations are referenced from Montgomery, D. C. (2009). Design and Analysis of Experiments (7th ed.). Hoboken, NJ: John Wiley & Sons, Inc.)

### **3.4 Instruments Used**

The main instruments utilized during the course of these experiments are as follows:

#### **3.4.1 Software**

Software used:

- CAD software: Used for creating base CAD geometry and subsequent design iterations to be studied. The built-in analysis module will also utilized to perform FEA analyses on design iterations.
- CFD Software: Used for analyzing and solving all pertinent CFD simulations.
- Statistical Analysis Software: Used of performing factorial design calculations and generating appropriate graphs.

#### **3.4.2 Data**

Data used:

- Specific existing data about our test subject is not necessarily required, but will be very helpful in emulating the application of the component within the simulations.
- Any specifications, including all pertinent performance data about the test subject is also not a necessary requirement. Again, it will be very useful in emulating the application of the component within the simulations.

### **3.5 Application of DRIVE Methodology**

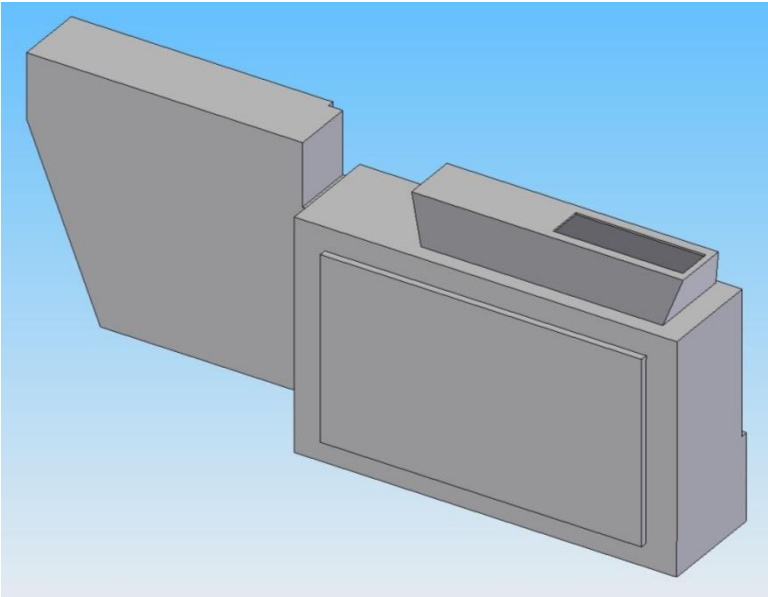
In the following chapters, we demonstrate the application of the DRIVE methodology to two real life case studies. Chapter 4 presents the first case study that involves configuring an HVAC component for use in on-highway industrial equipment. Chapter 5 presents the second

case study that involves configuring a mounting bracket for a steering column for use in on-highway industrial equipment. Both studies have the distinction of not being purely theoretical situations and have achievable goals for a true engineering design application.

# Chapter 4 – Application of DRIVE methodology to HVAC enclosure design (Case Study 1)

## 4.1 Application background

The application of DRIVE methodology as relates to the design of an HVAC enclosure is the subject of this case study, hereafter referred to as Case Study 1. See Figure 4-1 for a CAD rendered view of the HVAC enclosure.



**Figure 4-1. HVAC enclosure CAD render.**

Figure 4-2 shows the actual application of the HVAC enclosure as utilized on construction equipment.



**Figure 4-2. Actual HVAC enclosure.**

## 4.2 Case Study 1 Objectives

1. Design an HVAC component that yields a higher airflow than normal configuration.
2. Arrive at a decision for which design to utilize without building prototype models or conduct any physical testing of the design.
3. Follow DRIVE methodology to demonstrate how to design components that require air flow through or around them.

## 4.3 Selection of Response Variable & Choice of Factors, Levels and Ranges

The response variable selected for this experiment was the maximum air speed achieved through the HVAC enclosure. The factors chosen to vary in this factorial experiment were the opening size, whether or not internal baffles were present, and whether or not a fresh air intake was present. Each factor is comprised of two levels, both a high and a low. A summary of the above variables is shown in Table 4-1.

**Table 4-1. Summary of variables**

Variable	
Response Variable:	Max air speed
	Units: inch/sec
Factor A:	Intake & output opening sizes
	1 Large (Low) 2 Smaller (High)
Factor B:	Presence of internal baffles
	No (Low) Yes (High)
Factor C:	Presence of fresh air intake
	No (Low) Yes (High)

Each treatment combination had two replicates. The first of which had a mesh resolution of 0.99, and the second had a resolution of 1.00. This effectively introduced a type of virtual noise into the experiment so that we can adequately see if in fact there was any affect of the different treatment combinations.

## 4.4 Instruments Used

The main instruments utilized during the course of this experiment are as follows:

### 4.4.1 Software

Software used:

- SolidEdge CAD software: Used for creating base CAD geometry and subsequent design iterations to be studied. Also utilized to perform FEA analyses on design iterations.
- Autodesk Simulation CFD 2012: Used for analyzing and solving all pertinent CFD simulations.
- Minitab Statistical Software: Used of performing factorial design calculations and generating appropriate graphs.

#### **4.4.2 Data**

Data used:

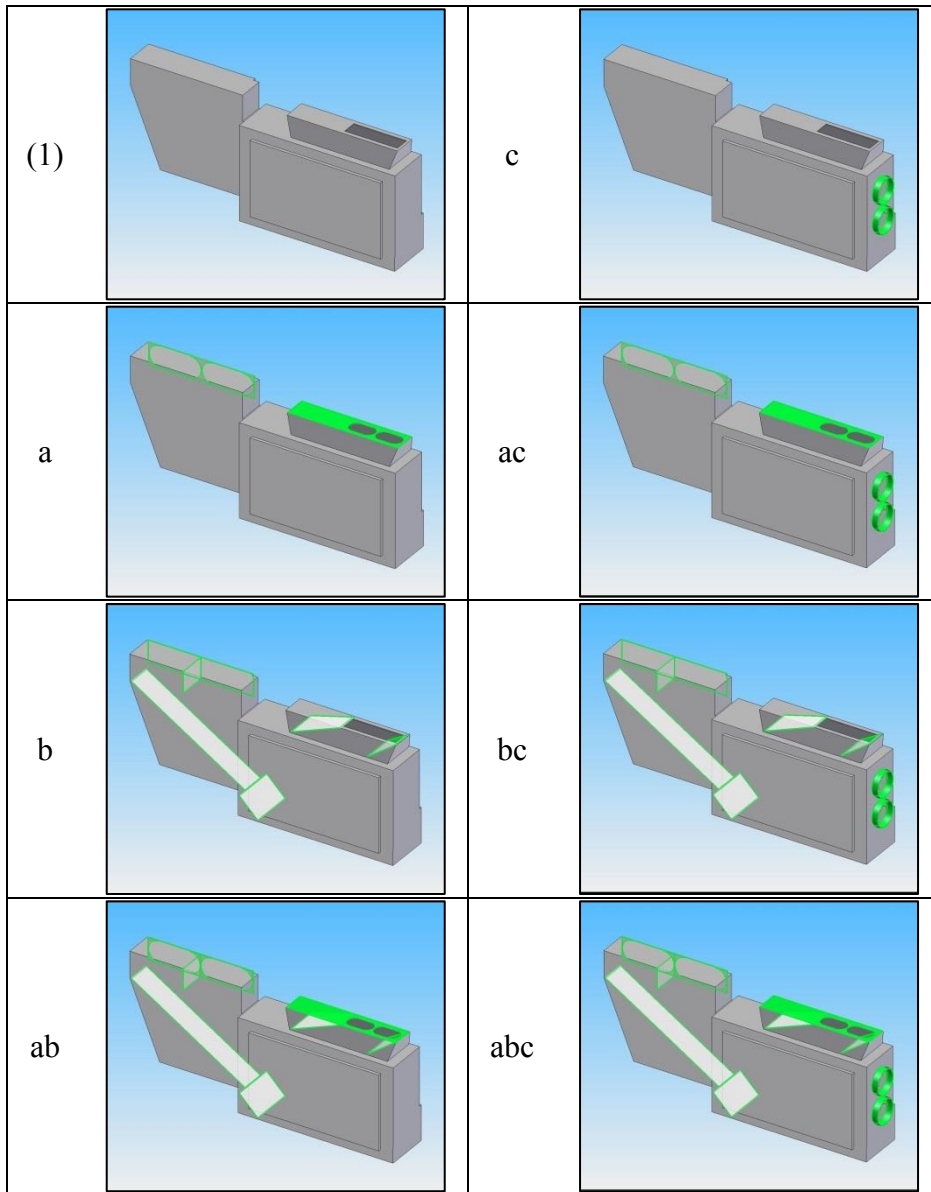
- Existing HVAC evaporator box design from an on-highway construction equipment vehicle.
- HVAC specification drawing, including all pertinent performance data. (Note: due to the proprietary nature of the design of this unit, no vital details shall be disseminated.)

### **4.5 CFD Simulations on 3D CAD models**

#### **4.5.1 Geometry Setup**

Figure 4-3 depicts the CAD geometry representations of the various combinations of treatments.





**Figure 4-3. CAD geometry of treatments**

Large scale images of the various combinations of the treatments and their associated CAD geometry representations are catalogued in Appendix I in accordance with the standard design of a  $2^3$  experimental design, utilizing the factors as listed in Table 4-1. Each iteration was implicitly modeled within the CAD software and then imported into the CFD software.

### 4.5.2 Boundary Conditions

The boundary conditions of the CFD analyses are listed in Table 4-2. Since the HVAC blower is rated at a volumetric flow of 425 CFM maximum, this was converted into a relative velocity by dividing the volumetric flow by the opening size of 0.1475 sq.ft. which yielded a blower output speed of 48 ft/s. This was subsequently converted into inches per second.

**Table 4-2. Boundary conditions.**

Inlets:	0 psi	Static pressure
Outlets	0 psi	Static pressure
Blower output velocity:	2880 in/s	Relative velocity

Further, the CFD solver was set to calculate 50 iterations on the mesh of each treatment level for both of the replicates.

### 4.6 Data Collection Methods

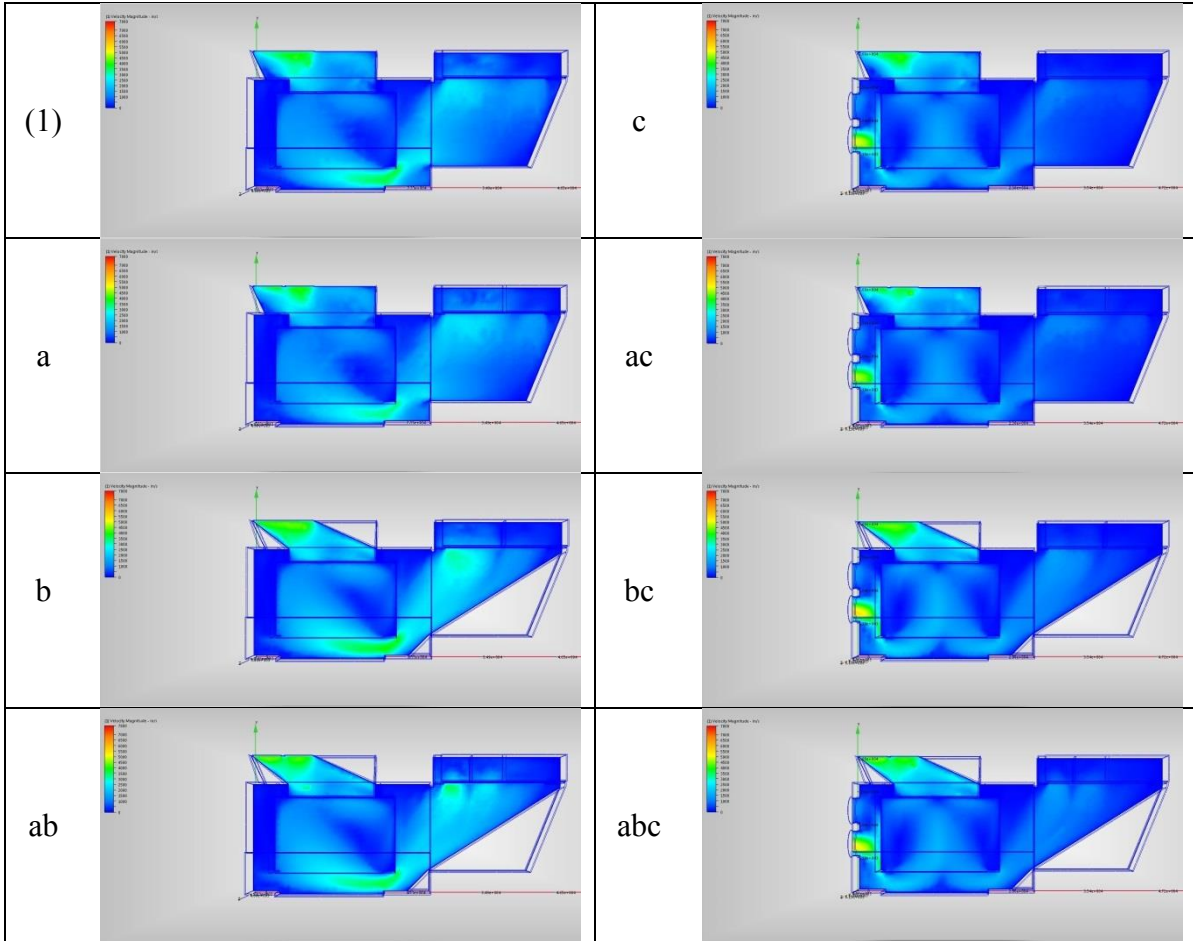
Data was collected on the completed CFD analyses and the subsequent maximum observed air velocity was recorded for each replicate of each treatment of the experiment. This data is catalogued in Table 4-3. In addition to the response variable data being collected, the relative number of elements that made up each treatment within each replicate was also documented. This data is catalogued in Table 4-4. Figure 4-4 and Figure 4-5 depict the CFD simulation results for the various combinations of treatments at their corresponding resolution sizes. Large scale images of the various combinations of the treatments and their associated CFD simulation results for each replicate of each treatment are catalogued in Appendix II.

**Table 4-3. Maximum airflow observed.**

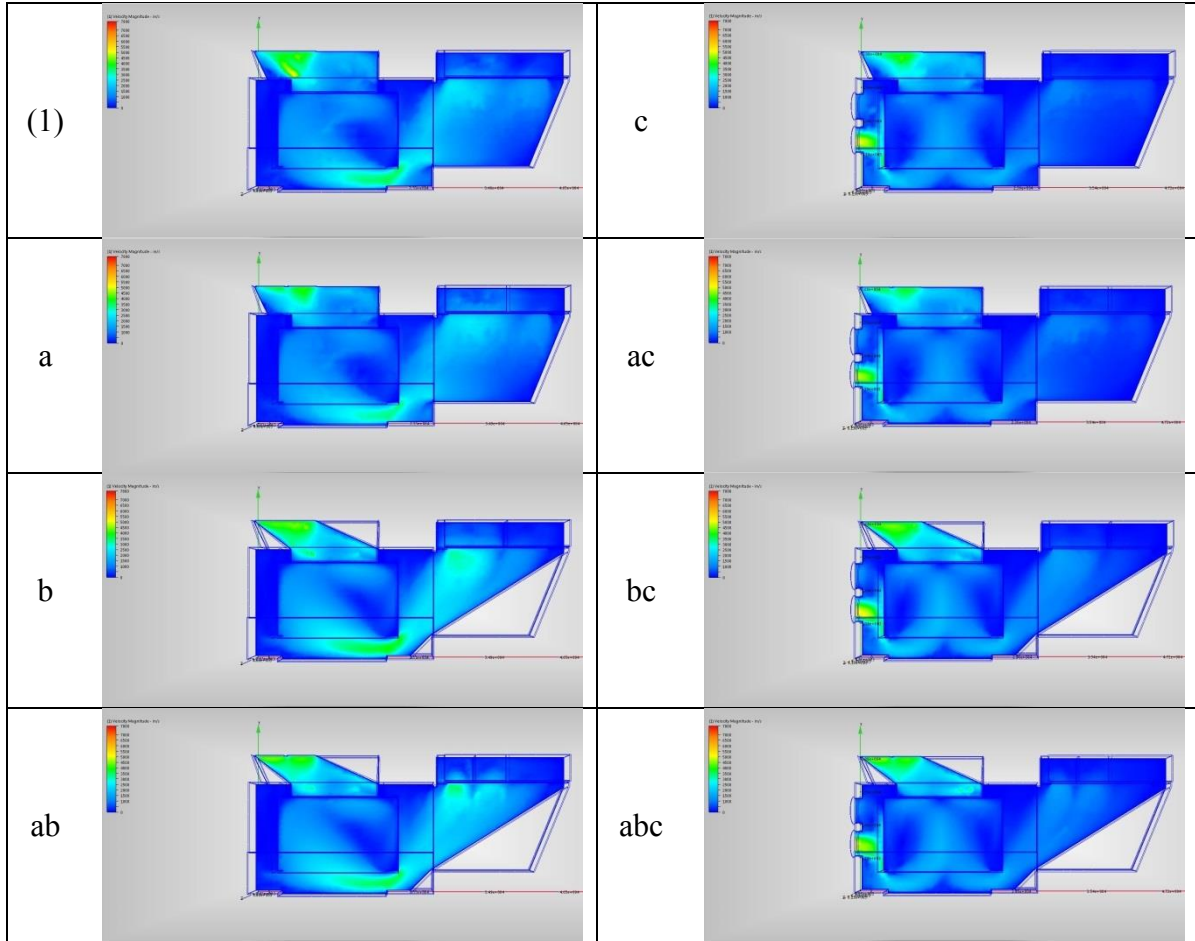
Run #	A	B	C	Treatment	Replicate 1 (in/s)	Replicate 2 (in/s)	Description
1	-	-	-	(1)	5182.56	5610.02	None
2	+	-	-	a	4525.54	4573.79	2 sm openings
3	-	+	-	b	5517.10	5713.44	Baffles
4	+	+	-	ab	4703.65	4877.85	2 sm + Baffles
5	-	-	+	c	6311.83	6162.70	Fr. Air
6	+	-	+	ac	6040.33	5810.46	2 sm + Fr. Air
7	-	+	+	bc	6713.01	6665.29	Baffles + Fr. Air
8	+	+	+	abc	7725.96	7291.97	All

**Table 4-4. Relative mesh sizes.**

Run #	0.99 Resolution (# elements)	1.00 Resolution (# elements)
1	219,789	218,671
2	227,824	225,819
3	451,008	450,825
4	480,517	480,324
5	219,246	216,573
6	226,389	223,621
7	453,220	453,032
8	482,836	482,641



**Figure 4-4. CFD simulation results (0.99 resolution)**



**Figure 4-5. CFD simulation results (1.00 Resolution)**

## 4.7 Statistical Analysis

Statistical analysis was performed utilizing Minitab statistical software. The input worksheet was configured for a  $2^3$  factorial design with two replicates. The data obtained for the maximum observed airflow was entered into the worksheet and then the factorial design was then analyzed at an alpha level of 0.01. Appropriate plots were generated which include a four in one plot of normality, residuals versus fit, histogram, and residuals versus order. Subsequent graphs include: Residuals versus A, Residuals versus B, Residuals versus C, Main effects plot for air speed, Interaction plot for air speed, and Cube plot for air speed.

## 4.8 Findings – Air Speed

A combination of high levels of factors A, B and C yielded the highest air speed. However, at the alpha = 0.01 level of significance, only the main effects of factor B and C are significant, in addition to the interactions of: A\*C and B\*C, since their P values are less than that of alpha value. A portion of the Minitab output is shown below in Figure 4-6.

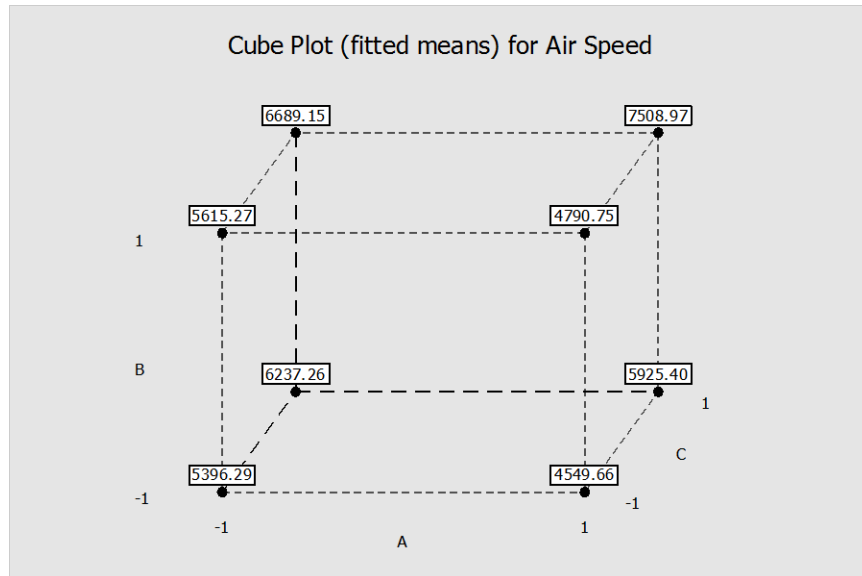
### Factorial Regression: Air Speed versus A, B, C

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	7	13369754	98.09%	13369754	1909965	58.81	0.000
Linear	3	10921583	80.13%	10921583	3640528	112.09	0.000
A	1	338259	2.48%	338259	338259	10.41	0.012
B	1	1556905	11.42%	1556905	1556905	47.94	0.000
C	1	9026419	66.23%	9026419	9026419	277.92	0.000
2-Way Interactions	3	2140380	15.70%	2140380	713460	21.97	0.000
A*B	1	332808	2.44%	332808	332808	10.25	0.013
A*C	1	1187108	8.71%	1187108	1187108	36.55	0.000
B*C	1	620463	4.55%	620463	620463	19.10	0.002
3-Way Interactions	1	307792	2.26%	307792	307792	9.48	0.015
A*B*C	1	307792	2.26%	307792	307792	9.48	0.015
Error	8	259825	1.91%	259825	32478		
Total	15	13629579	100.00%				

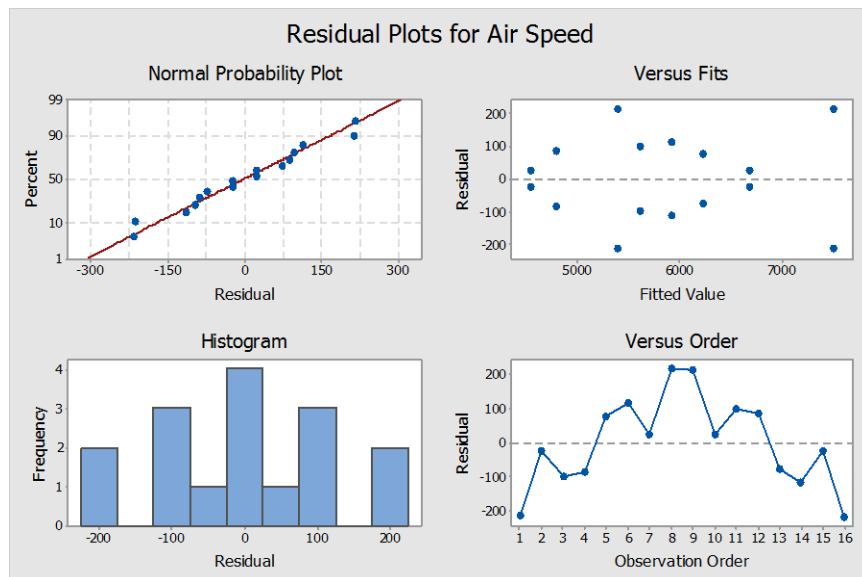
**Figure 4-6. Analysis of Variance for Air Speed.**

Figure 4-7 shows the Cube plot which lends useful information in determining under which circumstances we should progress with the design based on the maximum air speed obtained.



**Figure 4-7. Cube Plot for Air Speed.**

Upon review of the four in one plot, as seen in Figure 4-8, we find that the normality assumption of this experiment is acceptable, while the residuals versus fit exhibit an odd pattern indicating that the variance may be non-constant. Each of the individual residual versus factor plots exhibit normal behavior, as the residuals are randomly scattered about zero.



**Figure 4-8. Four In One Plot: Air Speed.**

#### **4.9 Recommendations and Implications**

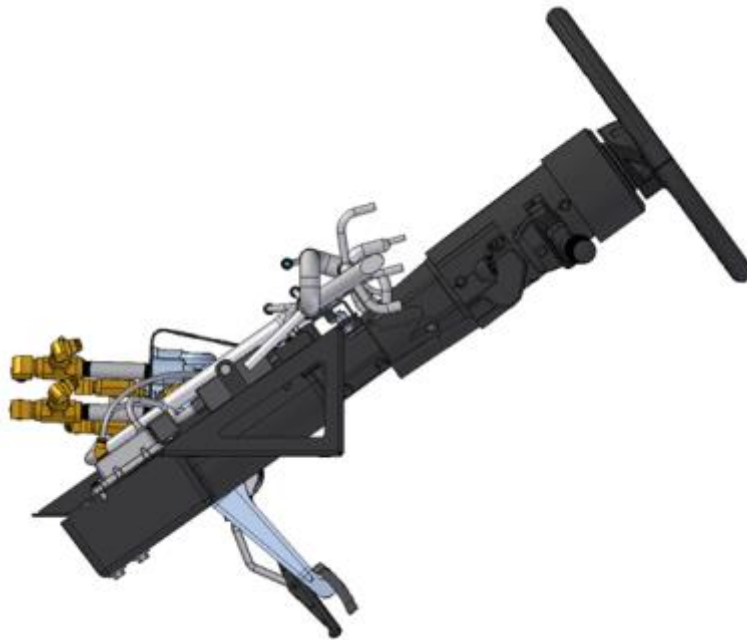
As observed from the results obtained from the experiment, the data suggests that the optimal configuration for the design of the component we have been studying could include all three factors: 2 small openings, the presence of internal baffles, and the presence of fresh air intake. However, based upon the statistical significance we ( $\alpha=0.01$ ) shall determine the optimal solution to be treatment 'bc' which contains internal baffles and fresh air intake. By simulation driven design methods, we have been able to produce a viable design of a component to be utilized within an HVAC system. As such, this component can be expected to function as the optimal solution for the situation given.



## **Chapter 5 – Application of DRIVE methodology to steering column mounting bracket design (Case Study 2)**

### **5.1 Application Background**

The application of DRIVE methodology as relates to the design of a steering column mounting bracket is the subject of this case study, hereafter referred to as Case Study 2. See Figure 5-1 and Figure 5-2 for a typical views of the steering column sub-assembly as installed in the construction equipment vehicle. Supplemental component application images for Case Study 2 can be seen in Appendix III.



**Figure 5-1. Steering column sub-assembly CAD render.**



**Figure 5-2. Actual steering column bracket sub-assembly.**

When an operator attempts to gain entry into the cabin, they will tend to grab the steering wheel and utilize it as a grab handle to aid the entry into the cabin. When this is repeated over multiple ingress and egress cycles, there is an undue stress put upon the mounting bracket, of which it is not intended to function as the base mounting bracket for an impromptu grab handle. In this case study we examine the means by which we can reduce the maximum observed stress within the mounting bracket.

## **5.2 Case Study 2 Objectives**

1. Design industrial equipment componentry that yields higher functionality. As a practical measurement, for a given load, the resultant maximum stress will be minimized.
2. Arrive at a decision for which design to utilize without building prototype models or conduct any physical testing of the design.
3. Follow DRIVE methodology to demonstrate how to design components that require strength analyses.

### 5.3 Selection of Response Variable & Choice of Factors, Levels and Ranges

The response variable selected for this experiment was the maximum observed stress on the bracket. The factors chosen to vary in this factorial experiment were: presence of flange radius, increased flange width, and presence of weight reduction holes. Each factor is comprised of two levels, both a high and a low. A summary of the above variables is shown in Table 5-1.

**Table 5-1. Summary of variables**

Variable		Units: psi	
Response Variable:	Max stress	No Radius (Low)	1.00" Radius (High)
Factor A:	Presence of flange radius	1.25" (Low)	1.75" (High)
Factor B:	Increased flange width	3.00" holes (Low)	No Holes (High)
Factor C:	Removal of weight reduction holes		

Each treatment combination had two replicates. The first of which had a subjective mesh size of 8, and the second had a subjective mesh size of 9. This effectively introduced a type of virtual noise into the experiment so that we can adequately see if in fact there was any effect of the different treatment combinations.

### 5.4 Instruments Used

The main instruments utilized during the course of this experiment are as follows:

#### 5.4.1 Software

Software used:

- SolidEdge CAD software: Used for creating base CAD geometry and subsequent design iterations to be studied.
- SolidEdge CAD built-in FEA module: Used for analyzing and solving all pertinent FEA simulations.
- Minitab Statistical Software: Used of performing factorial design calculations and generating appropriate graphs.

### **5.4.2 Data**

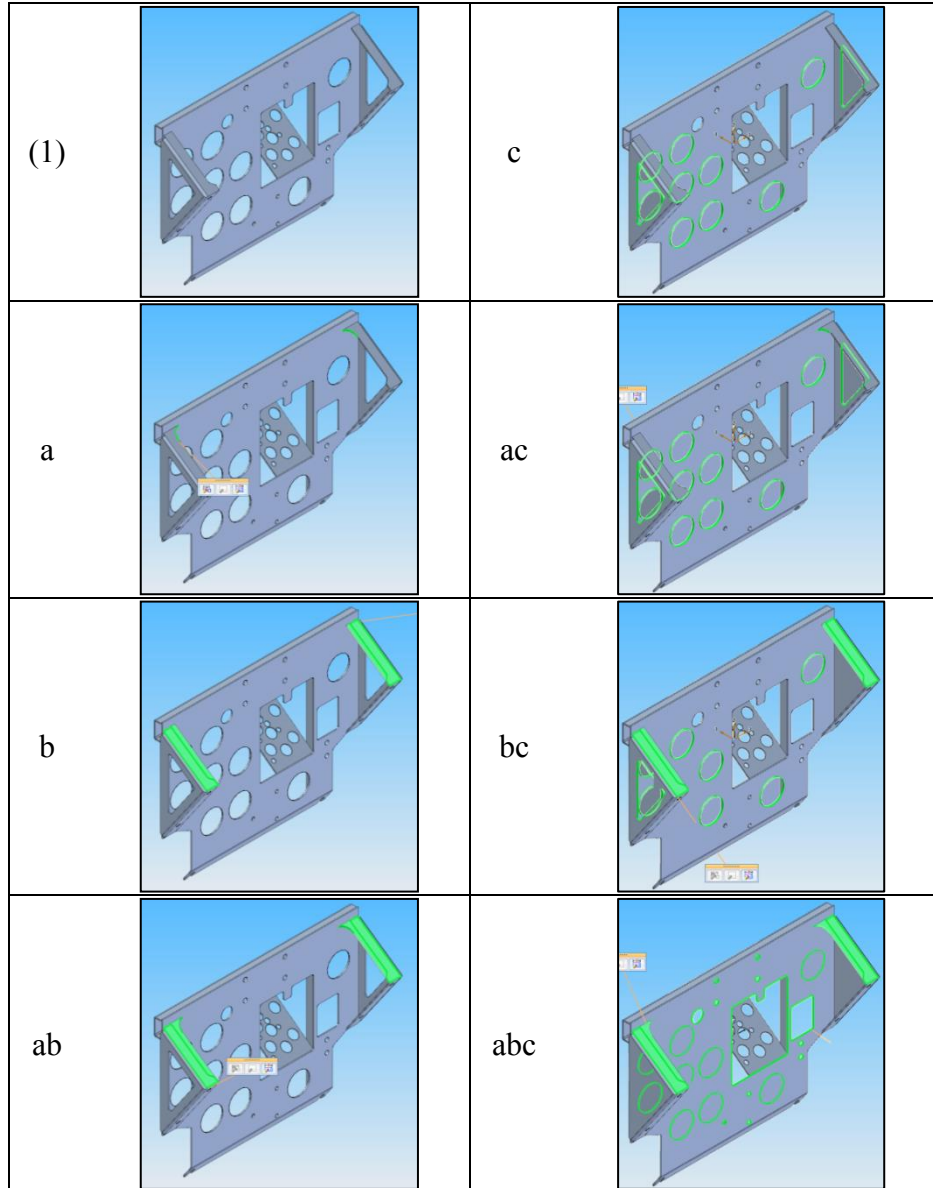
Data used:

- Existing steering column mounting bracket design from an on-highway construction equipment vehicle.
- Feedback from existing construction equipment customers.

## **5.5 FEA Simulations on 3D CAD models**

### **5.5.1 Geometry Setup**

Figure 5-3 depicts the CAD geometry representations of the various combinations of treatments.



**Figure 5-3. CAD geometry of treatments**

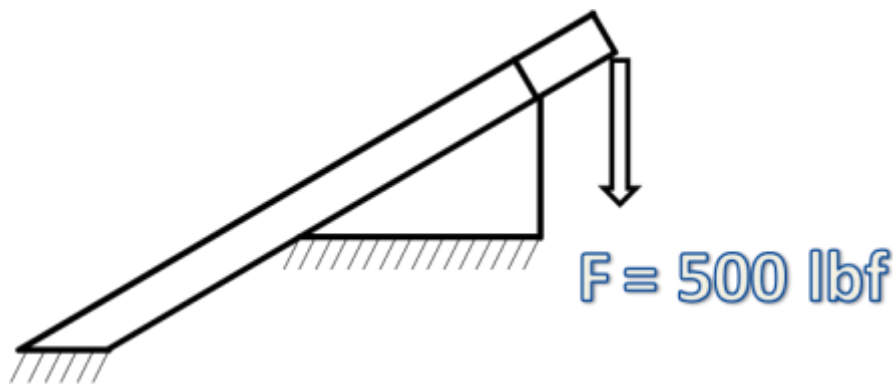
Large scale images of the various combinations of the treatments and their associated CAD geometry representations are catalogued in Appendix III in accordance with the standard design of a  $2^3$  experimental design, utilizing the factors as listed in Table 5-1. Each iteration was implicitly modeled within the CAD software and then the FEA analysis was performed from within the CAD software.

### 5.5.2 Loading Conditions

The loading conditions of the FEA analyses are listed in Table 5-2. Since bracket has a steering column attached, the subsequent maximum loading upon the bracket is visualized in the free body diagram in Figure 5-4.

**Table 5-2. Loading conditions.**

Load:	500 lbf	Pounds Force
Constraints:	Fixed	Zero DOF



**Figure 5-4. Free body diagram of loading**

For the purpose of this study, it was assumed that a resultant force was encountered in the negative Y direction (straight down) and that the magnitude of that force was approximately 500 lbf.

### 5.6 Data Collection Methods

Data was collected on the completed FEA analyses and the subsequent maximum observed stress was recorded for each replicate of each treatment of the experiment. This data is catalogued in Table 5-3. In addition to the response variable data being collected, the relative number of elements that made up each treatment within each replicate was also documented. This data is catalogued in Table 5-4. The relative maximum displacements observed in each replicate were documented in Table 5-5, as well as the minimum factor of safety observed, which is documented in Table 5-6. Figure 5-5 and Figure 5-6 depict the FEA simulation results

for the various combinations of treatments at their corresponding resolution sizes. Large scale images of the various combinations of the treatments and their associated FEA simulation results for each replicate of each treatment are catalogued in Appendix IV.

**Table 5-3. Maximum stress observed.**

Run #	A	B	C	Treatment	Replicate 1 (psi)	Replicate 2 (psi)	Description
1	-	-	-	(1)	23,700	32,000	None
2	+	-	-	a	17,600	18,500	Flange Radii
3	-	+	-	b	22,800	25,200	Incr. Flange width
4	+	+	-	ab	19,600	19,400	Radii + Width
5	-	-	+	c	23,600	26,100	Rem. Wgt holes
6	+	-	+	ac	17,800	17,900	Radii + Rem. holes
7	-	+	+	bc	23,300	27,800	Width + Rem. holes
8	+	+	+	abc	19,300	19,100	All

**Table 5-4. Relative mesh sizes.**

Run #	Size 8 (# elements)	Size 9 (# elements)	Average
1	106,144	242,796	174,470
2	107,363	248,543	177,953
3	100,566	224,805	162,686
4	101,593	221,190	161,392
5	123,077	283,195	203,136
6	123,142	296,814	209,978
7	114,323	247,964	181,144
8	115,649	250,642	183,146

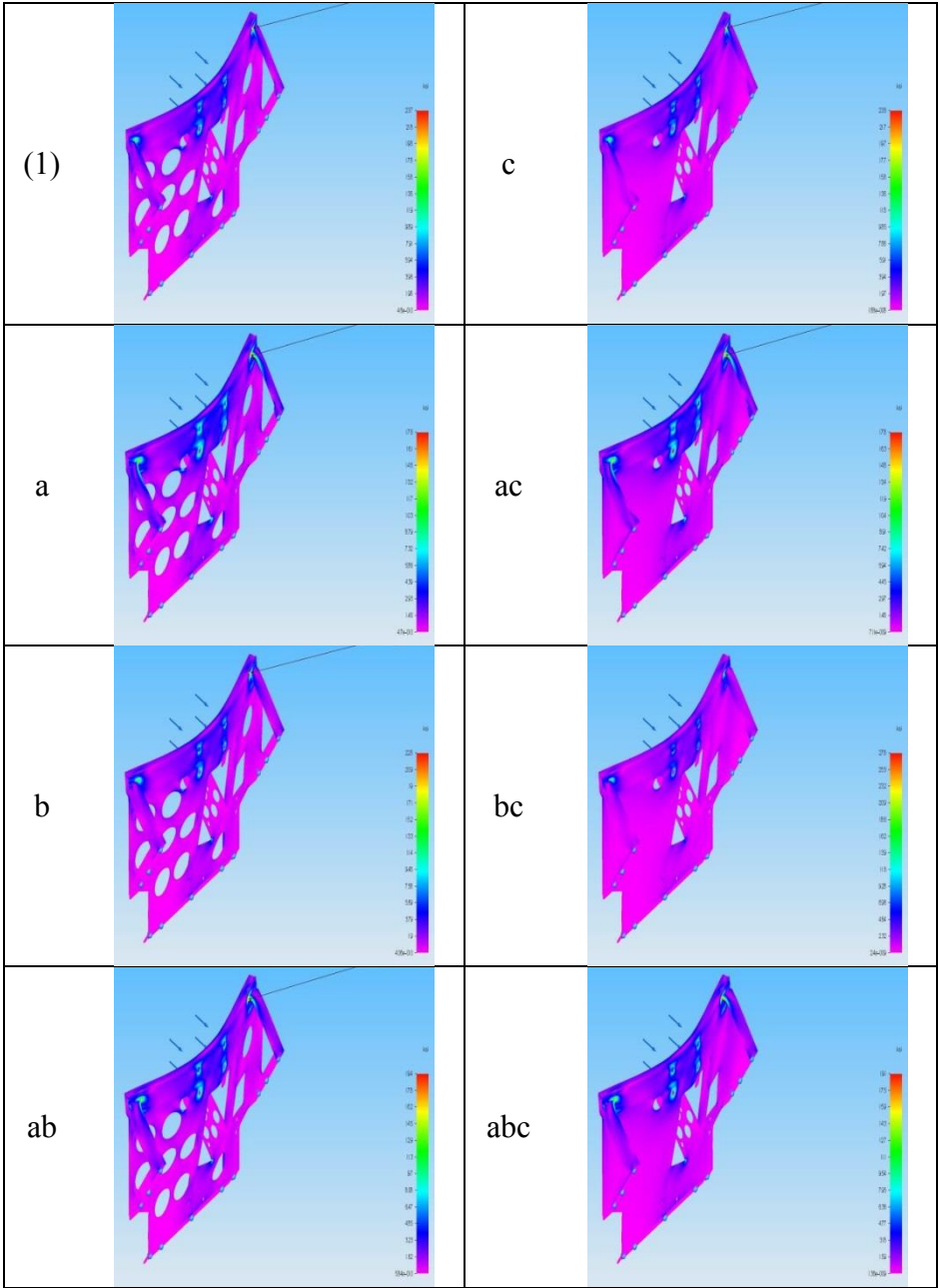
**Table 5-5: Maximum Displacement**

Run #	Size 8 (translation, inches)	Size 9 (translation, inches)	Average
1	0.0204	0.0203	0.0204
2	0.0184	0.0183	0.0184
3	0.0176	0.0176	0.0176
4	0.0161	0.0161	0.0161
5	0.0197	0.0196	0.0197
6	0.0176	0.0175	0.0176
7	0.0168	0.0168	0.0168
8	0.0154	0.0154	0.0154

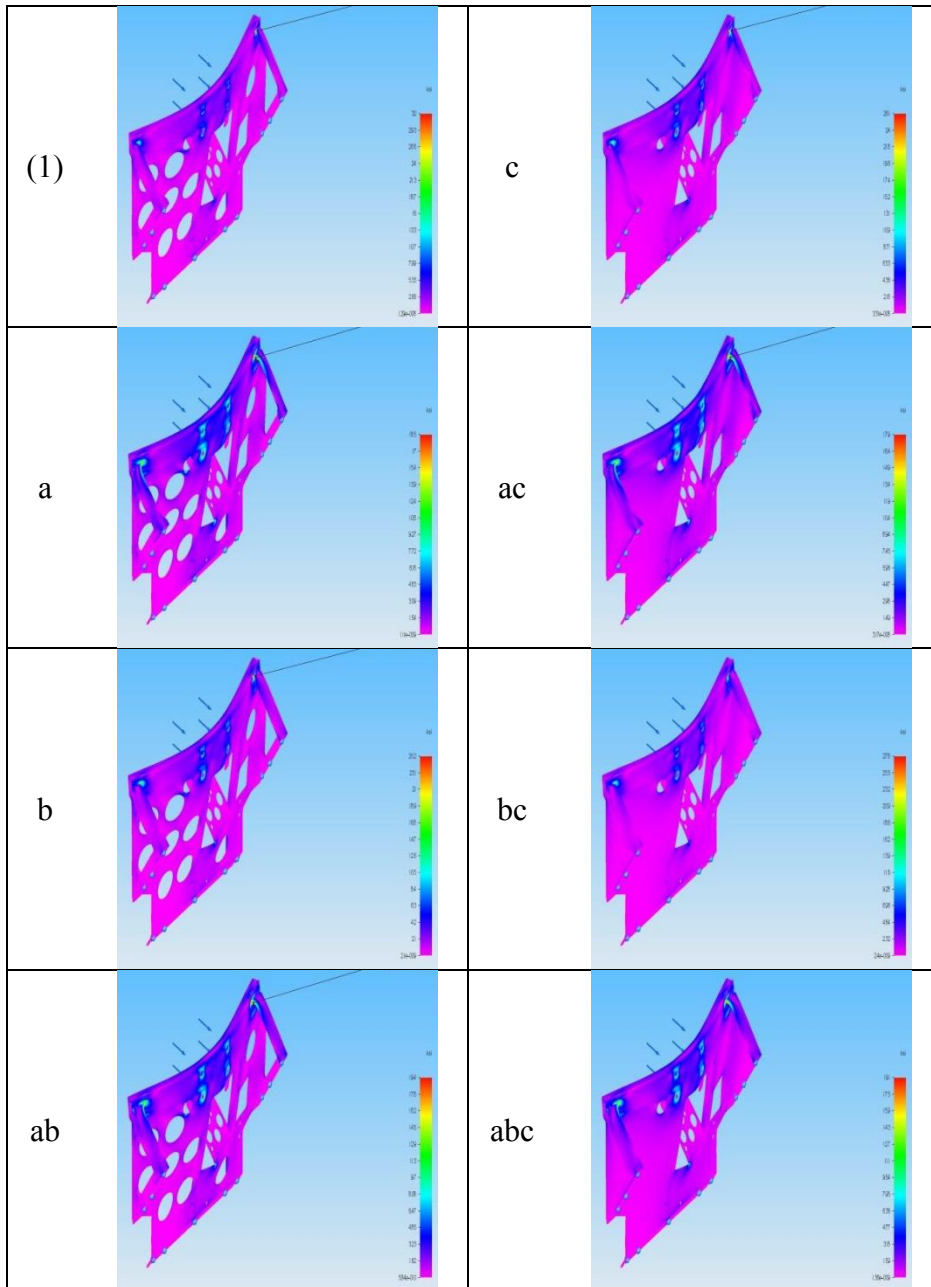
**Table 5-6: Minimum Factor of Safety**

Run #	Size 8 (translation, inches)	Size 9 (translation, inches)	Average
1	1.60	1.19	1.40
2	2.16	2.05	2.11
3	1.67	1.51	1.59
4	1.94	1.96	1.95
5	1.61	1.45	1.53
6	2.13	2.13	2.13
7	1.63	1.37	1.50
8	1.97	1.99	1.98





**Figure 5-5. FEA simulation results (Size 8 mesh)**



**Figure 5-6. FEA simulation results (Size 9 mesh)**

### 5.7 Statistical Analysis

Statistical analysis was performed utilizing Minitab statistical software. The input worksheet was configured for a  $2^3$  factorial design with two replicates. The data obtained for the maximum observed stress was entered into the worksheet and then the factorial design was analyzed at an alpha level of 0.05. Appropriate plots were generated which include plots of:

normal plot of standardized effects, half normal plot of standardized effects, pareto chart of standardized effects, normal probability, residuals versus fit, histogram, and residuals versus order. Subsequent graphs include: Residuals versus A, Residuals versus B, Residuals versus C, Main effects plot for max stress, Interaction plot for max stress, and Cube plot for max stress.

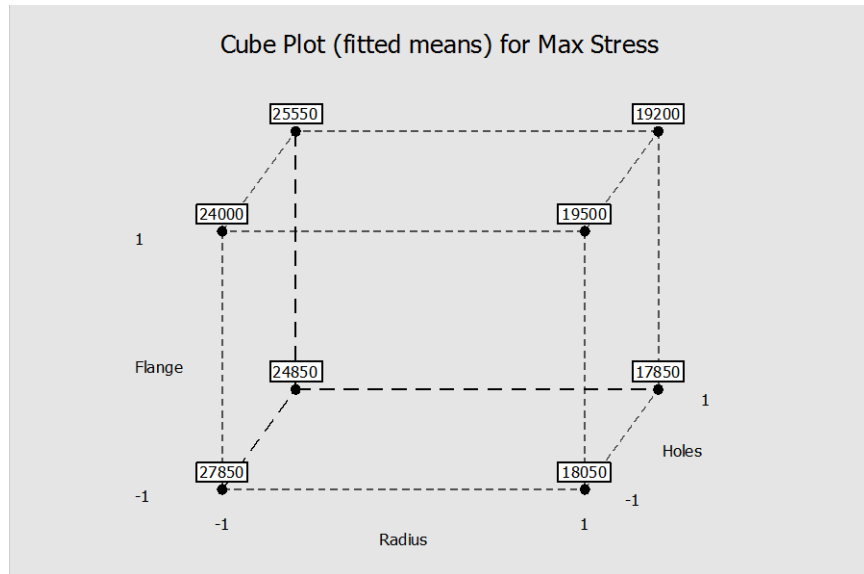
### 5.8 Findings – Maximum Stress

A combination of high levels of factors A and B yielded the lowest maximum stress. However, at the  $\alpha = 0.01$  level of significance, only the main effects of factor A are significant since the P value was less than that of alpha value. A portion of the Minitab output is shown below in Figure 5-7.

Analysis of Variance						
Source	DF	Adj SS	Adj MS	F-Value	P-Value	
Model	7	211544375	30220625	4.74	0.022	
Linear	3	192111875	64037292	10.04	0.004	
Radius	1	191130625	191130625	29.97	0.001	
Flange	1	30625	30625	0.00	0.946	
Holes	1	950625	950625	0.15	0.710	
2-Way Interactions	3	14026875	4675625	0.73	0.561	
Radius*Flange	1	8850625	8850625	1.39	0.273	
Radius*Holes	1	225625	225625	0.04	0.855	
Flange*Holes	1	4950625	4950625	0.78	0.404	
3-Way Interactions	1	5405625	5405625	0.85	0.384	
Radius*Flange*Holes	1	5405625	5405625	0.85	0.384	
Error	8	51025000	6378125			
Total	15	262569375				

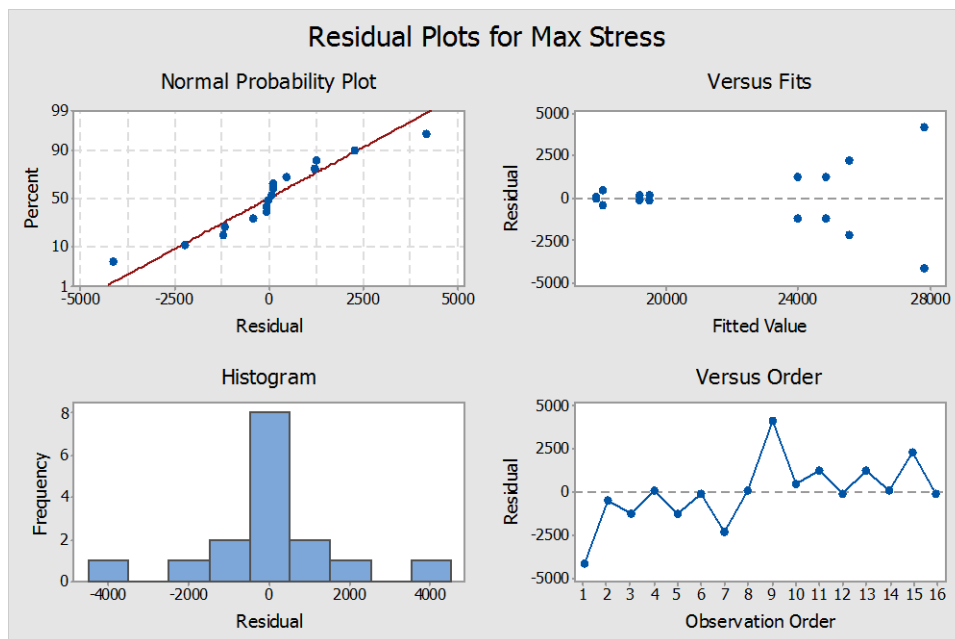
**Figure 5-7. Analysis of Variance for Max Stress.**

Figure 5-8 shows the Cube plot which lends useful information in determining under which circumstances we should progress with the design based on the minimum stress observed.



**Figure 5-8. Cube Plot for Max Stress.**

Upon review of the four in one plot, as seen in Figure 5-9, we find that the normality assumption of this experiment is acceptable, while the residuals versus fit exhibit an odd pattern indicating that the variance may be non-constant. Each of the individual residual versus factor plots exhibit normal behavior, as the residuals are randomly scattered about zero. All data for this portion of the analysis can be found in Appendix IV.



**Figure 5-9: Four In One Plot for Max Stress**

## 5.9 Recommendations and Implications

As observed from the results of the experiment, the data suggests that the optimal configuration for the design of the component we have been studying *could* include all three factors: presence of flange radius, increased flange width, and the removal of weight reduction holes. However, as a result of the ANOVA calculations, the only factor that is statistically significant and guaranteed to improve the overall performance is Factor A: the presence of flange radii. Thus, this would be the only feature that should be included in the further refinement of this design analysis. By simulation driven design methods, we have been able to produce a viable design of a component to be utilized within an on-highway construction vehicle. As such, this component can be expected to function as the optimal solution for the situation given.

## **Chapter 6 – Discussion, Conclusions, and Future Research**

### **6.1 Summary**

We have examined but one case of the potential application of utilizing the analysis tools of design of experiments coupled with computational fluid dynamics to help identify and lead us in the direction which will yield a more robust design of a component. Above all else, we must remember that function is the most vital characteristic of a design. According to Earle (2000), a product that does not function is regarded as a failure, no matter how many features it has. Further, by incorporating the aspects of DOE, this research further extends existing research as completed by Watson & Joshi (2012), (2013) whereby CFD was coupled with CAD analysis methods to effectively relocate a vital, yet non-functional component in an on-highway truck crane HVAC system. By adding the elements utilized in DOE, we are now able to effectively create many virtual designs and simulate those designs within the virtual environment to determine whether they pose a viable addition to the existing design. In the past, we would have to rely on tools that were very subjective, such as concept evaluations. Now we can now rely on hard data that is both objective and definitive, and has statistical evidence to support the idea that this general workflow can be replicated in other fashions and produce similar evidence. This evidence should tell us which design could be pursued for possible further optimization, or simply used as-is.

### **6.2 Conclusions**

Ultimately, the objectives set forth in these experiments have been accomplished. In Case Study 1, a viable design has been established for an HVAC component that yields a higher airflow than it would in a normal configuration. We have enough data to conclude which design iteration should be utilized to produce the higher than normal air flow—design “abc”. In Case Study 2, a viable design has also been established for an industrial equipment component that

yields a lesser maximum stress than it would in a normal configuration. We have enough data to conclude which design iteration should be utilized to produce the lower than normal maximum stress—design “a”. Further, the basic steps as outlined earlier, lead to a general model that can be followed and emulated. The generic sequence of design steps is intended to be flexible so that users can customize the method to suit their specific needs.

Further, as a direct result of this research, we now have a generic empirical model of how analysis-led design can be applied. With the application of the DRIVE methodology in the two case studies, we see how the virtual experimentation approach can be scaled to fit the application need.

### **6.3 Future Research**

We have utilized the DRIVE methodology in two case study examples and obtained positive results in both cases. While this has been approached from an industrial equipment design standpoint, the potential applications of the DRIVE methodology can be extended to serve in almost any engineering design related field. The basic principles are suited for tackling challenging engineering design problems where many factors combine to determine the performance of the particular component on a system level. Such applications can be explored in future research. Not only is the DRIVE methodology well suited for component level design, but it is also adaptable so that a complete system can be analyzed such as an entire machine functional group or even a complete piece of equipment. Ultimately, the options are only limited by what is within the realm of thought.

We can further corroborate the results of the DRIVE methodology by building the products of the case studies that have been discussed. Actual physical testing in this case will serve as a validation tool to show how effective the methodology can be.

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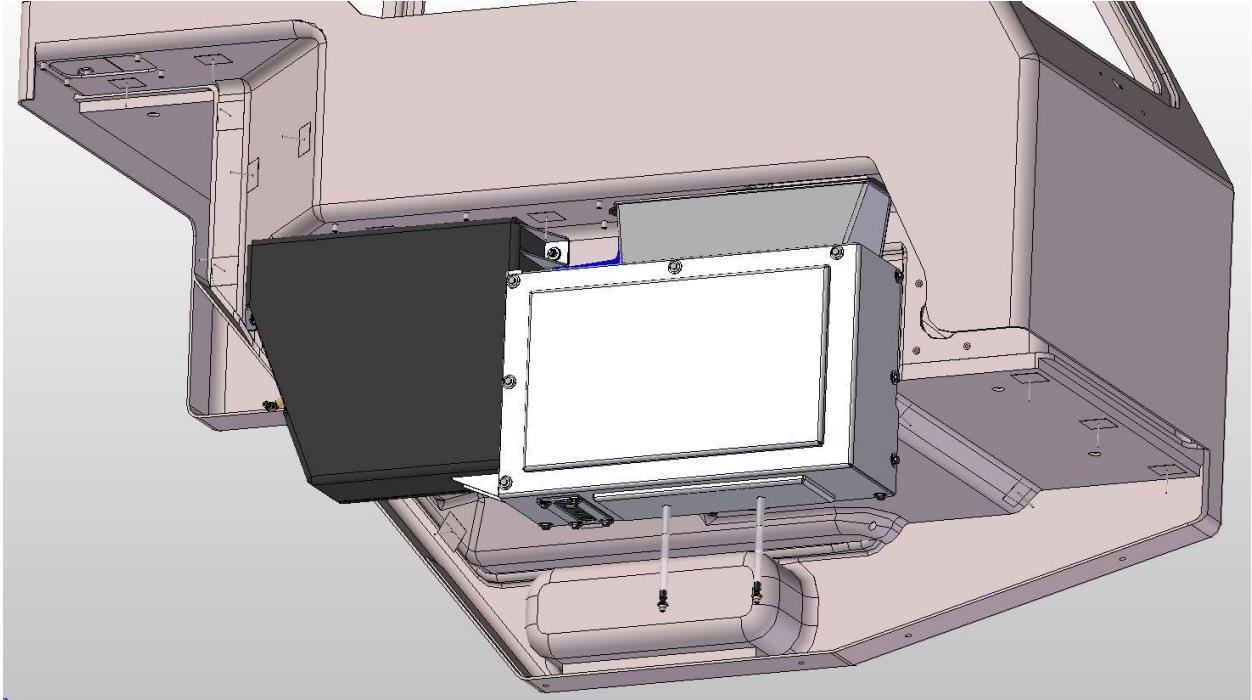


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## Appendix I – Case Study 1 Supplemental Application Images

Area of installation for HVAC box (CAD render)



Side view of HVAC box assembly (CAD render)

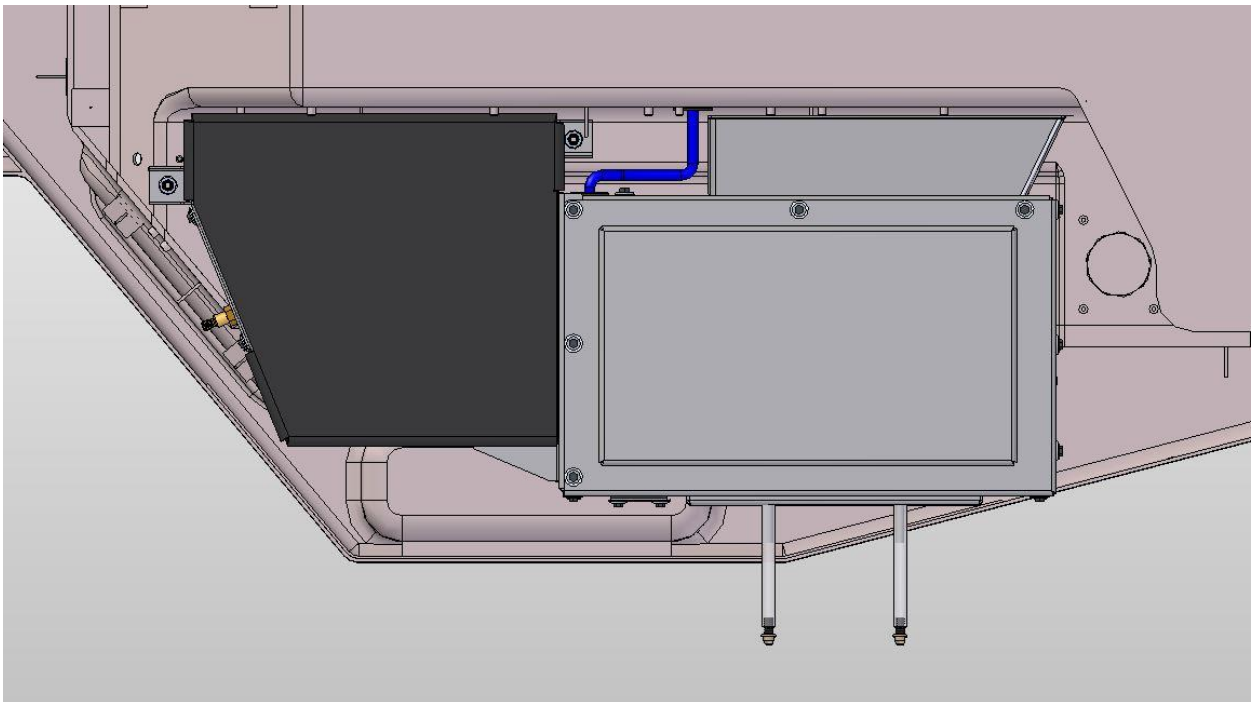
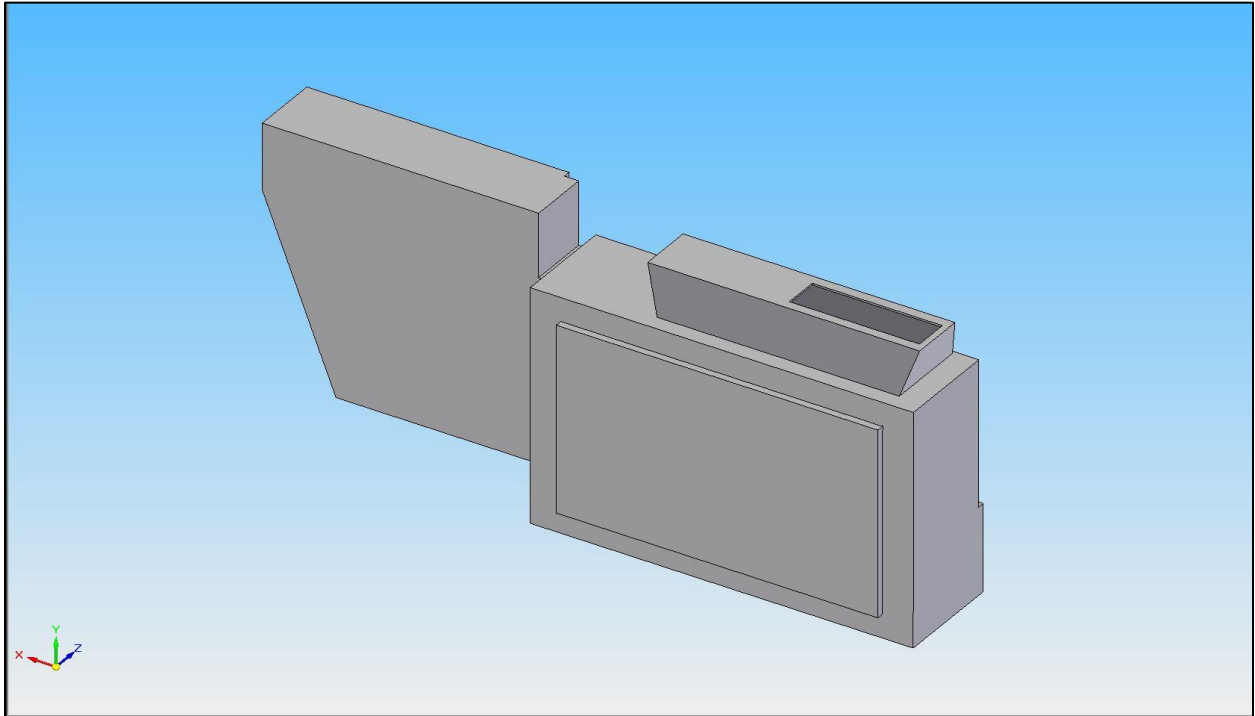


Photo of actual HVAC enclosure installation

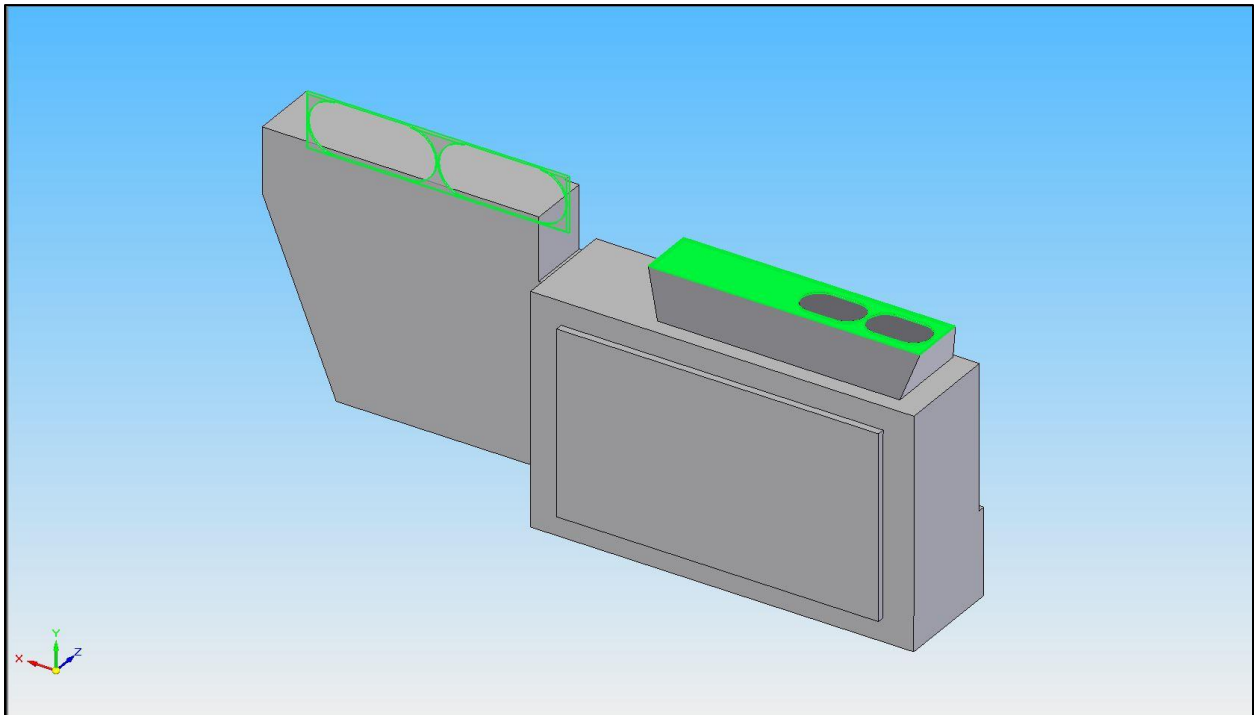


## Appendix II - CAD Geometry for CFD Analysis

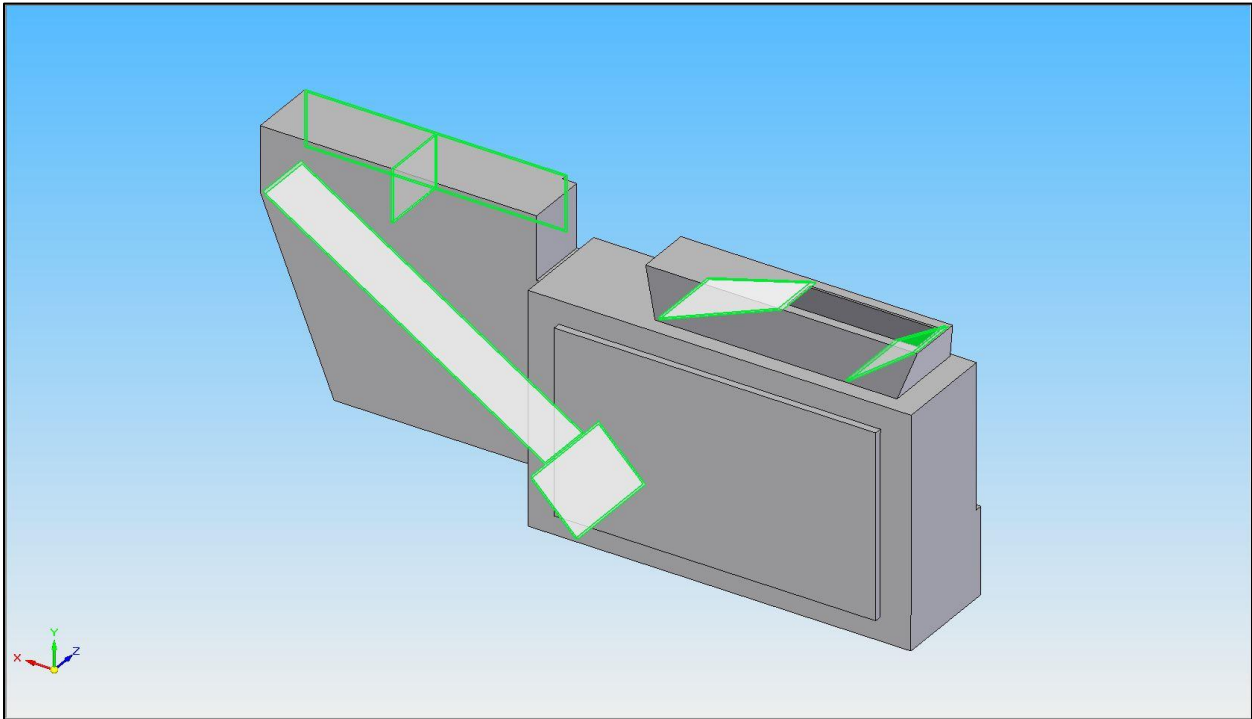
Treatment “(1)” CAD Geometry



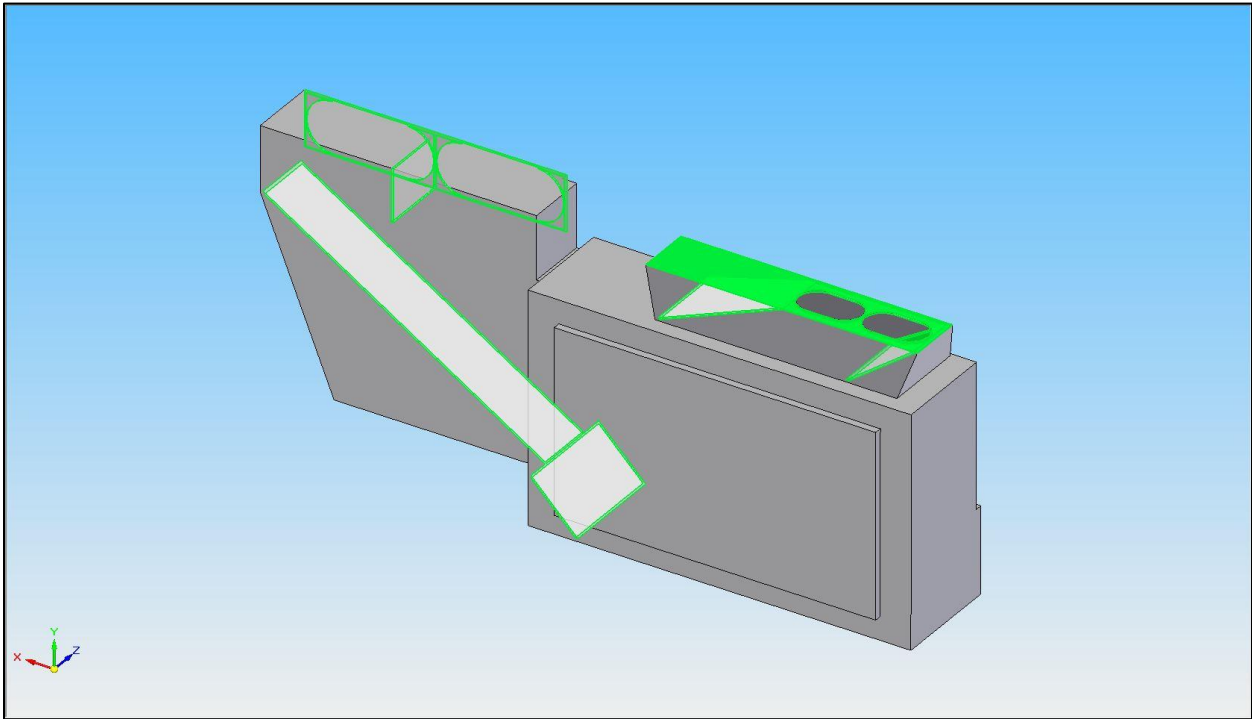
Treatment “a” CAD Geometry



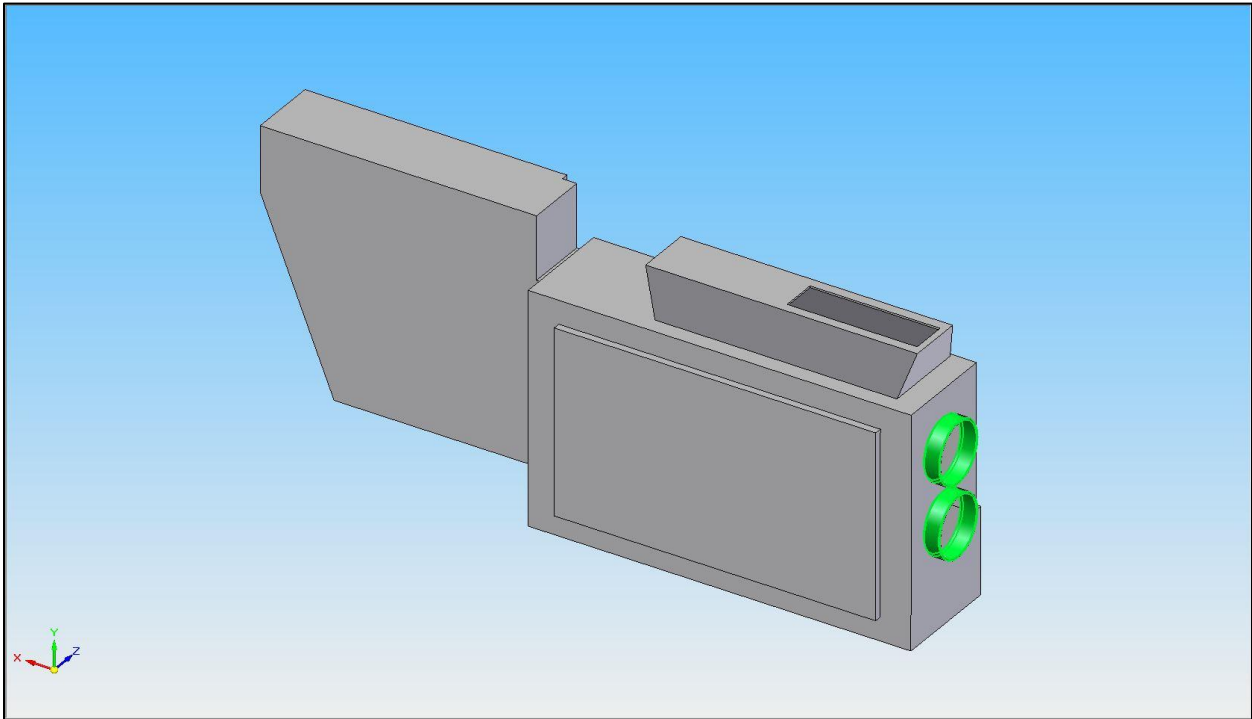
Treatment “b” CAD Geometry



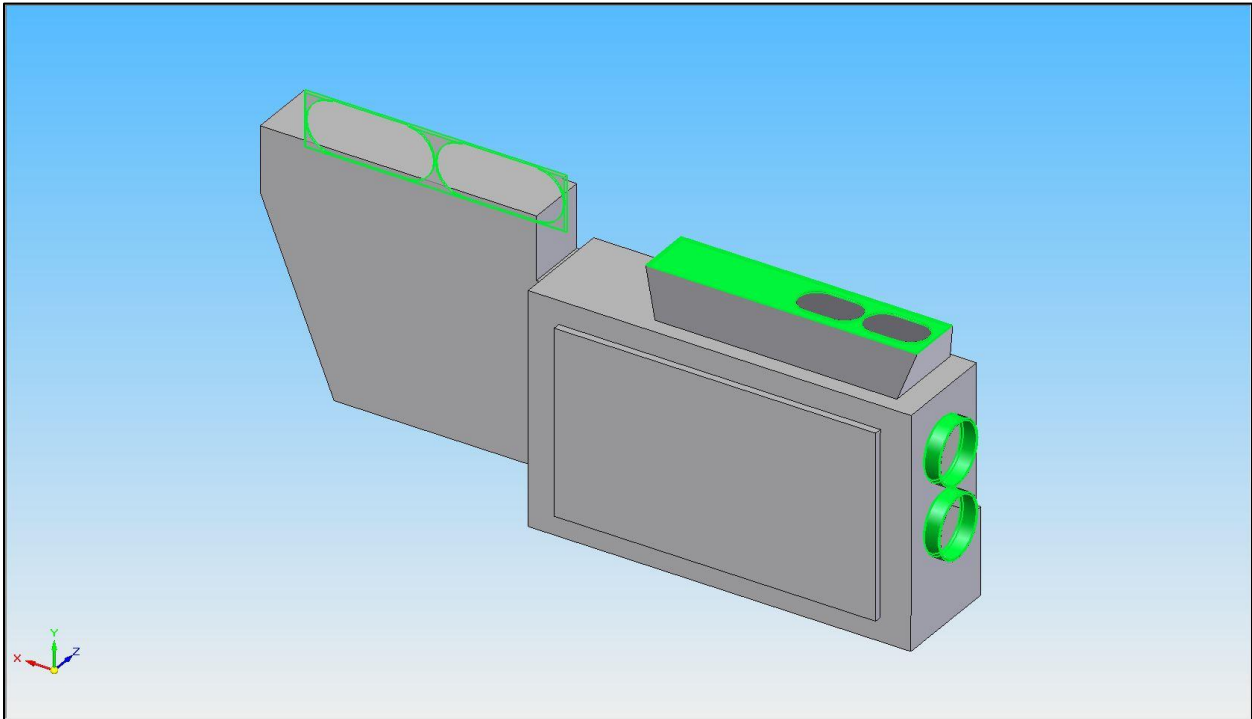
Treatment “ab” CAD Geometry



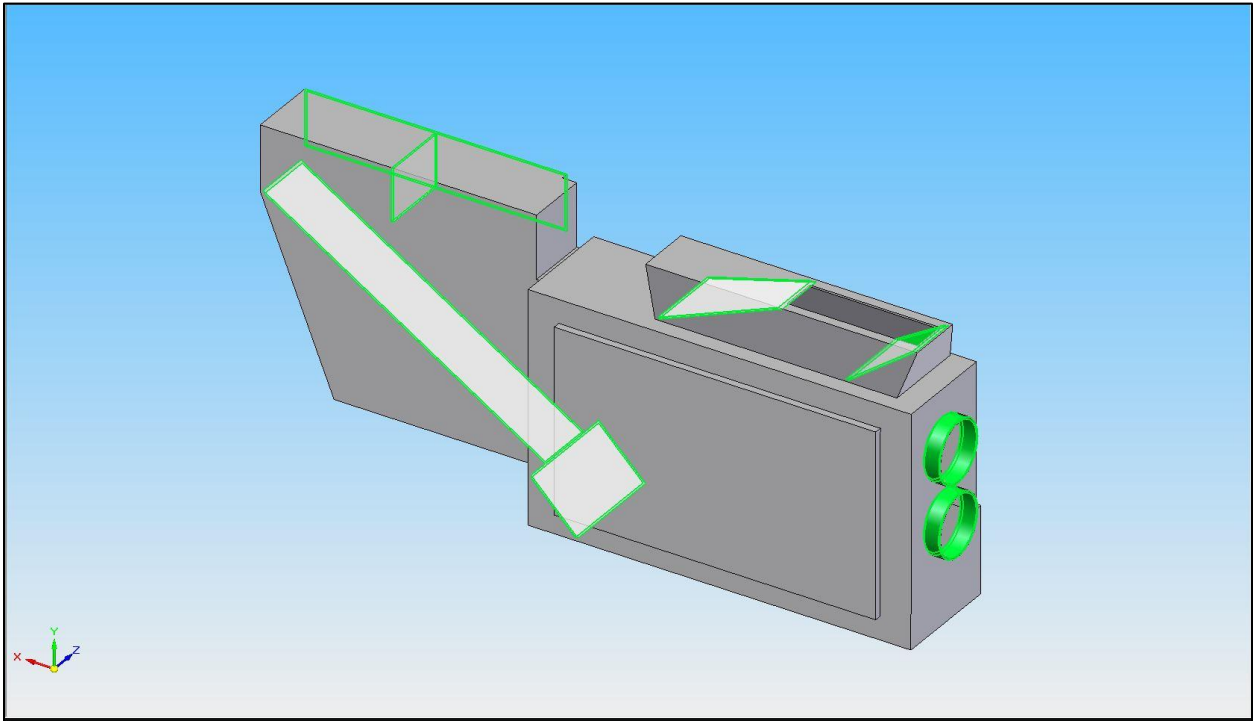
Treatment “c” CAD Geometry



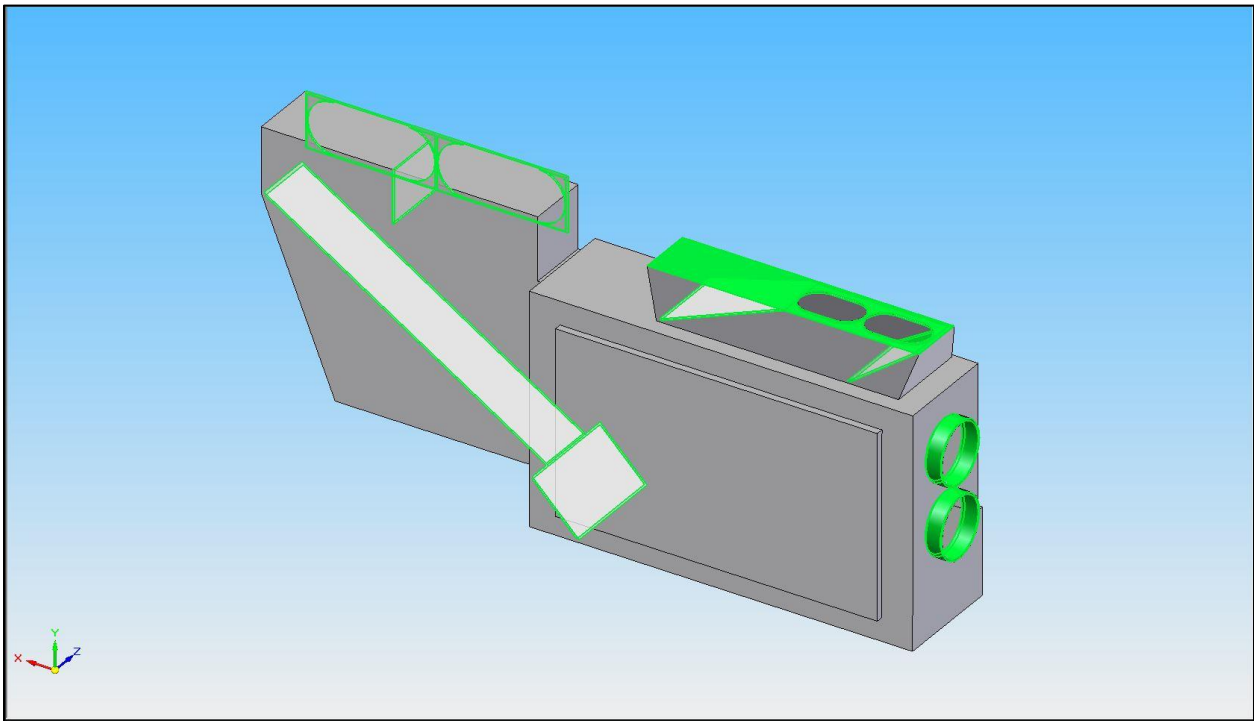
Treatment “ac” CAD Geometry



Treatment “bc” CAD Geometry



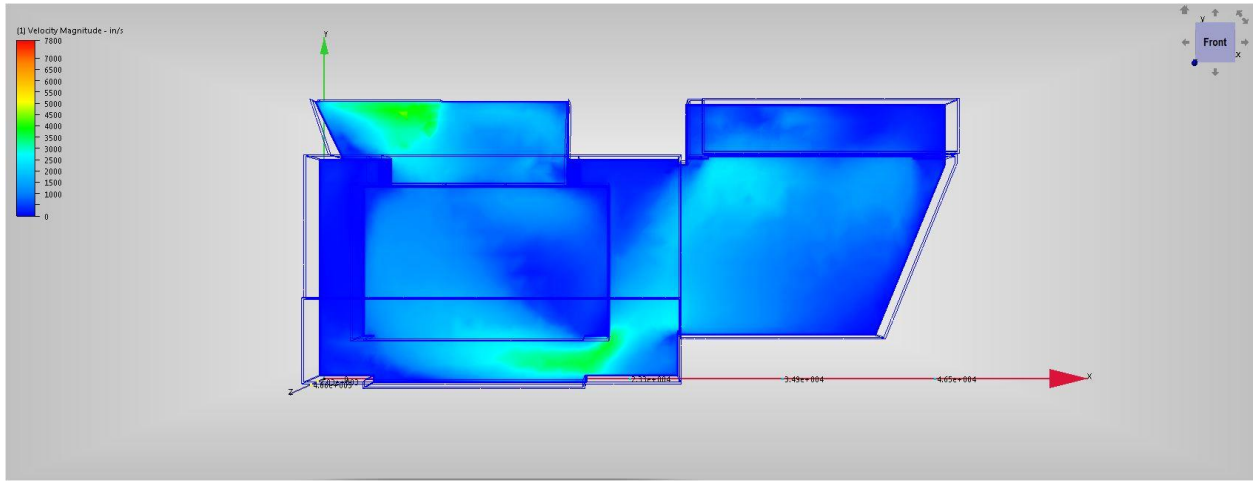
Treatment “abc” CAD Geometry



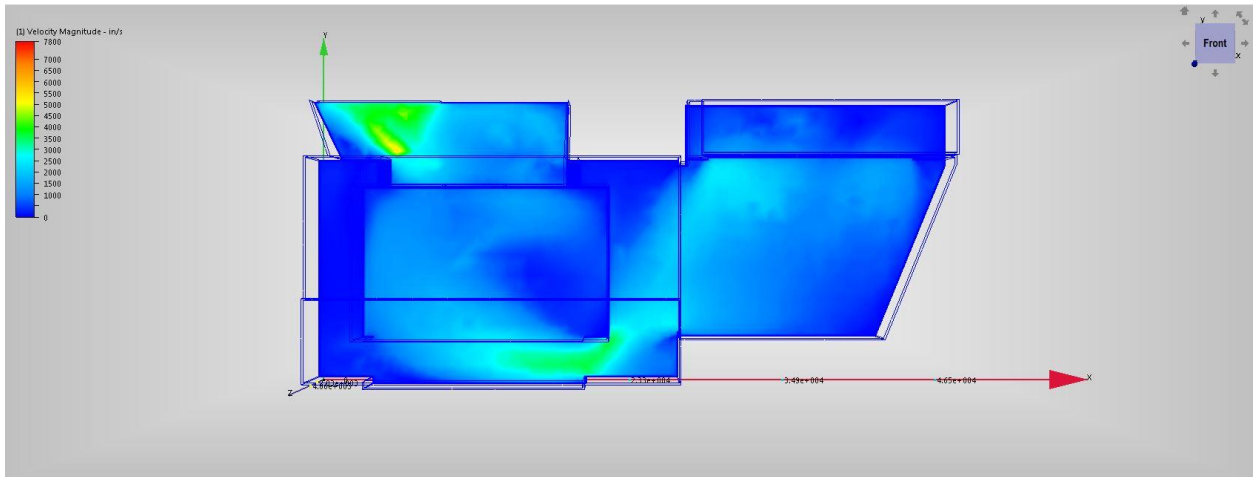


# Appendix III – CFD Airflow Velocity Diagrams

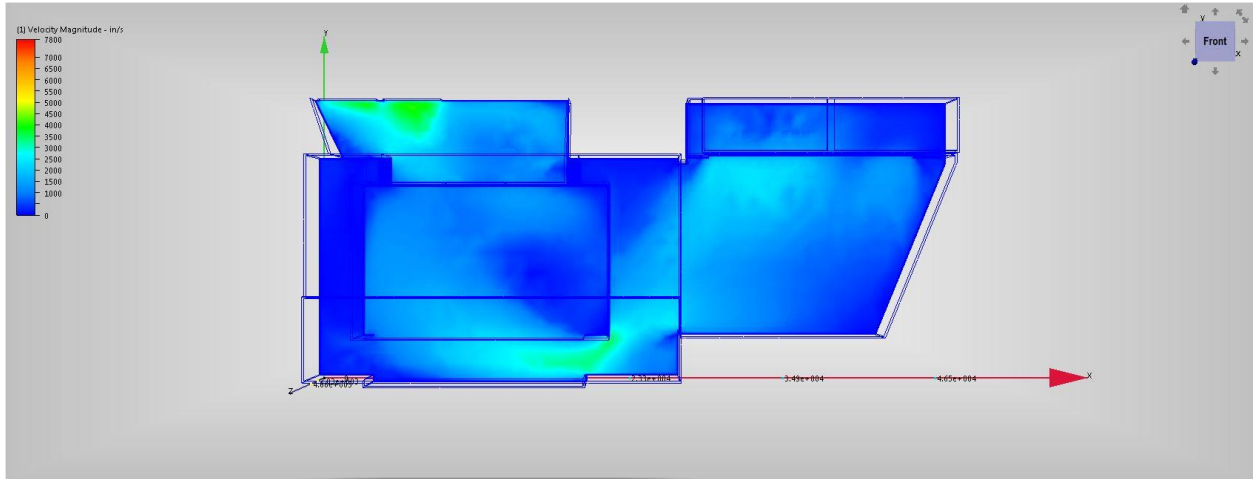
Treatment “(1)” CFD Airflow Velocity Diagram, 0.99 Resolution



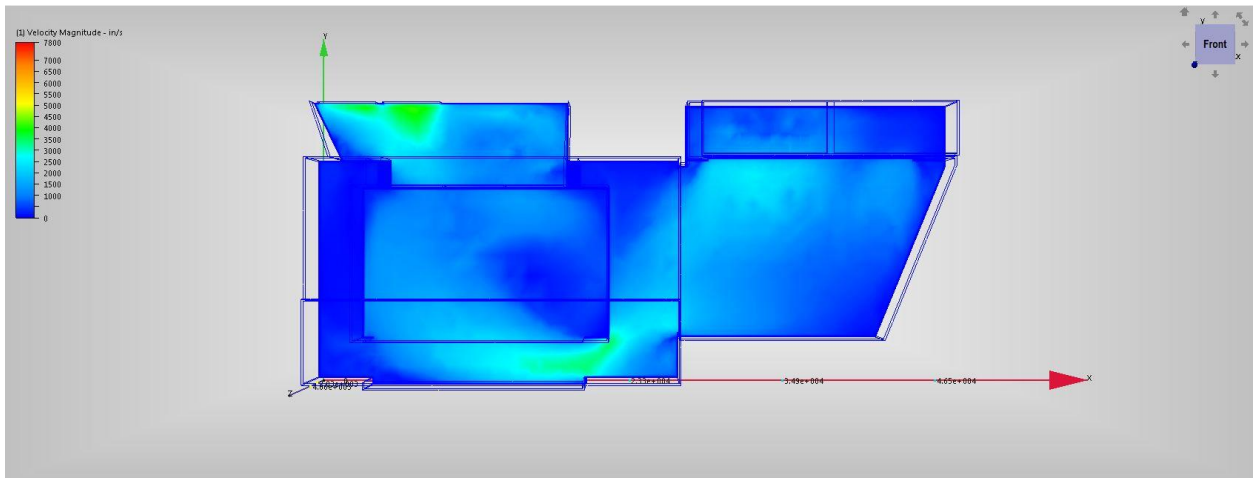
Treatment “(1)” CFD Airflow Velocity Diagram, 1.00 Resolution



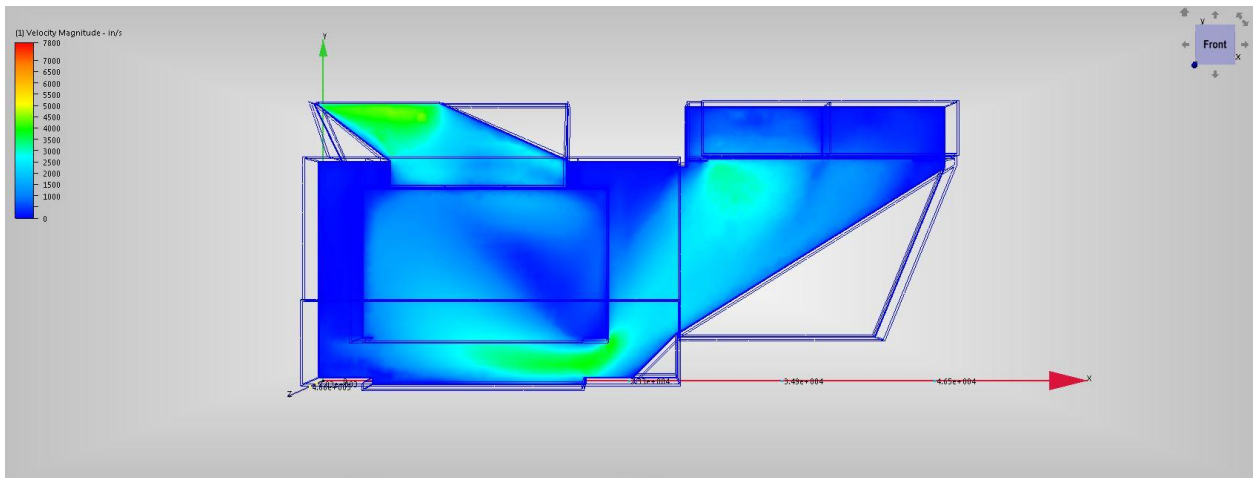
Treatment "a" CFD Airflow Velocity Diagram, 0.99 Resolution



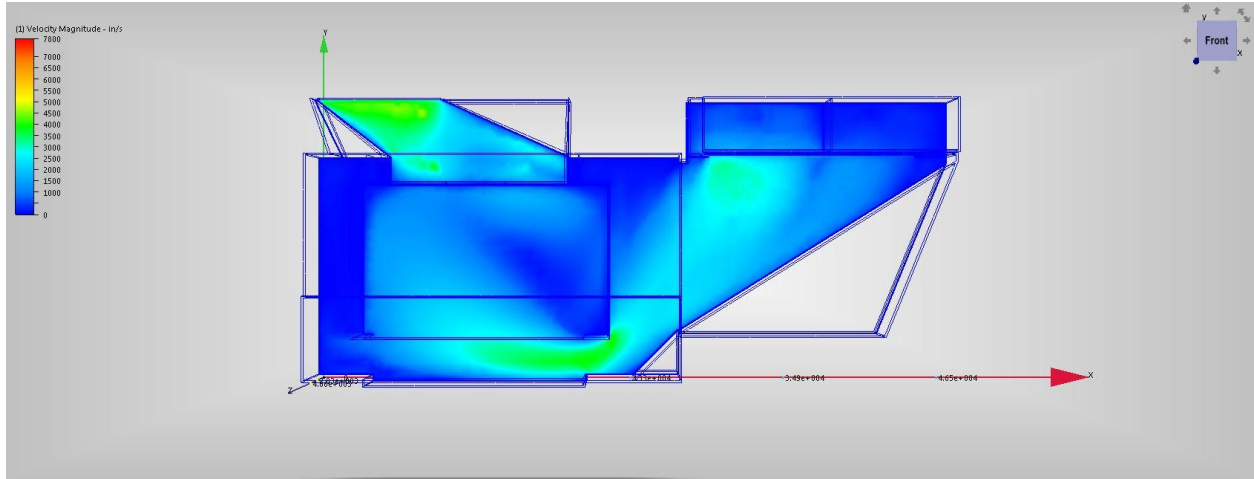
Treatment "a" CFD Airflow Velocity Diagram, 1.00 Resolution



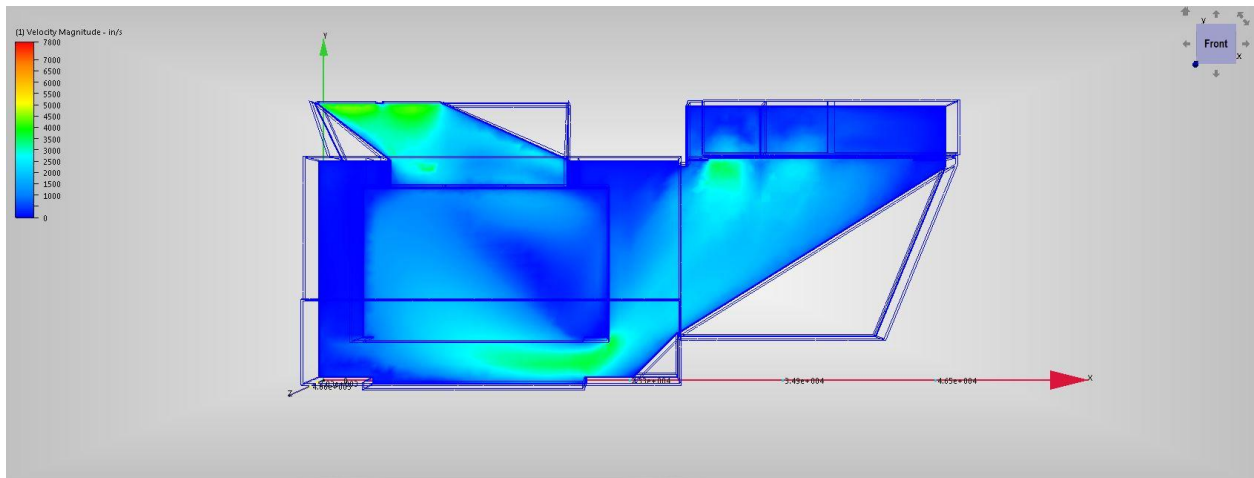
Treatment "b" CFD Airflow Velocity Diagram, 0.99 Resolution



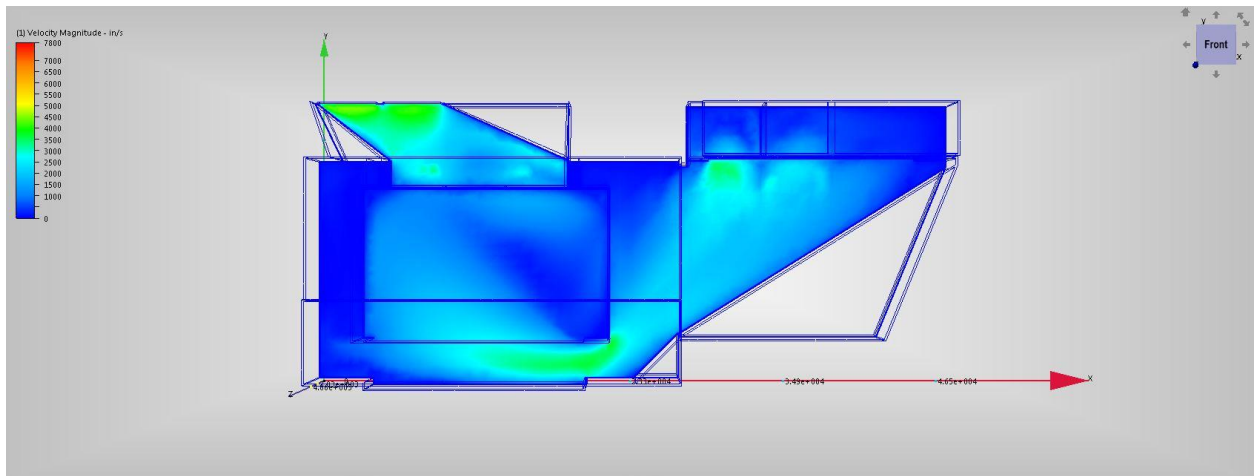
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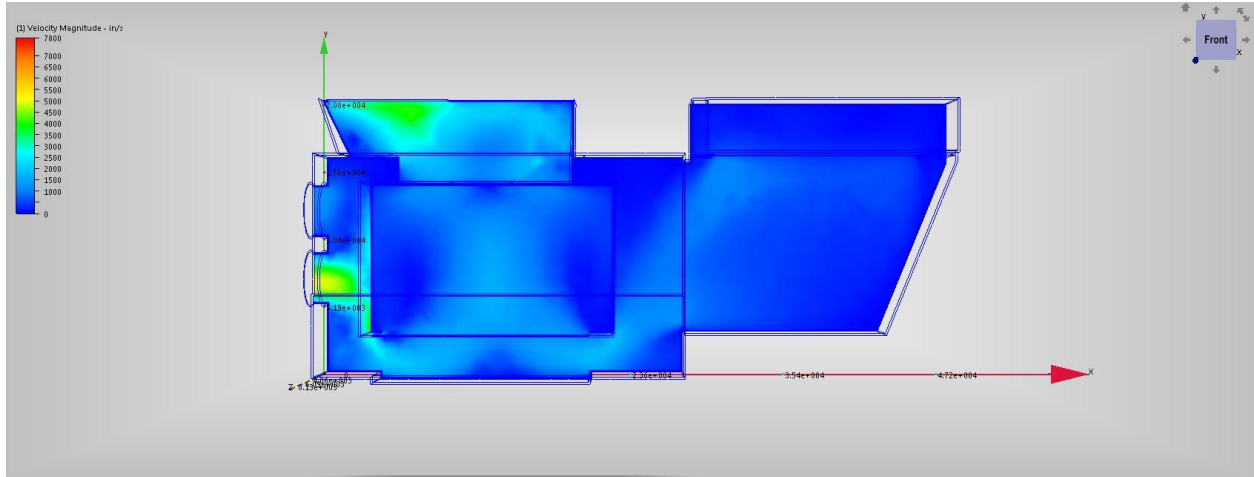
Treatment “ab” CFD Airflow Velocity Diagram, 0.99 Resolution



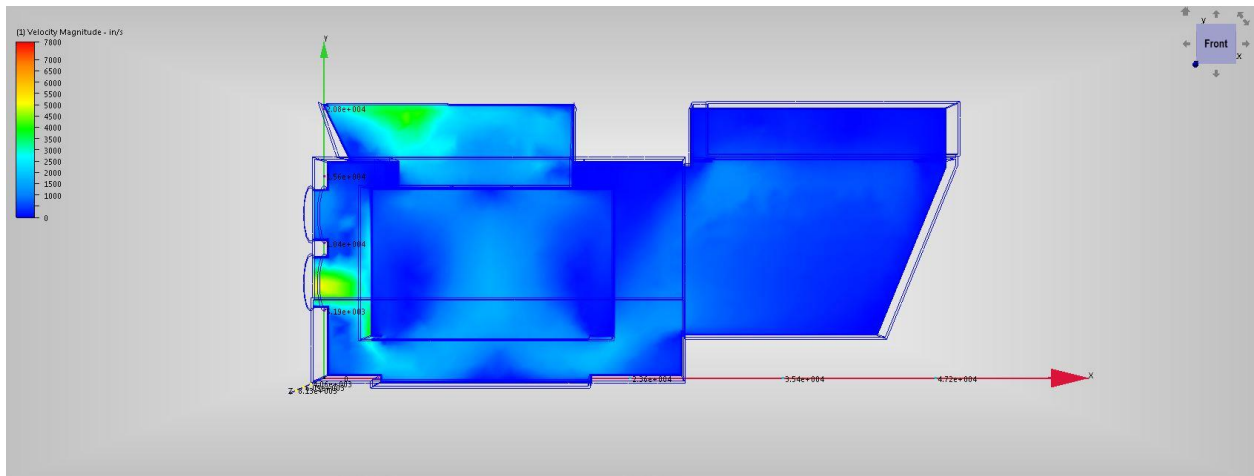
Treatment “ab” CFD Airflow Velocity Diagram, 1.00 Resolution



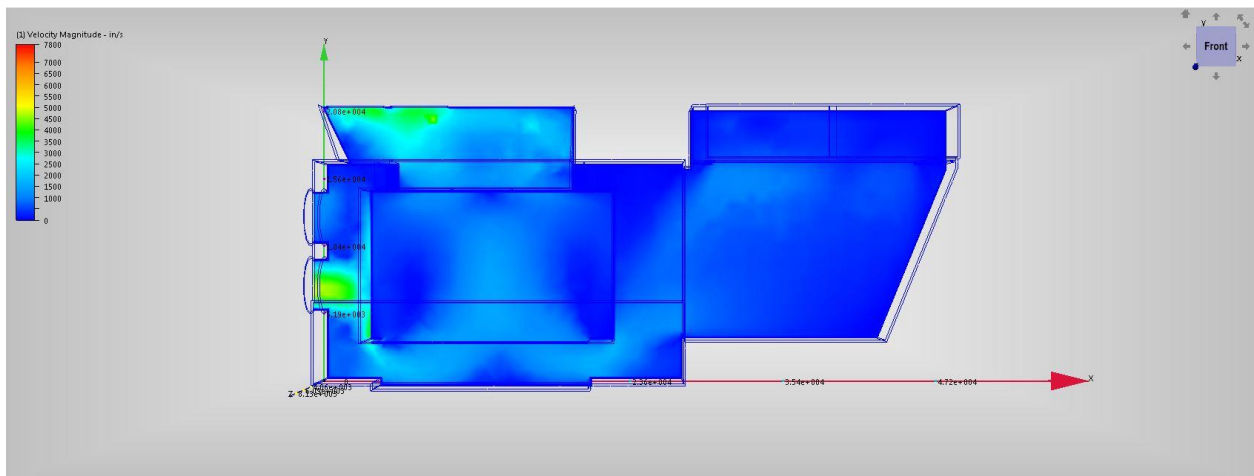
Treatment “c” CFD Airflow Velocity Diagram, 0.99 Resolution



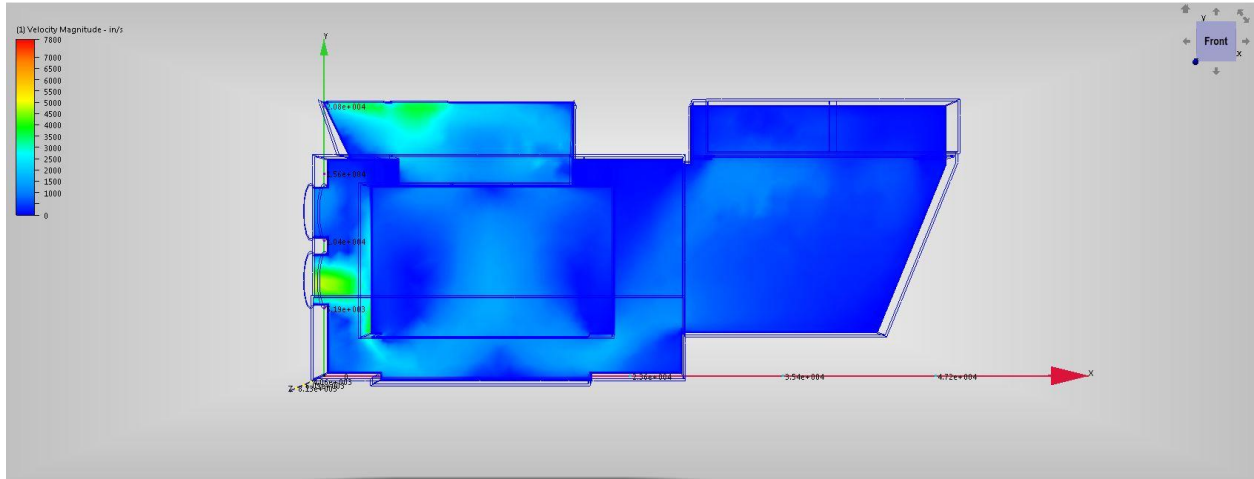
Treatment “c” CFD Airflow Velocity Diagram, 1.00 Resolution



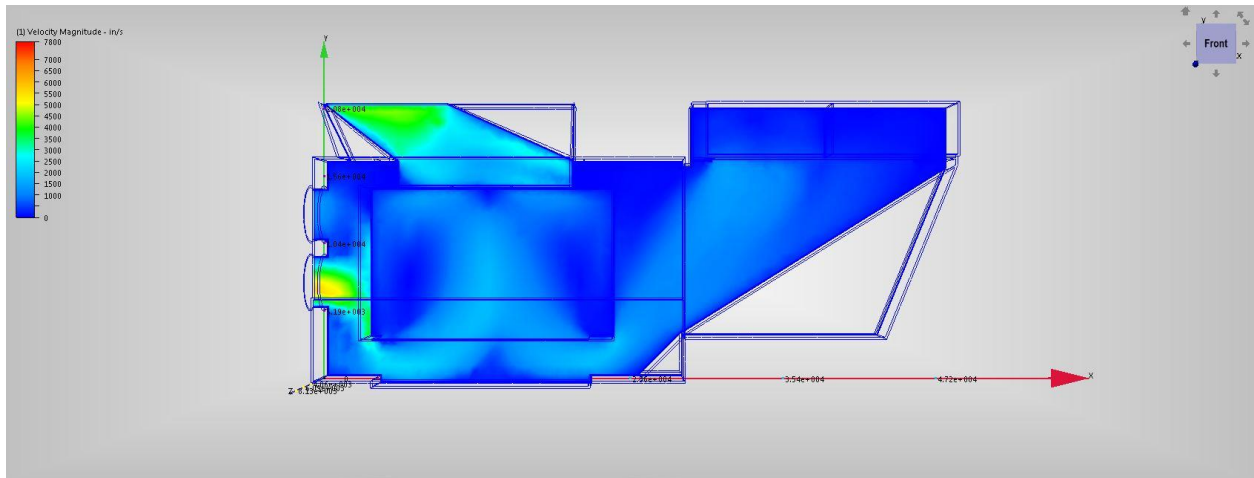
Treatment “ac” CFD Airflow Velocity Diagram, 0.99 Resolution



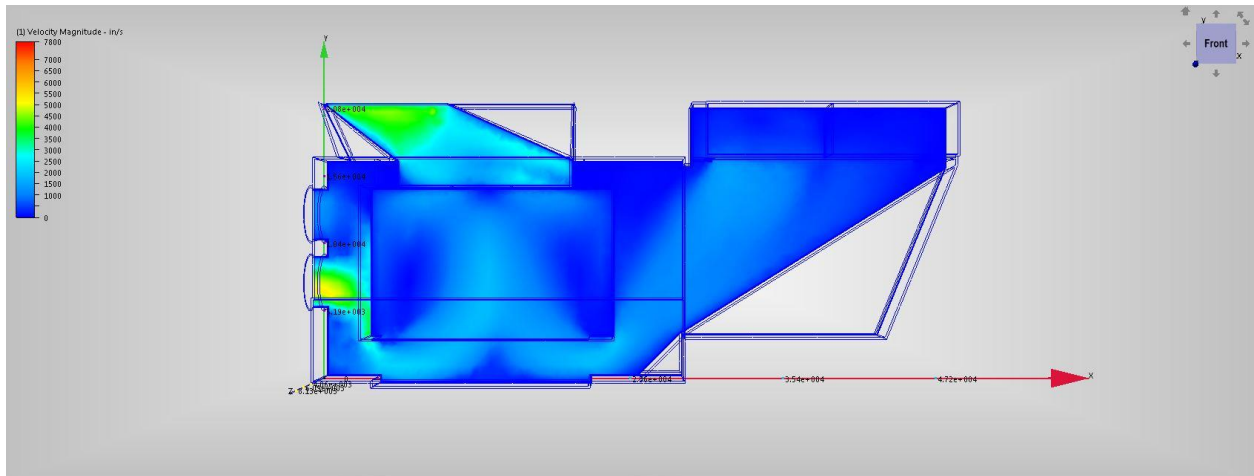
Treatment “ac” CFD Airflow Velocity Diagram, 1.00 Resolution



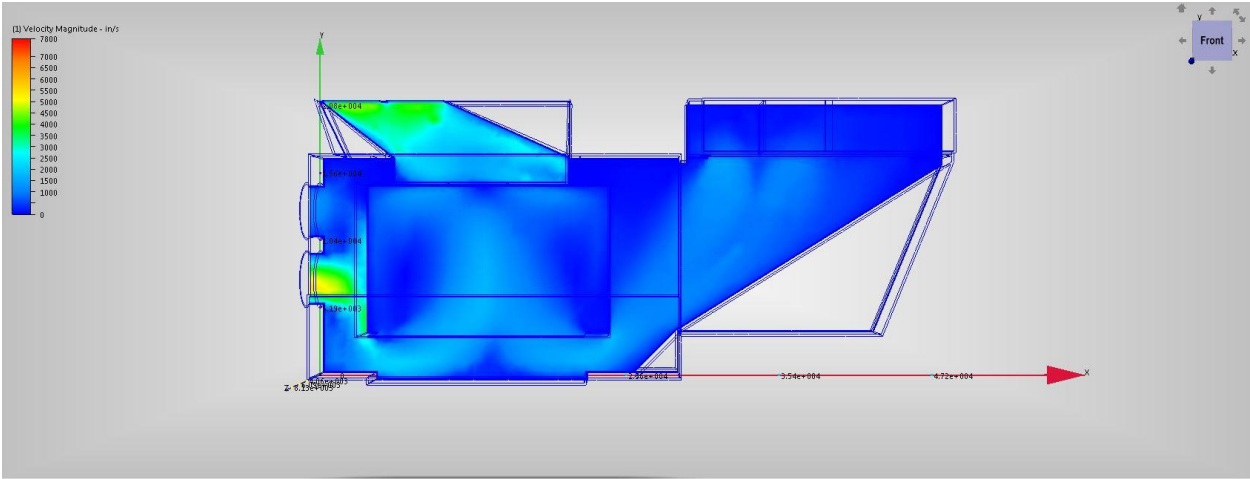
Treatment “bc” CFD Airflow Velocity Diagram, 0.99 Resolution



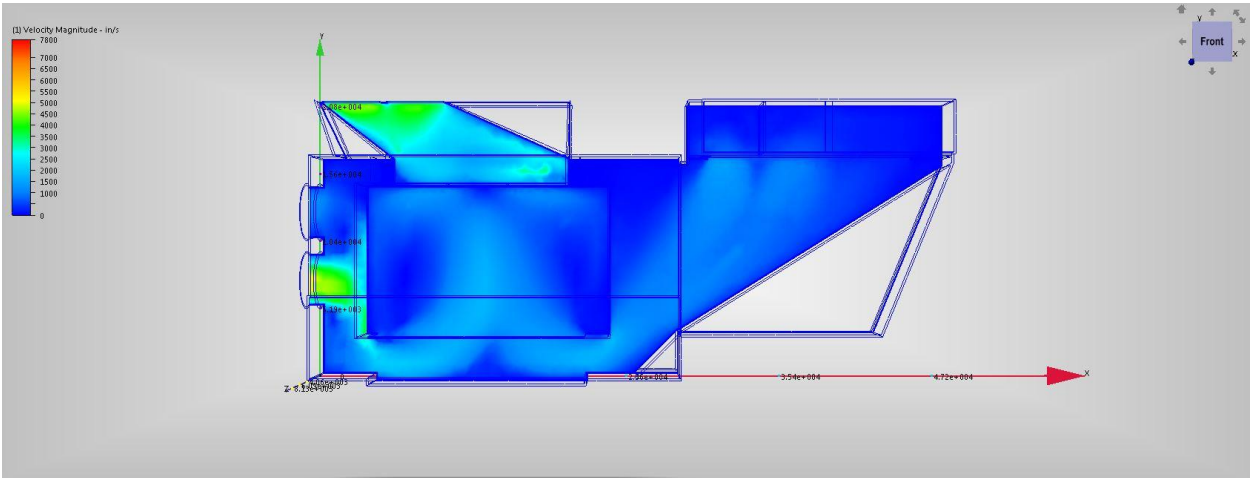
Treatment “bc” CFD Airflow Velocity Diagram, 1.00 Resolution



Treatment “abc” CFD Airflow Velocity Diagram, 0.99 Resolution



Treatment “abc” CFD Airflow Velocity Diagram, 1.00 Resolution



## Appendix IV - Statistical Analysis Results: Air Speed

### Factorial Regression: Air Speed versus A, B, C

#### Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	7	13369754	98.09%	13369754	1909965	58.81	0.000
Linear	3	10921583	80.13%	10921583	3640528	112.09	0.000
A	1	338259	2.48%	338259	338259	10.41	0.012
B	1	1556905	11.42%	1556905	1556905	47.94	0.000
C	1	9026419	66.23%	9026419	9026419	277.92	0.000
2-Way Interactions	3	2140380	15.70%	2140380	713460	21.97	0.000
A*B	1	332808	2.44%	332808	332808	10.25	0.013
A*C	1	1187108	8.71%	1187108	1187108	36.55	0.000
B*C	1	620463	4.55%	620463	620463	19.10	0.002
3-Way Interactions	1	307792	2.26%	307792	307792	9.48	0.015
A*B*C	1	307792	2.26%	307792	307792	9.48	0.015
Error	8	259825	1.91%	259825	32478		
Total	15	13629579	100.00%				

#### Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
180.217	98.09%	96.43%	1039299	92.37%

#### Coded Coefficients

Term	Effect	Coef	SE Coef	99% CI	T-Value	P-Value	VIF
Constant		5839.1	45.1	(5687.9, 5990.3)	129.60	0.000	
A	-290.8	-145.4	45.1	(-296.6, 5.8)	-3.23	0.012	1.00
B	623.9	311.9	45.1	( 160.8, 463.1)	6.92	0.000	1.00
C	1502.2	751.1	45.1	( 599.9, 902.3)	16.67	0.000	1.00
A*B	288.4	144.2	45.1	( -7.0, 295.4)	3.20	0.013	1.00
A*C	544.8	272.4	45.1	( 121.2, 423.6)	6.05	0.000	1.00
B*C	393.8	196.9	45.1	( 45.7, 348.1)	4.37	0.002	1.00
A*B*C	277.4	138.7	45.1	( -12.5, 289.9)	3.08	0.015	1.00

#### Regression Equation in Uncoded Units

$$\text{Air Speed} = 5839.1 - 145.4 A + 311.9 B + 751.1 C + 144.2 A*B + 272.4 A*C + 196.9 B*C + 138.7 A*B*C$$

#### Alias Structure

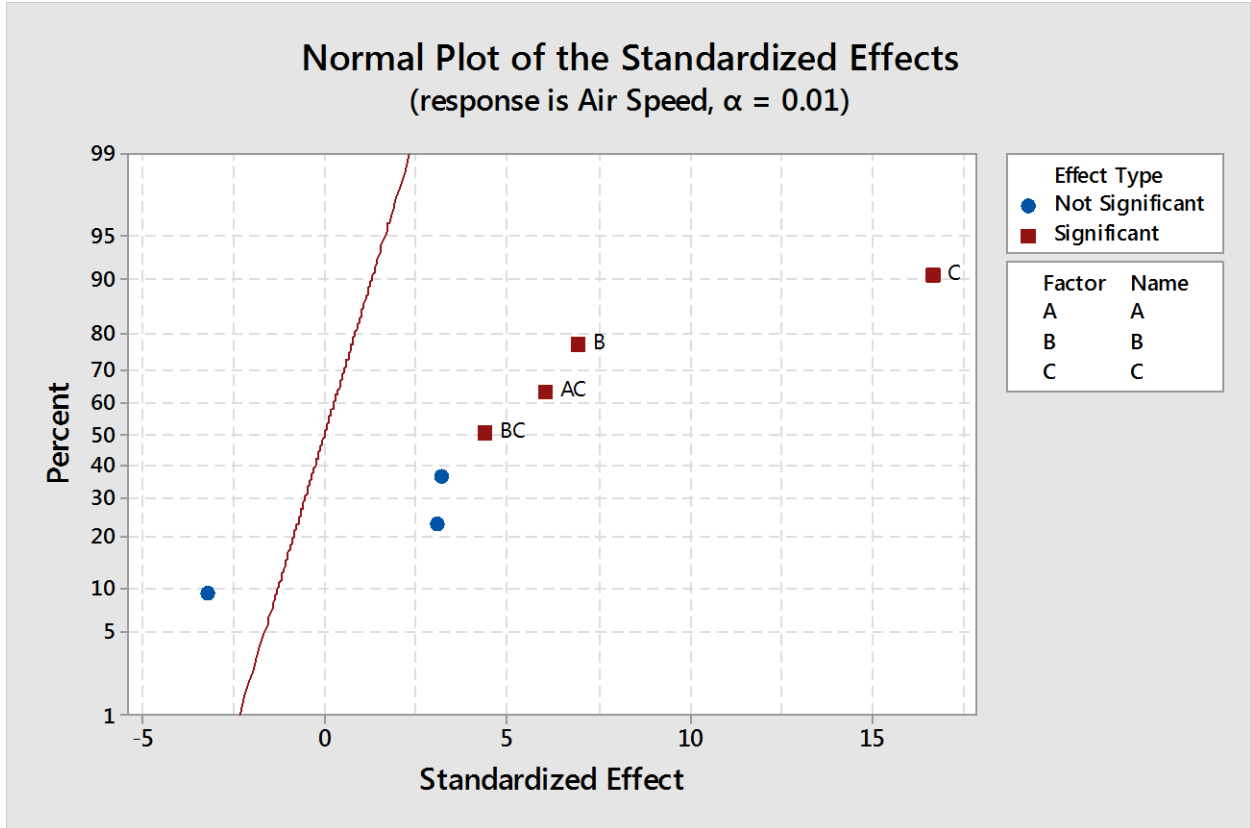
##### Factor Name

A	A
B	B
C	C

#### Aliases

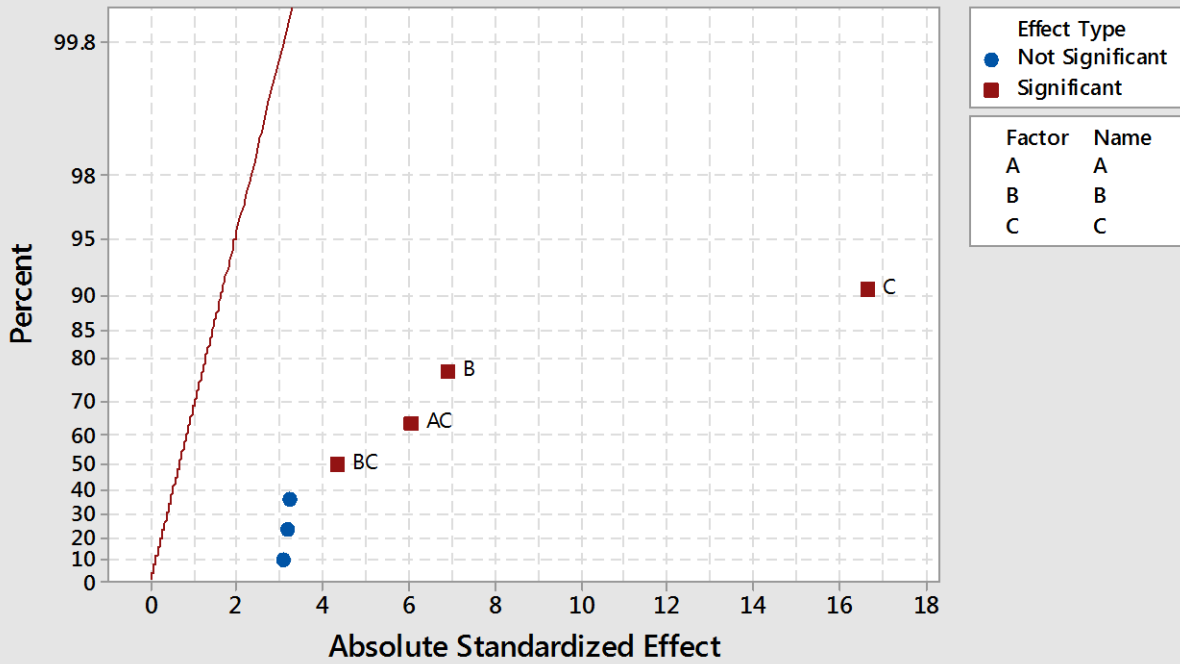
I  
A  
B

C  
AB  
AC  
BC  
ABC

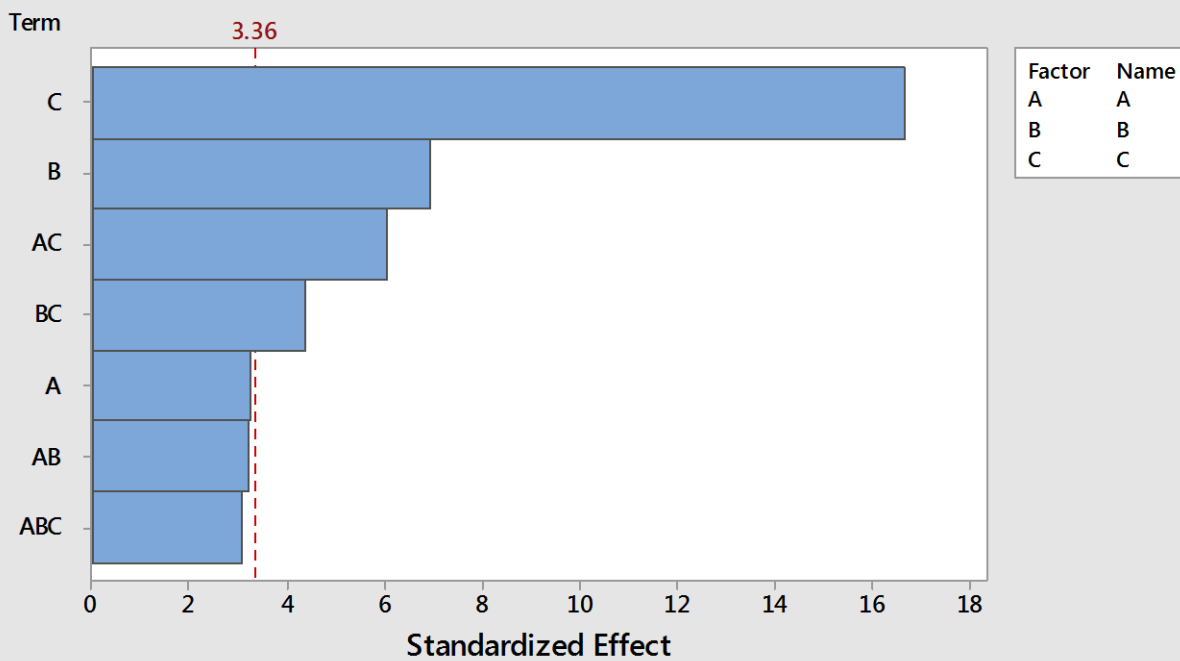




Half Normal Plot of the Standardized Effects  
(response is Air Speed,  $\alpha = 0.01$ )

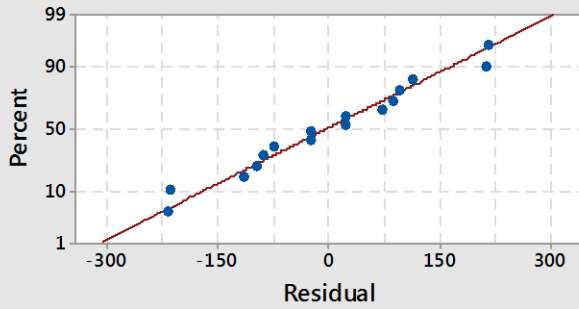


Pareto Chart of the Standardized Effects  
(response is Air Speed,  $\alpha = 0.01$ )

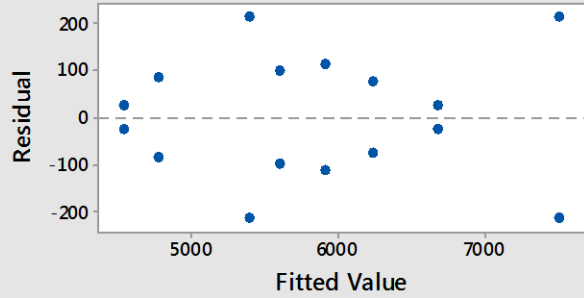


# Residual Plots for Air Speed

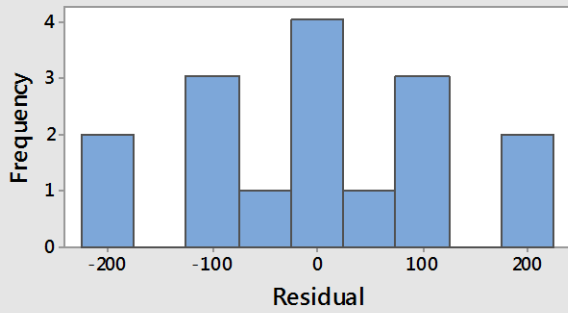
### Normal Probability Plot



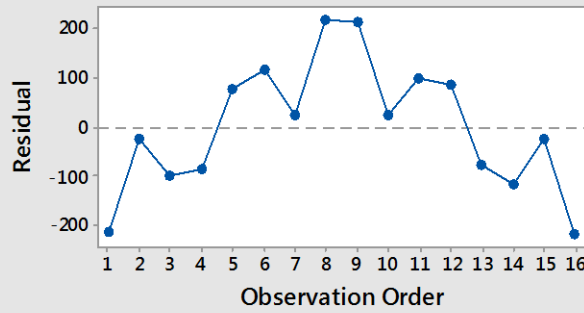
### Versus Fits

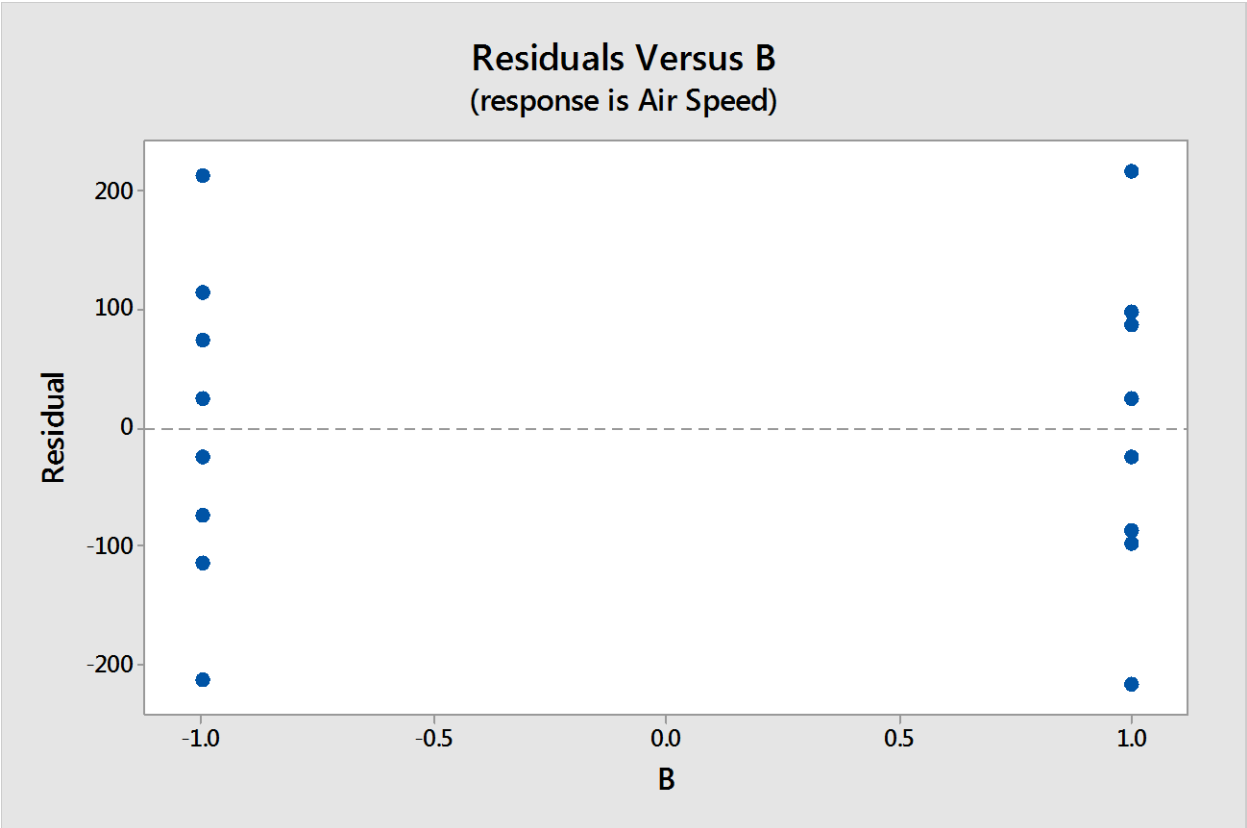
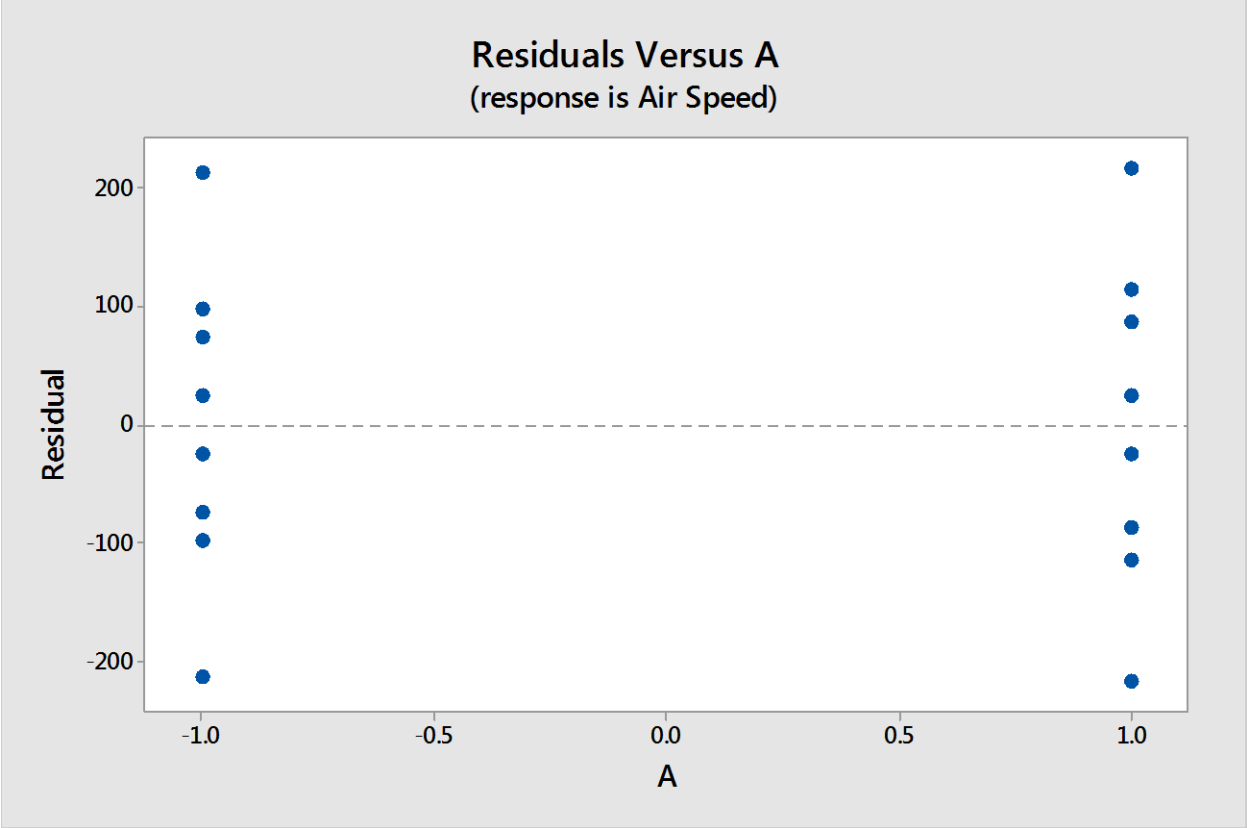


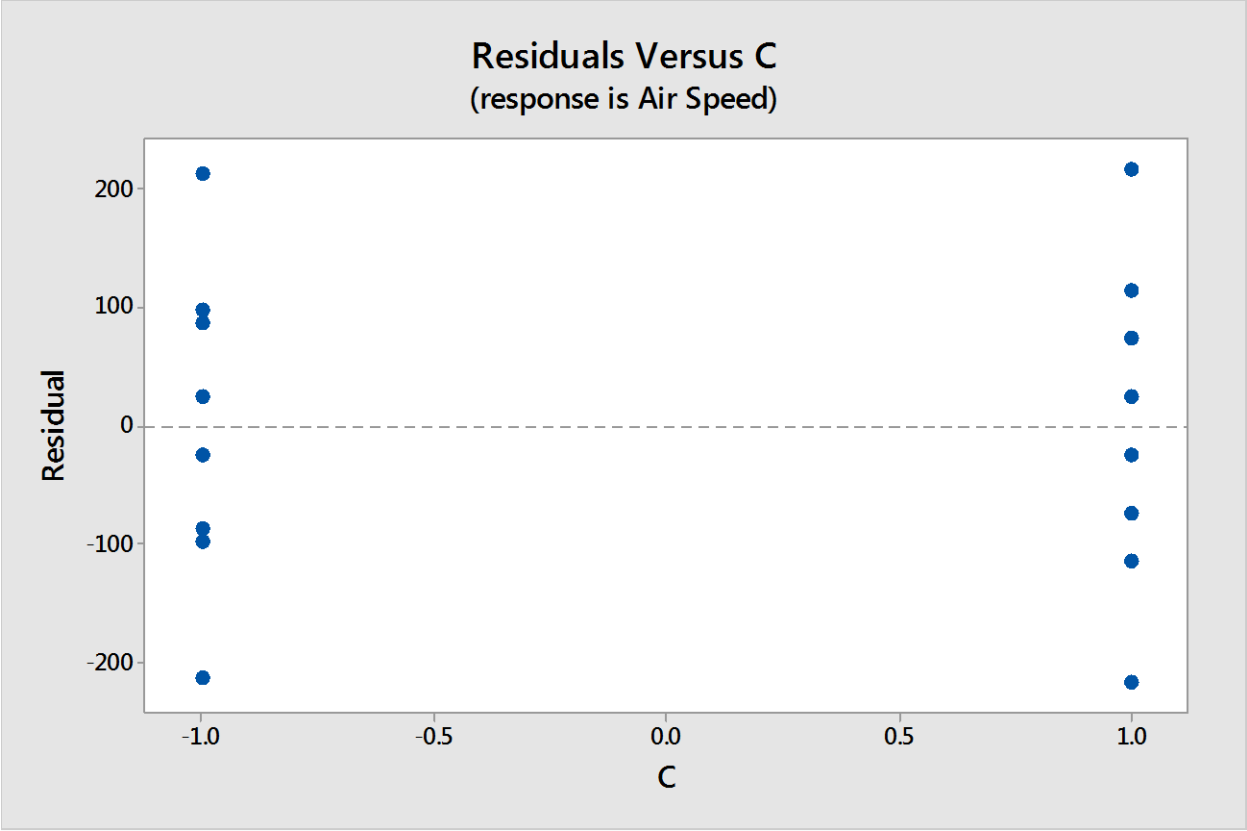
### Histogram



### Versus Order







## Response Optimization: Air Speed

### Parameters

Response	Goal	Lower	Target	Upper	Weight	Importance
Air Speed	Maximum	4525.54	7725.96		1	1

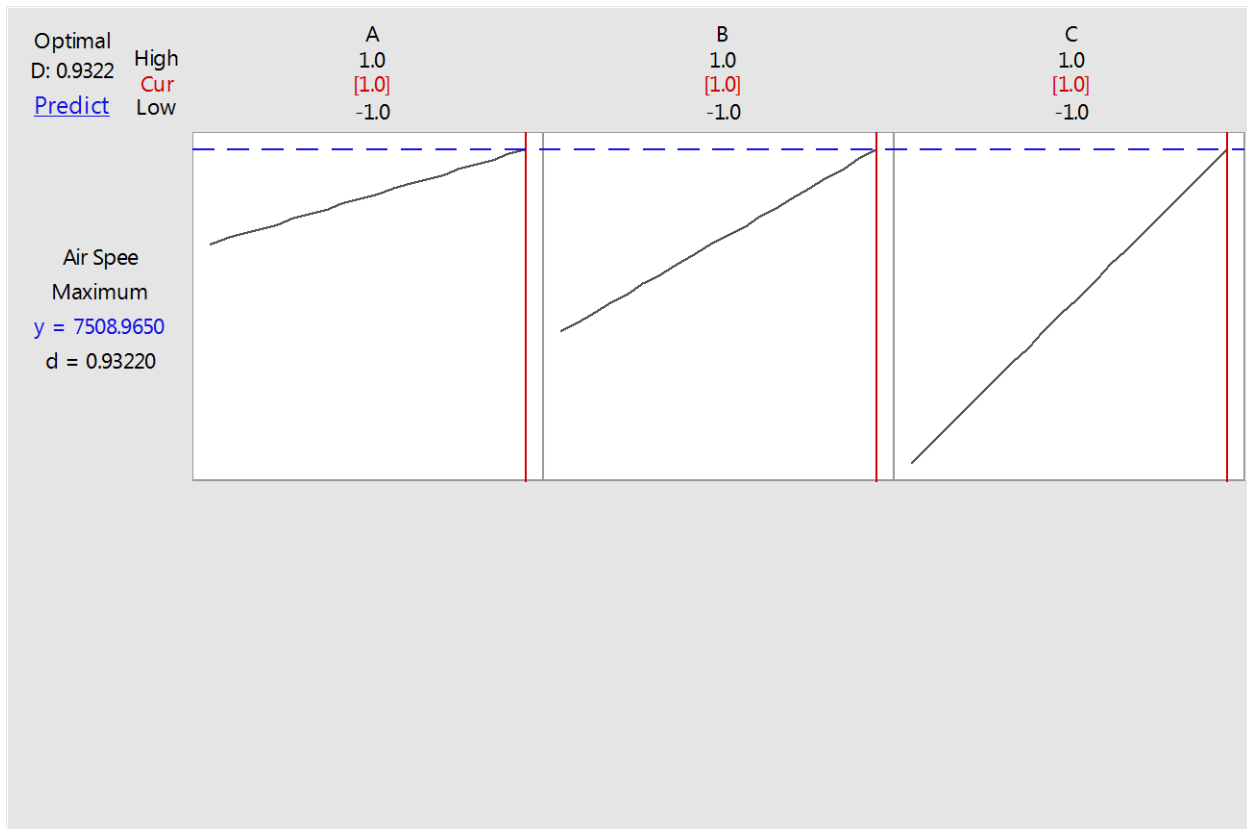
### Solution

Solution	Air Speed			Fit	Composite Desirability
	A	B	C		
1	1	1	1	7508.97	0.932198

### Multiple Response Prediction

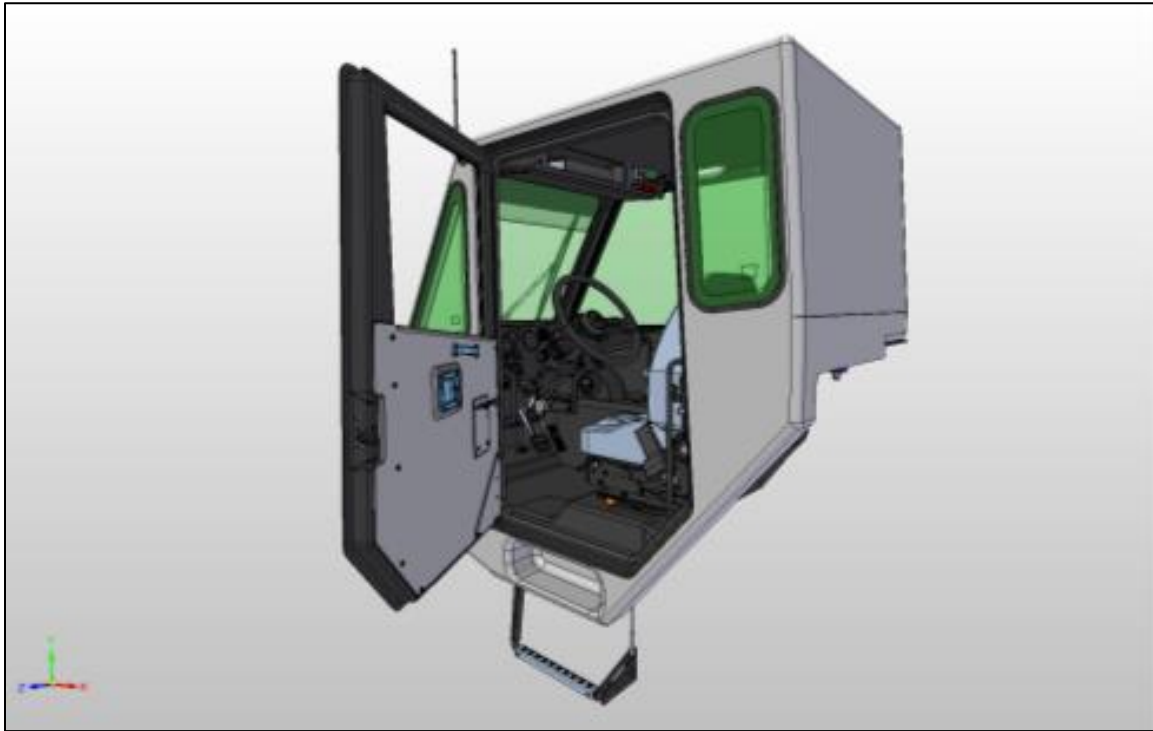
Variable	Setting
A	1
B	1
C	1

Response	Fit	SE Fit	95% CI	95% PI
Air Speed	7509	127	(7215, 7803)	(7000, 8018)



## Appendix V – Case Study 2 Supplemental Application Images

External view of driver's cabin (CAD render)



View of driver's cabin entry point (CAD render)



Photo of driver's cabin entry point



View of Driver's Cabin Interior (CAD render)



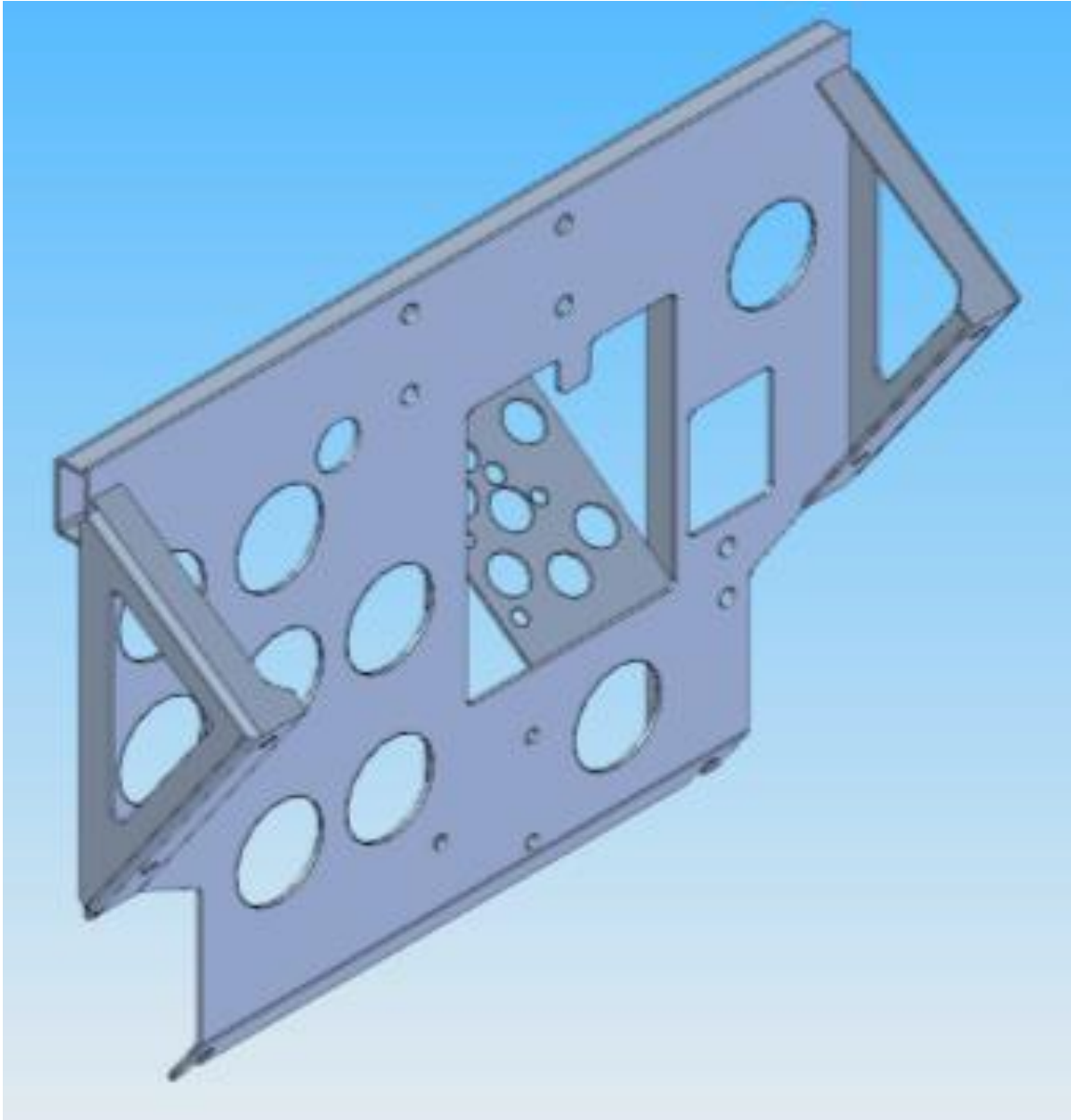
View of Steer Column Sub-Assembly



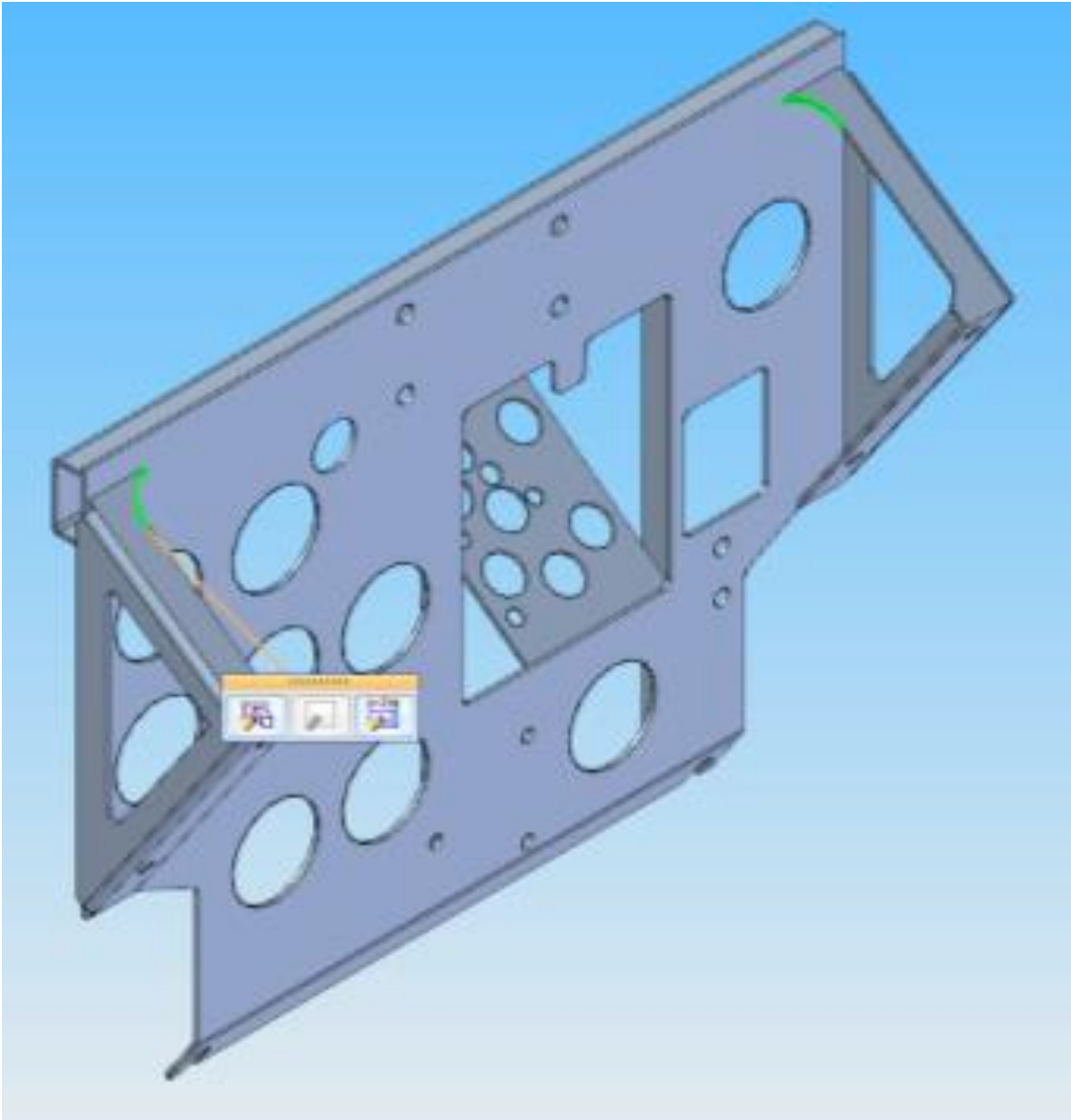


## Appendix VI – CAD Geometry for FEA analysis

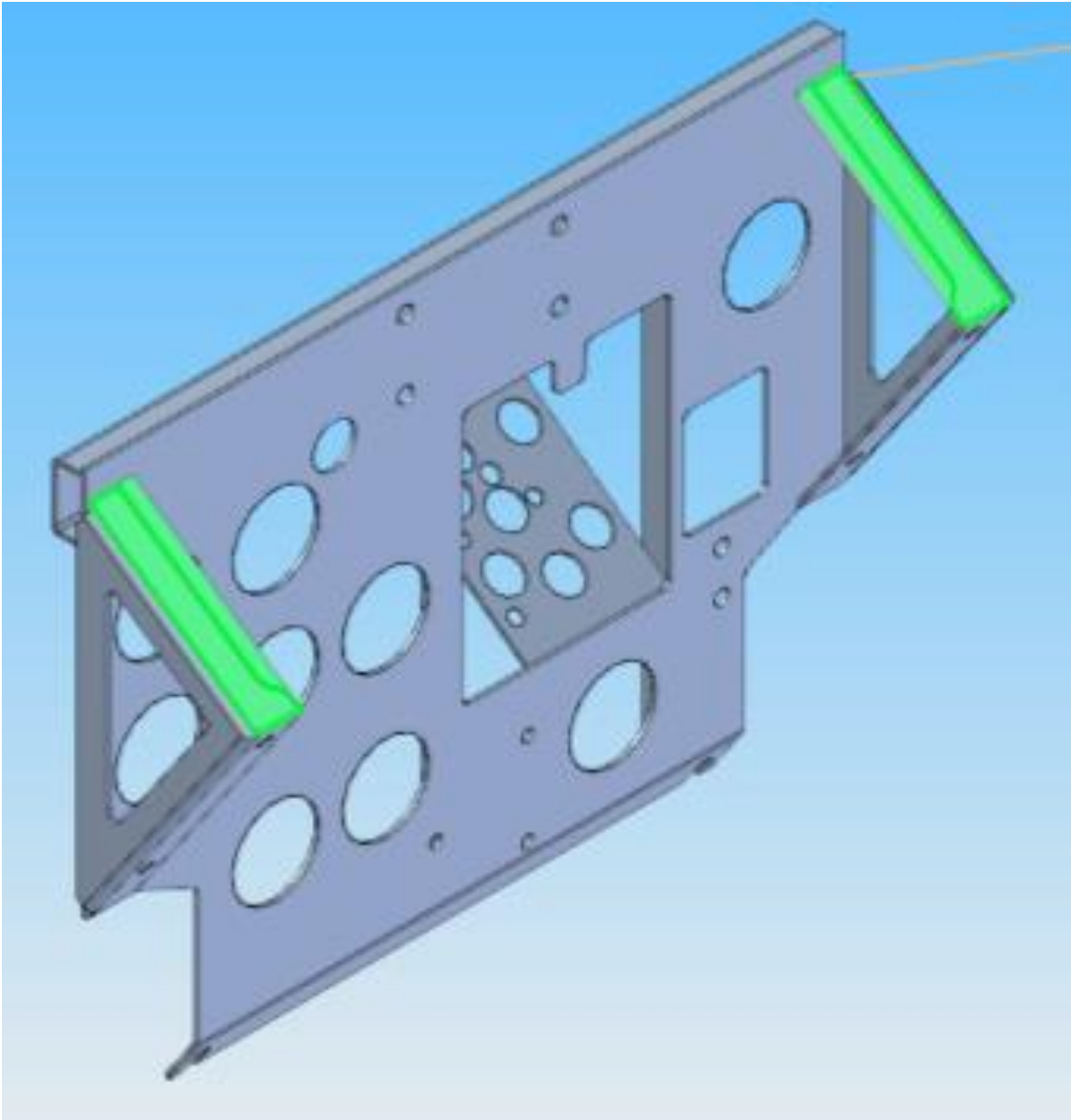
Treatment “(1)” CAD Geometry



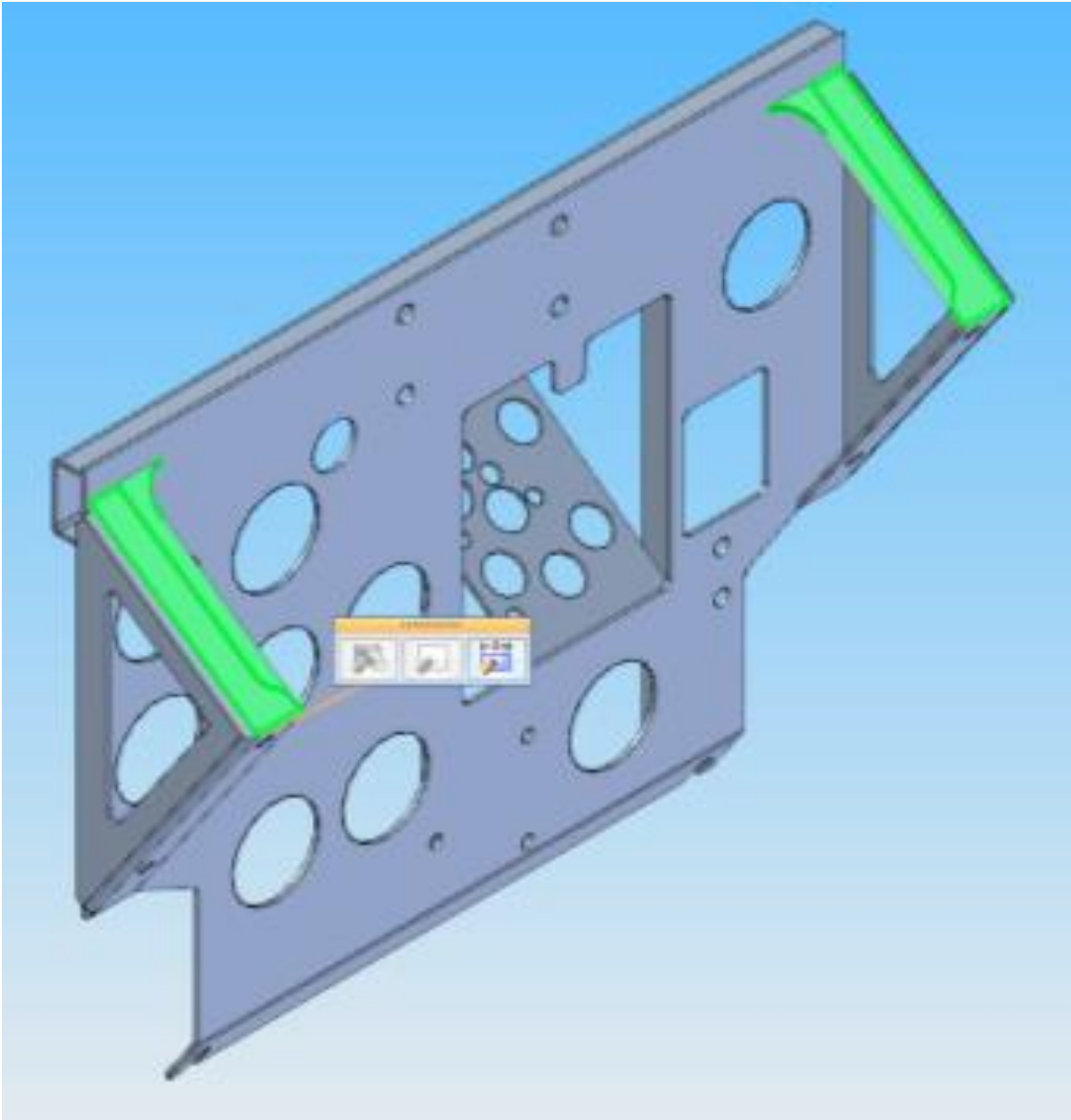
Treatment “a” CAD Geometry



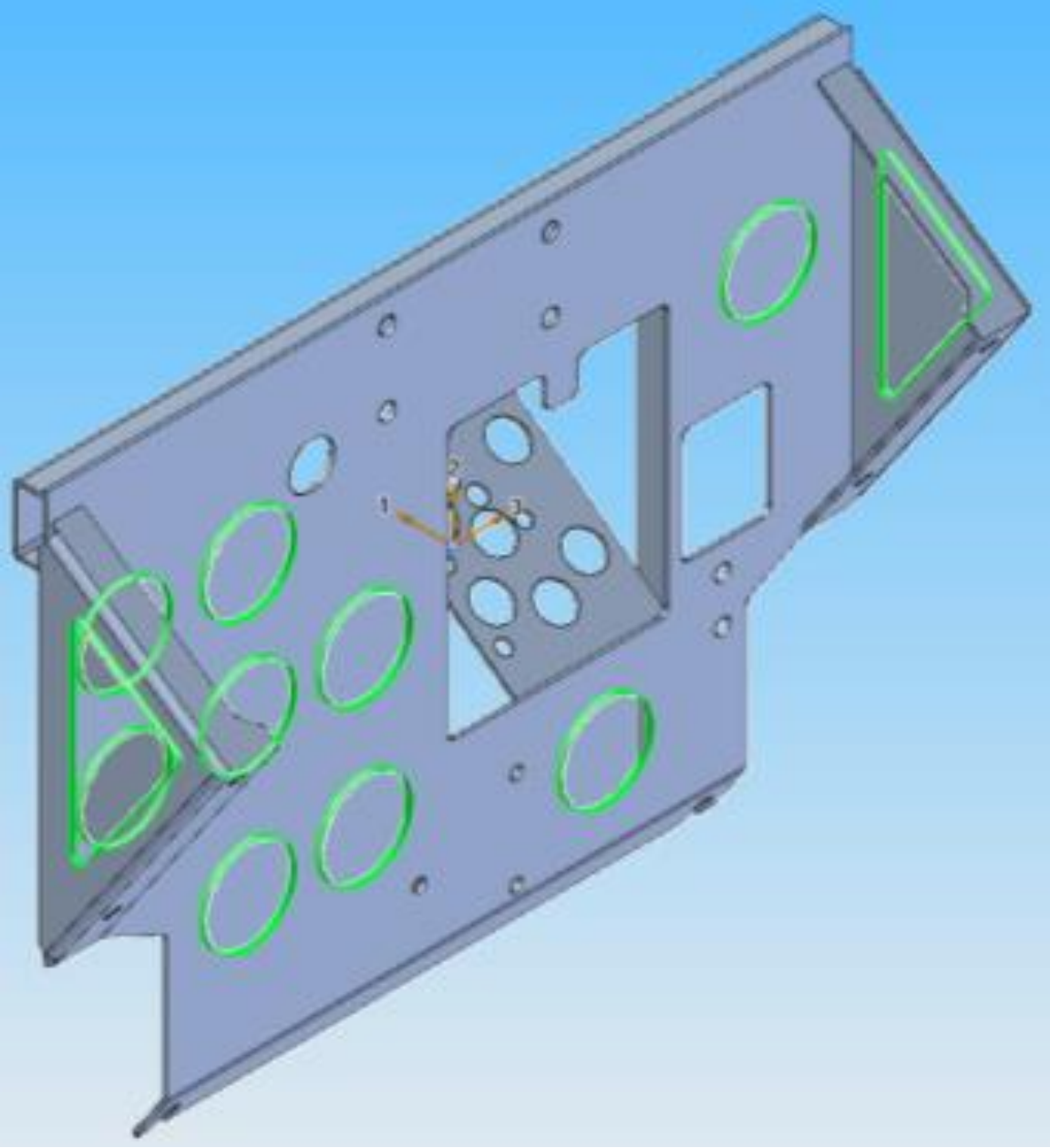
Treatment “b” CAD Geometry



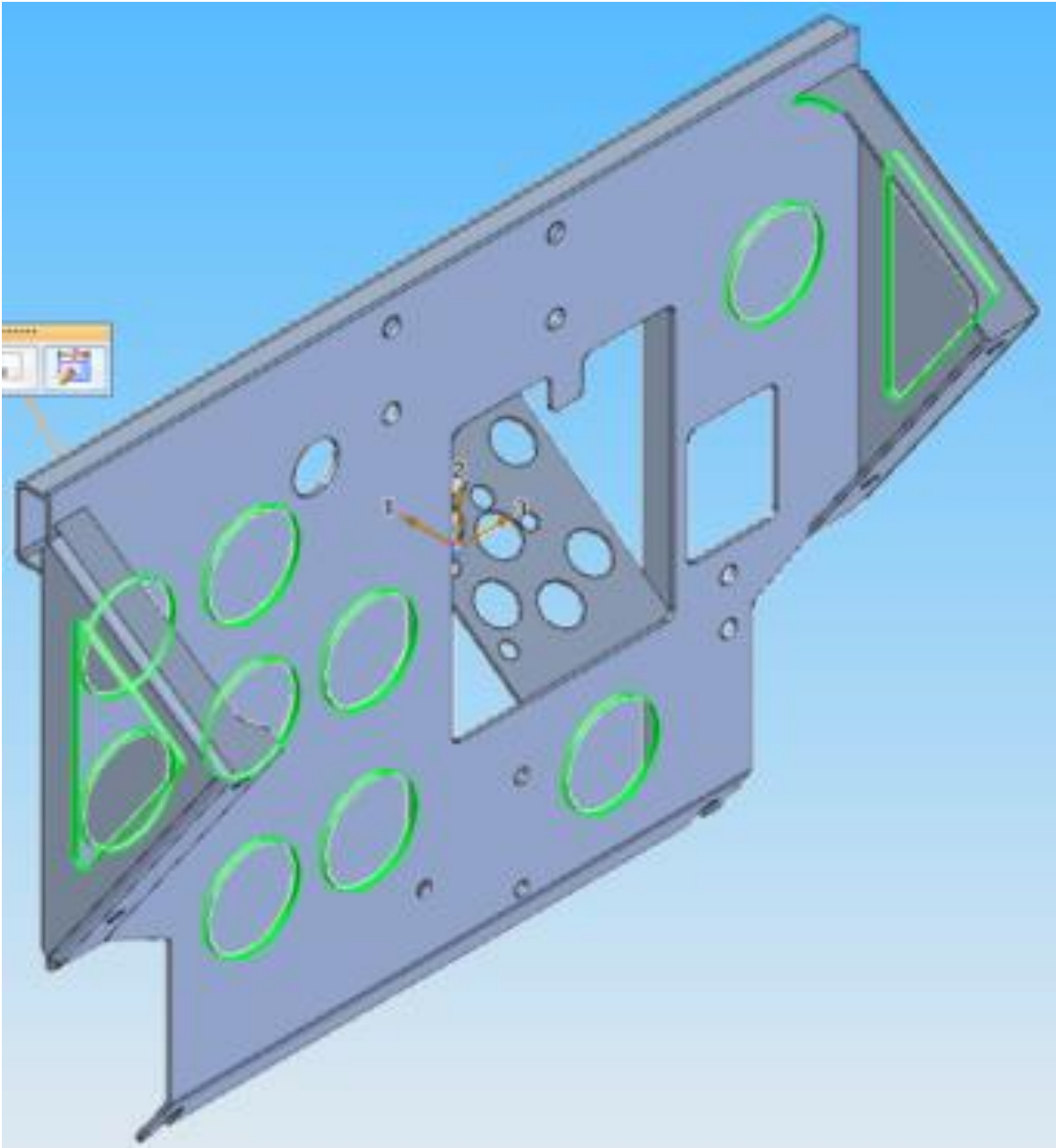
Treatment “ab” CAD Geometry



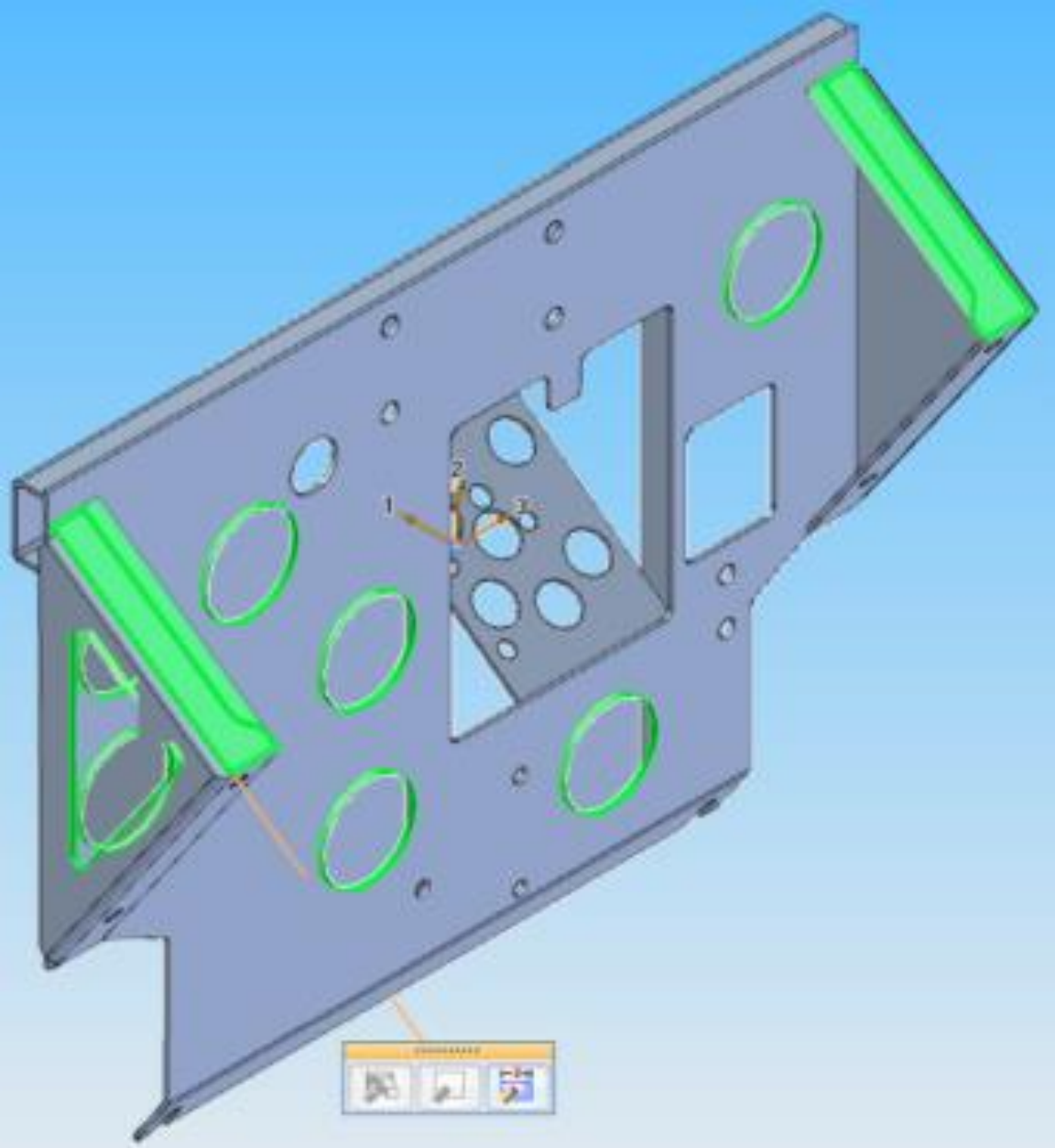
Treatment “c” CAD Geometry



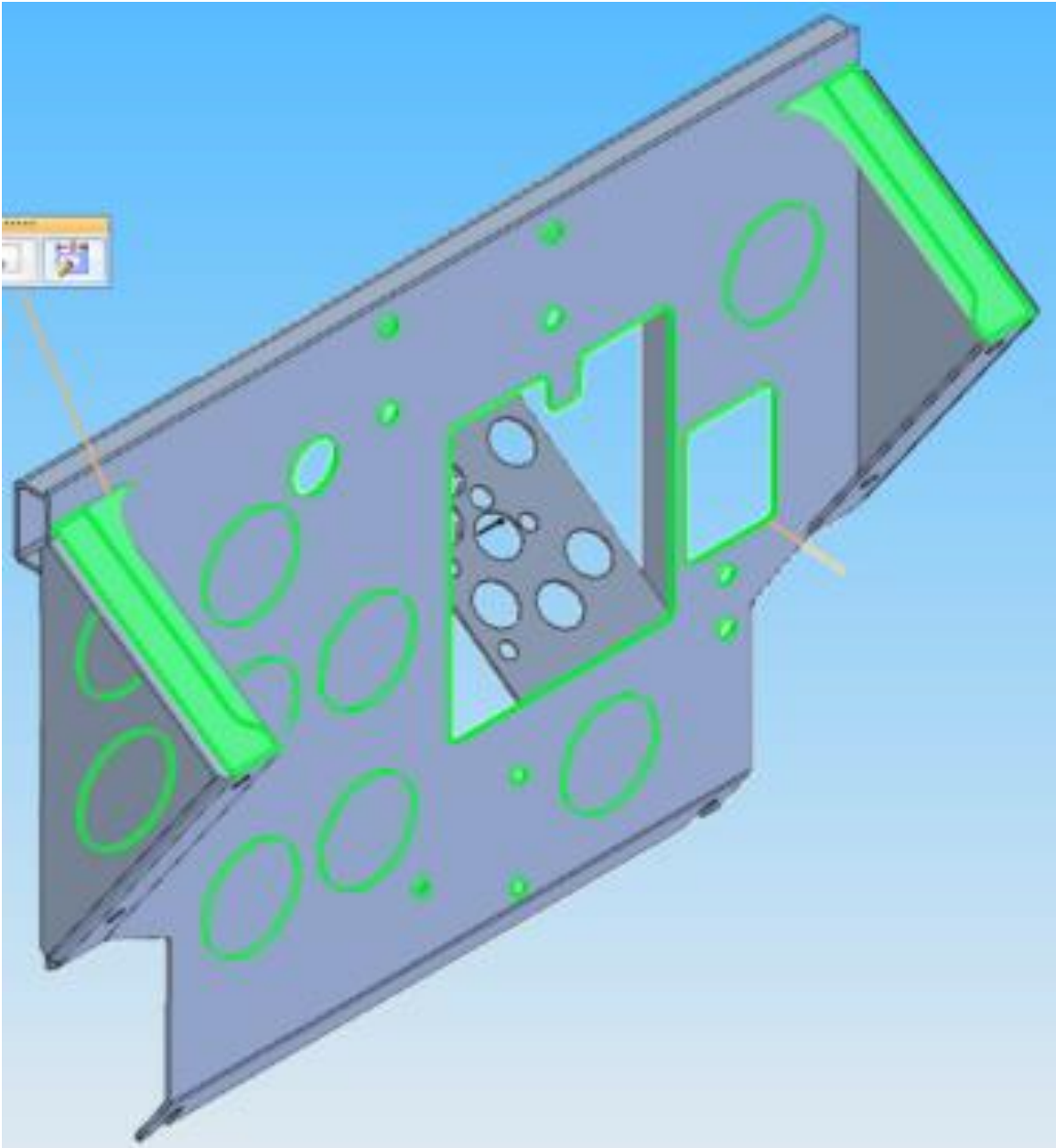
Treatment “ac” CAD Geometry



Treatment “bc” CAD Geometry



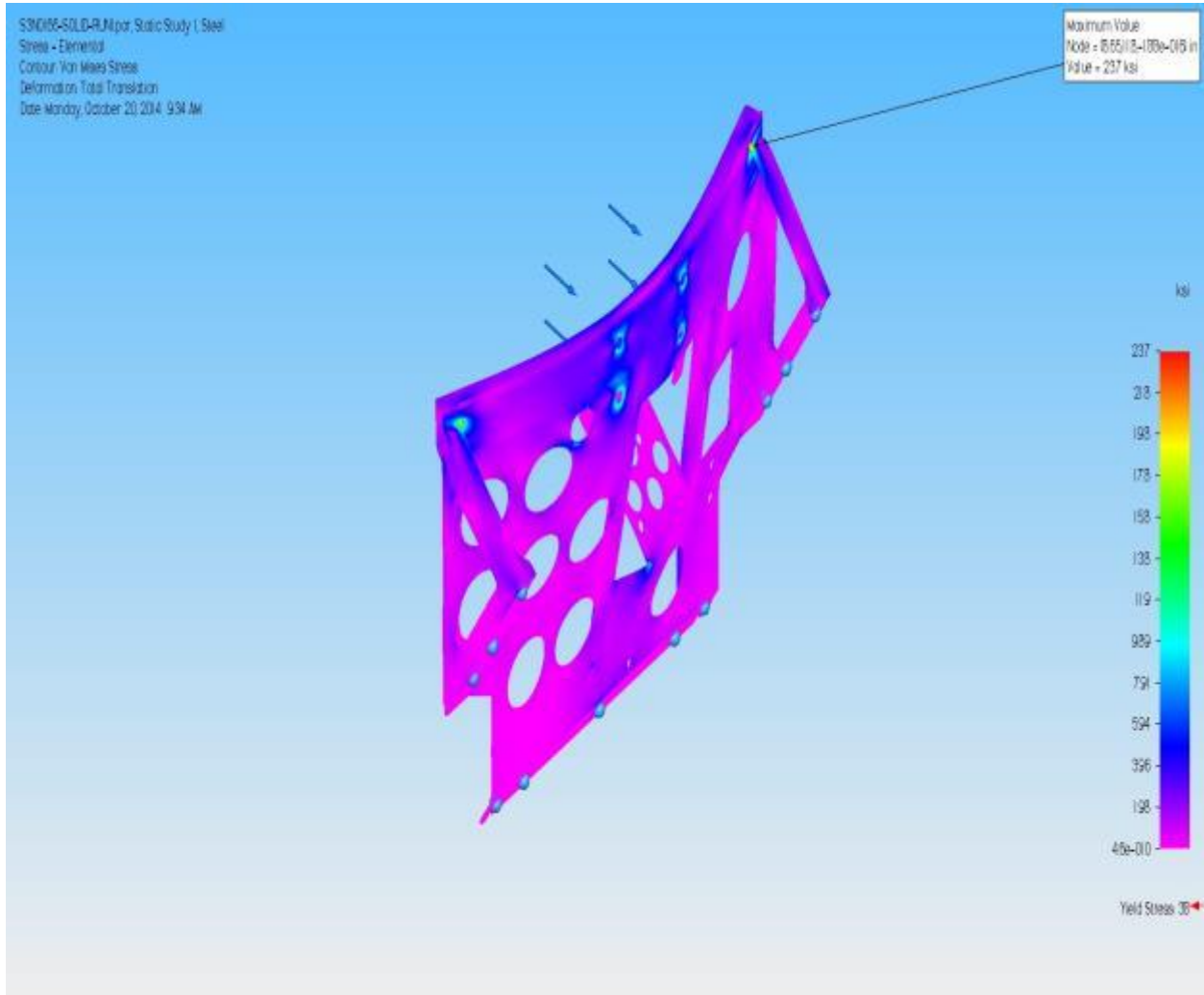
Treatment “abc” CAD Geometry



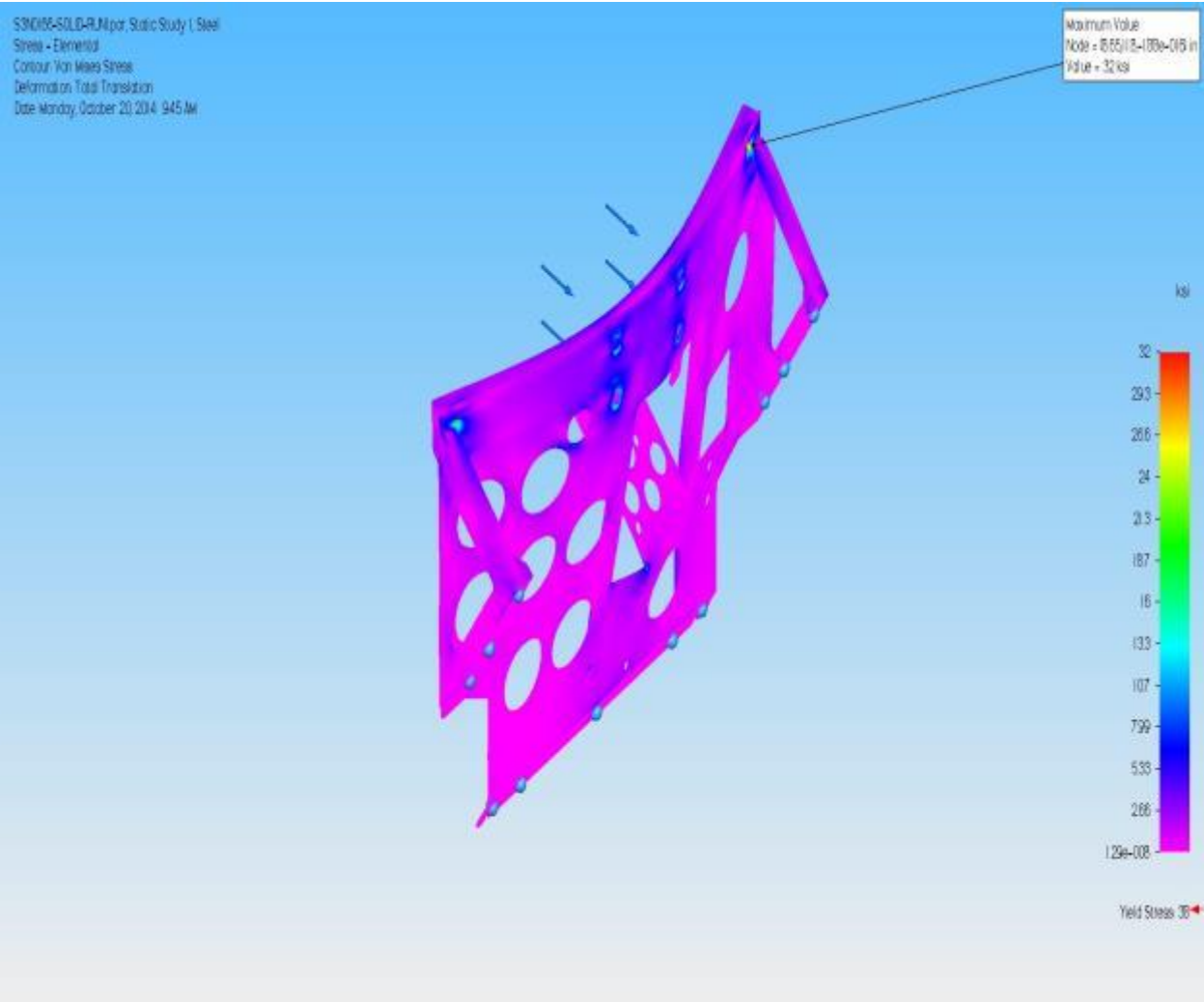


# Appendix VII – FEA Maximum Stress Diagrams

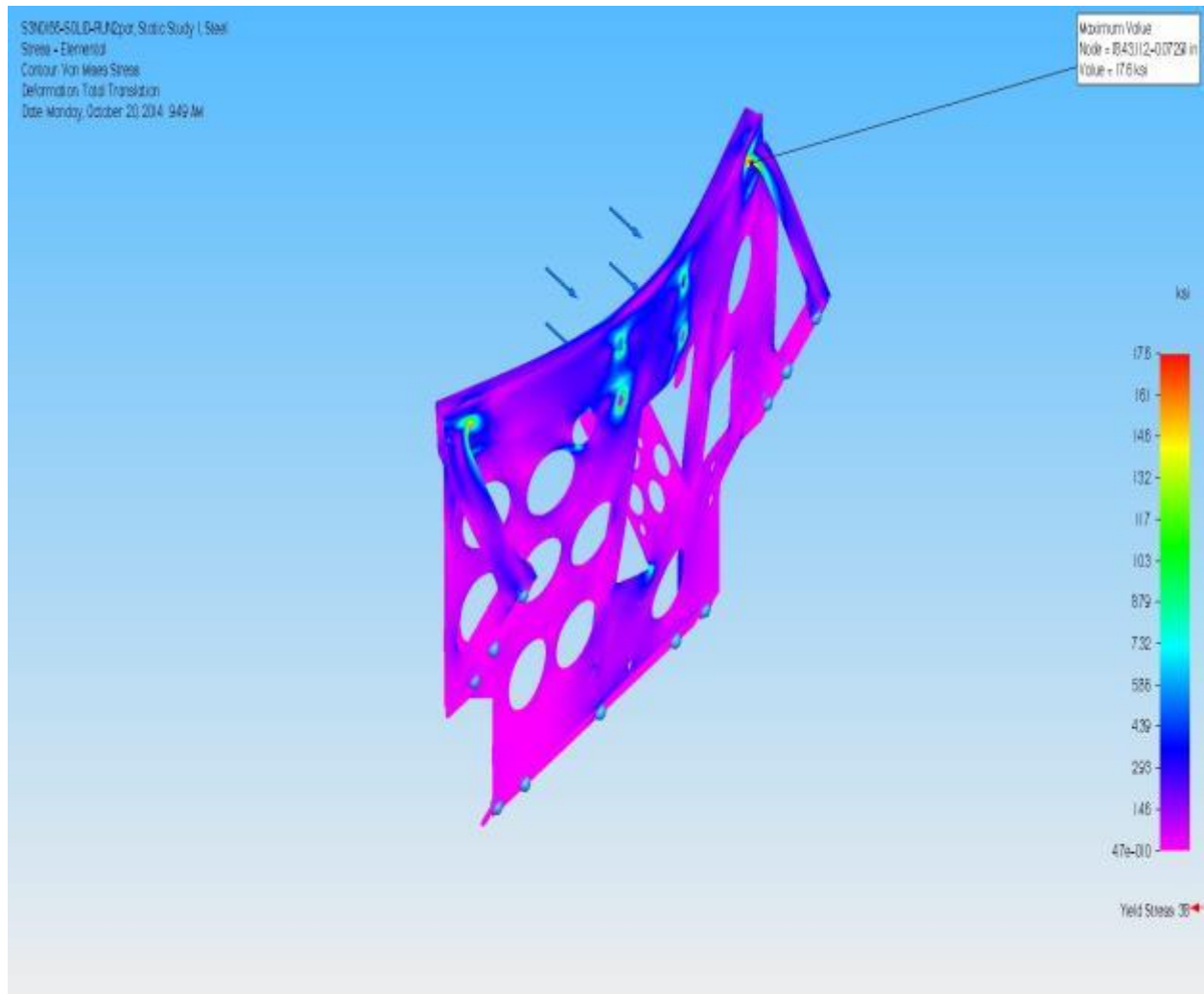
Treatment “(1)” FEA Maximum Stress Diagram, Size 8 Mesh



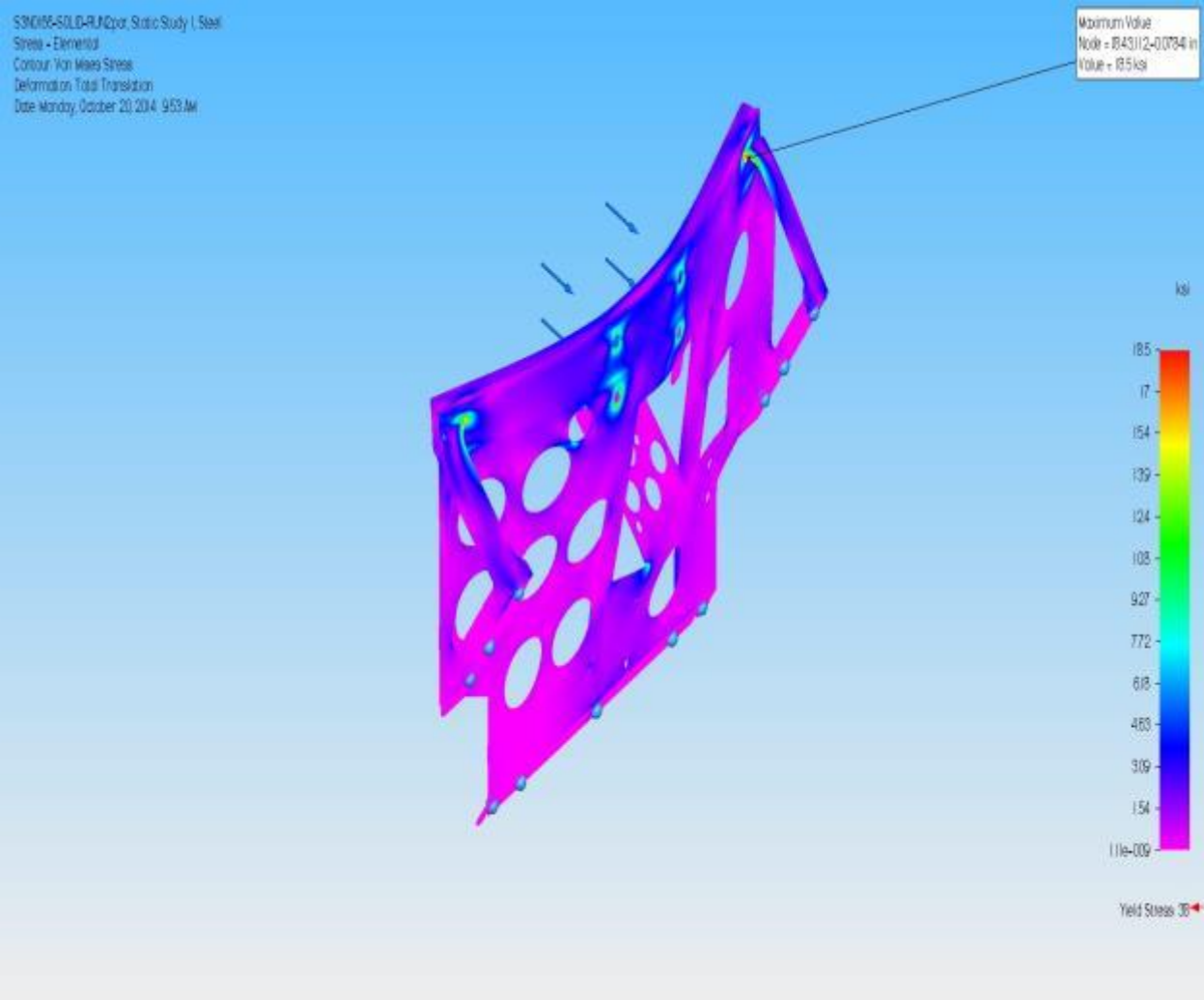
Treatment “(1)” FEA Maximum Stress Diagram, Size 9 Mesh



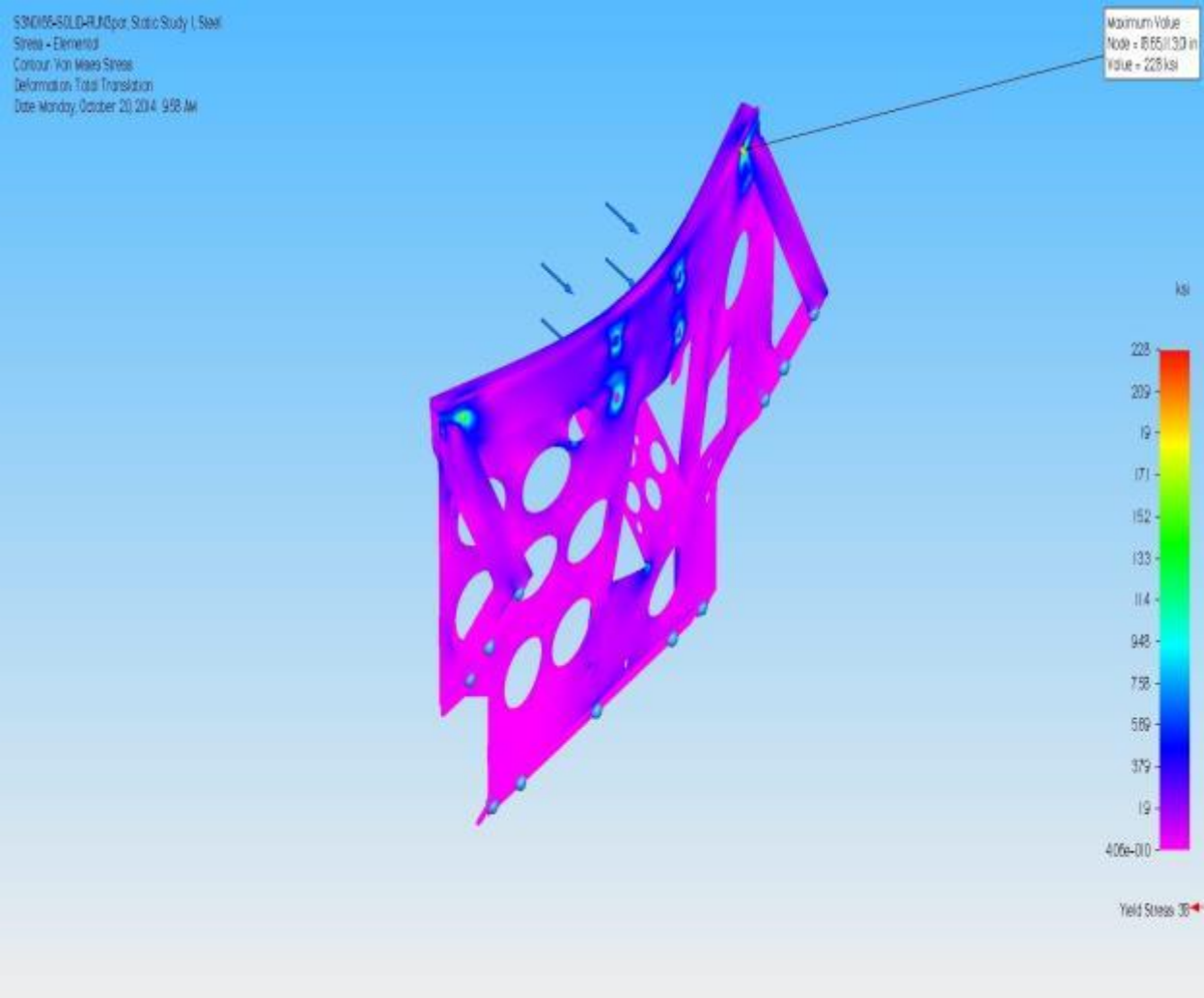
# Treatment "a" FEA Maximum Stress Diagram, Size 8 Mesh



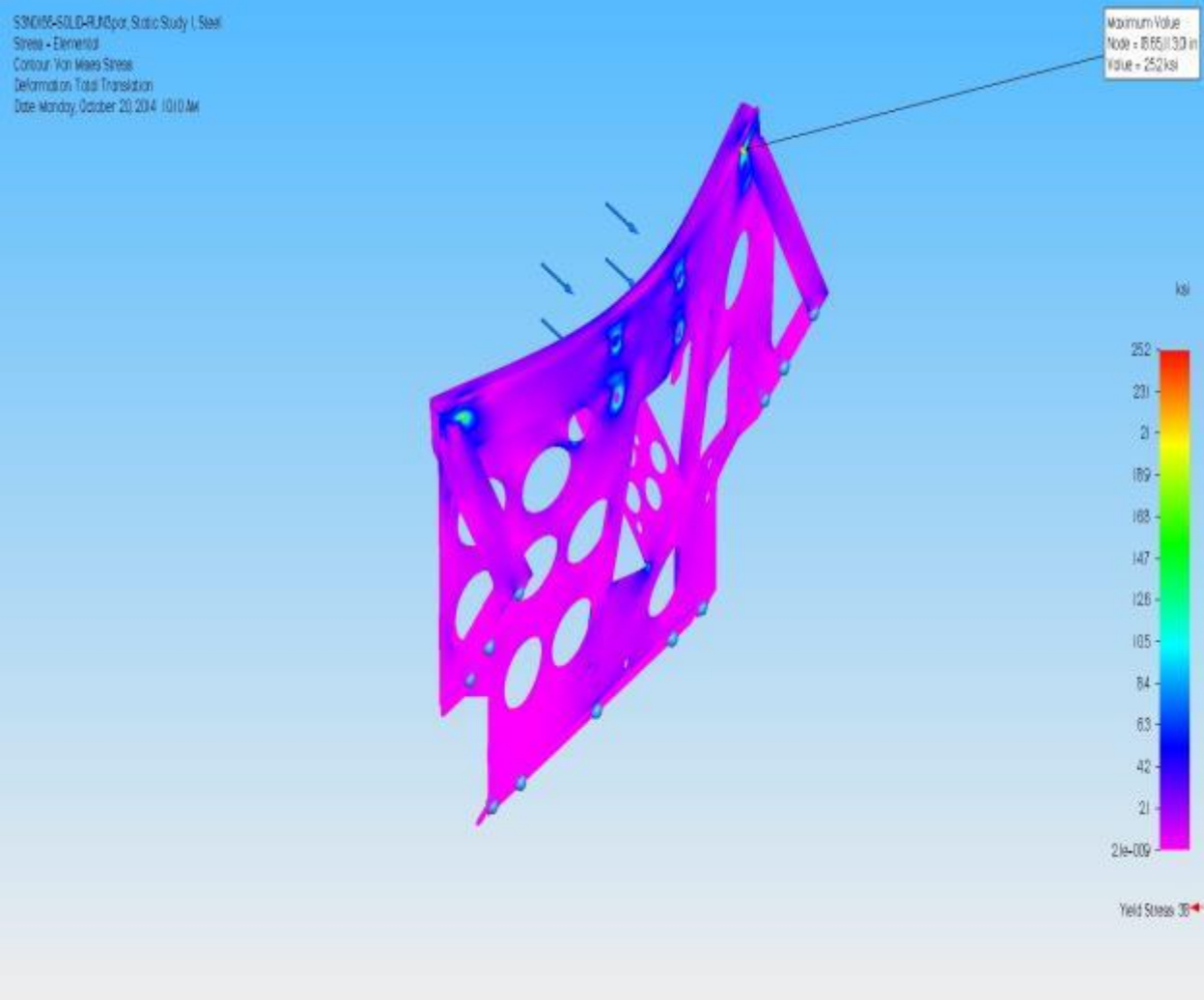
Treatment "a" FEA Maximum Stress Diagram, Size 9 Mesh



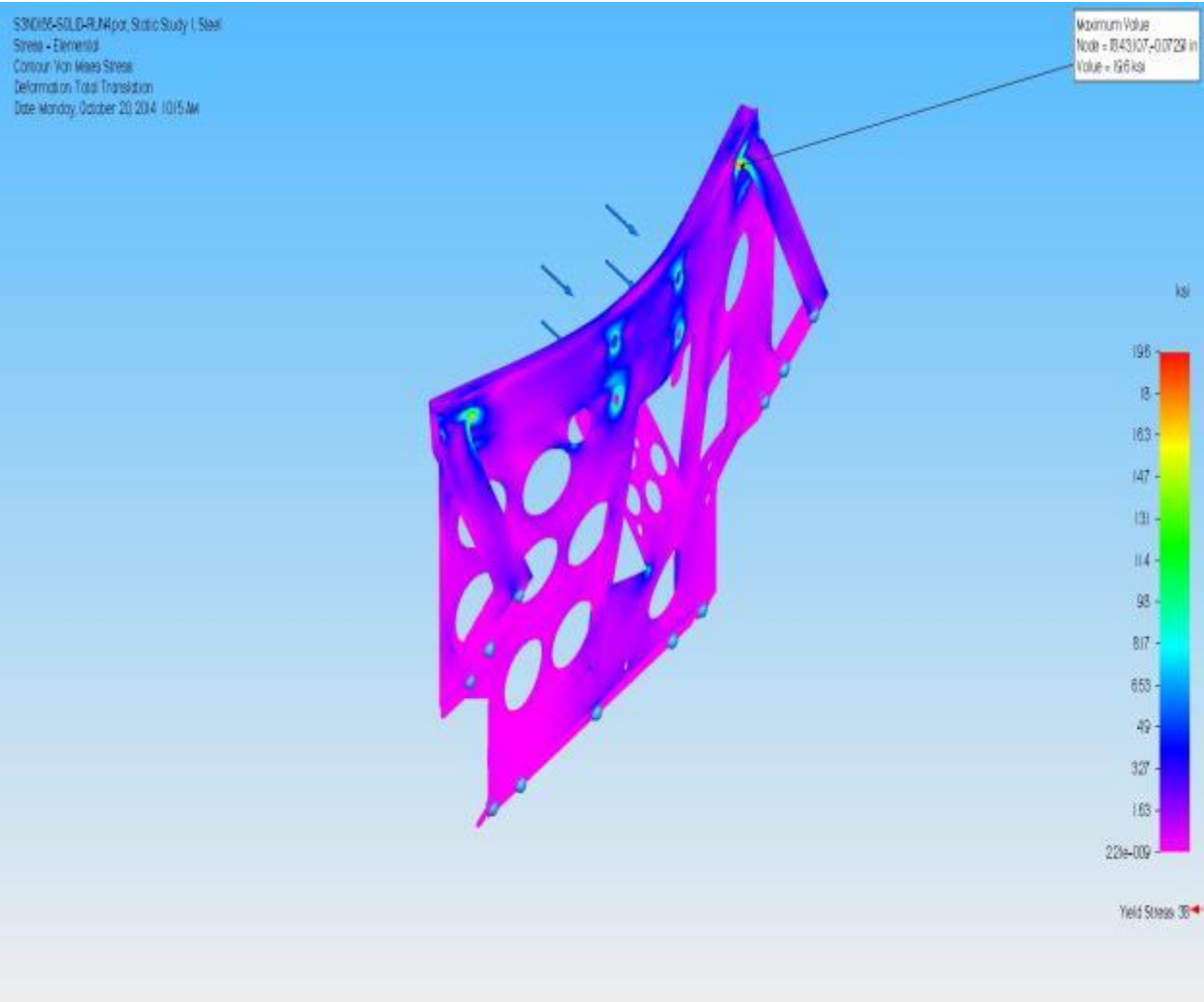
Treatment "b" FEA Maximum Stress Diagram, Size 8 Mesh



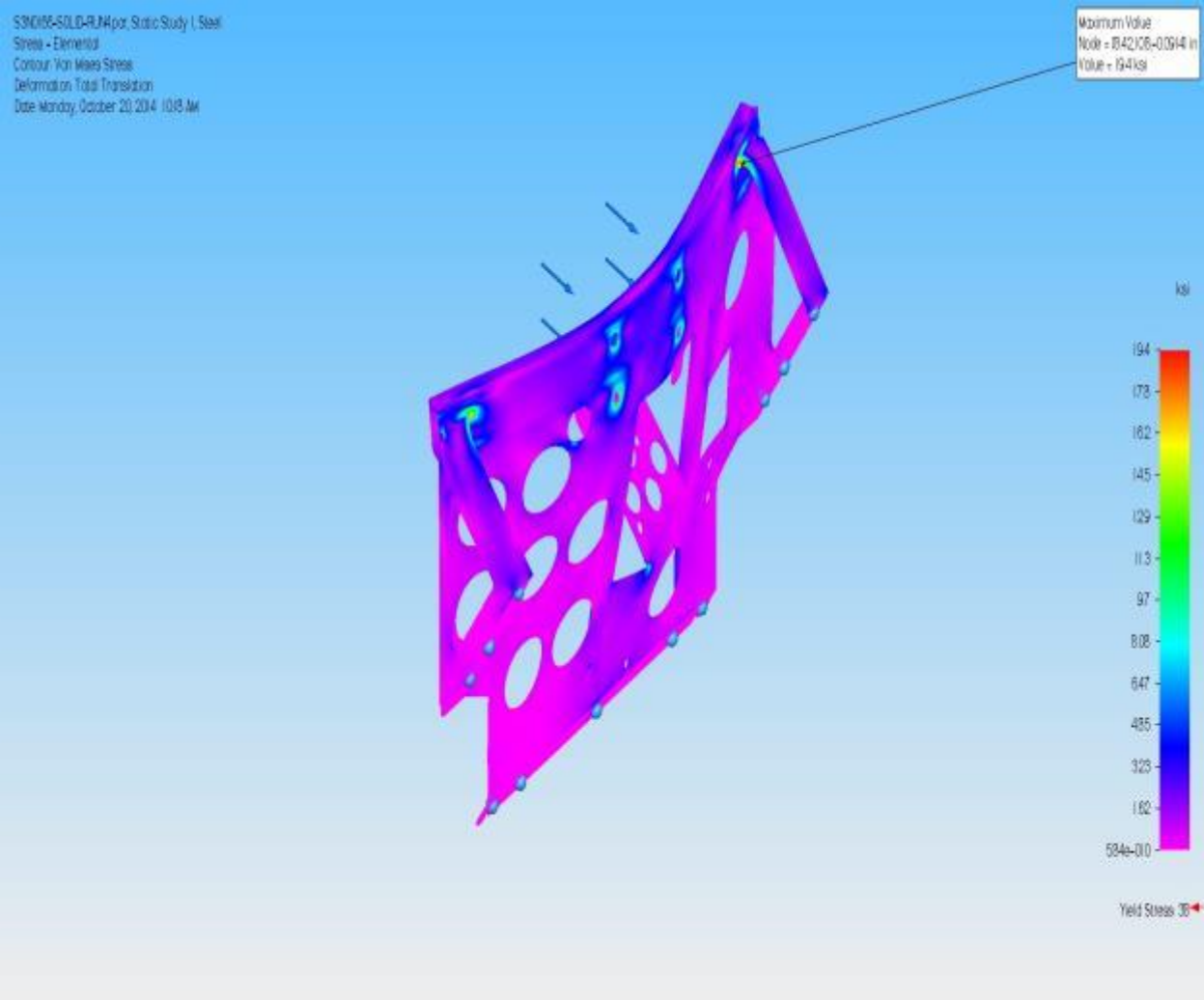
Treatment "b" FEA Maximum Stress Diagram, Size 9 Mesh



Treatment "ab" FEA Maximum Stress Diagram, Size 8 Mesh

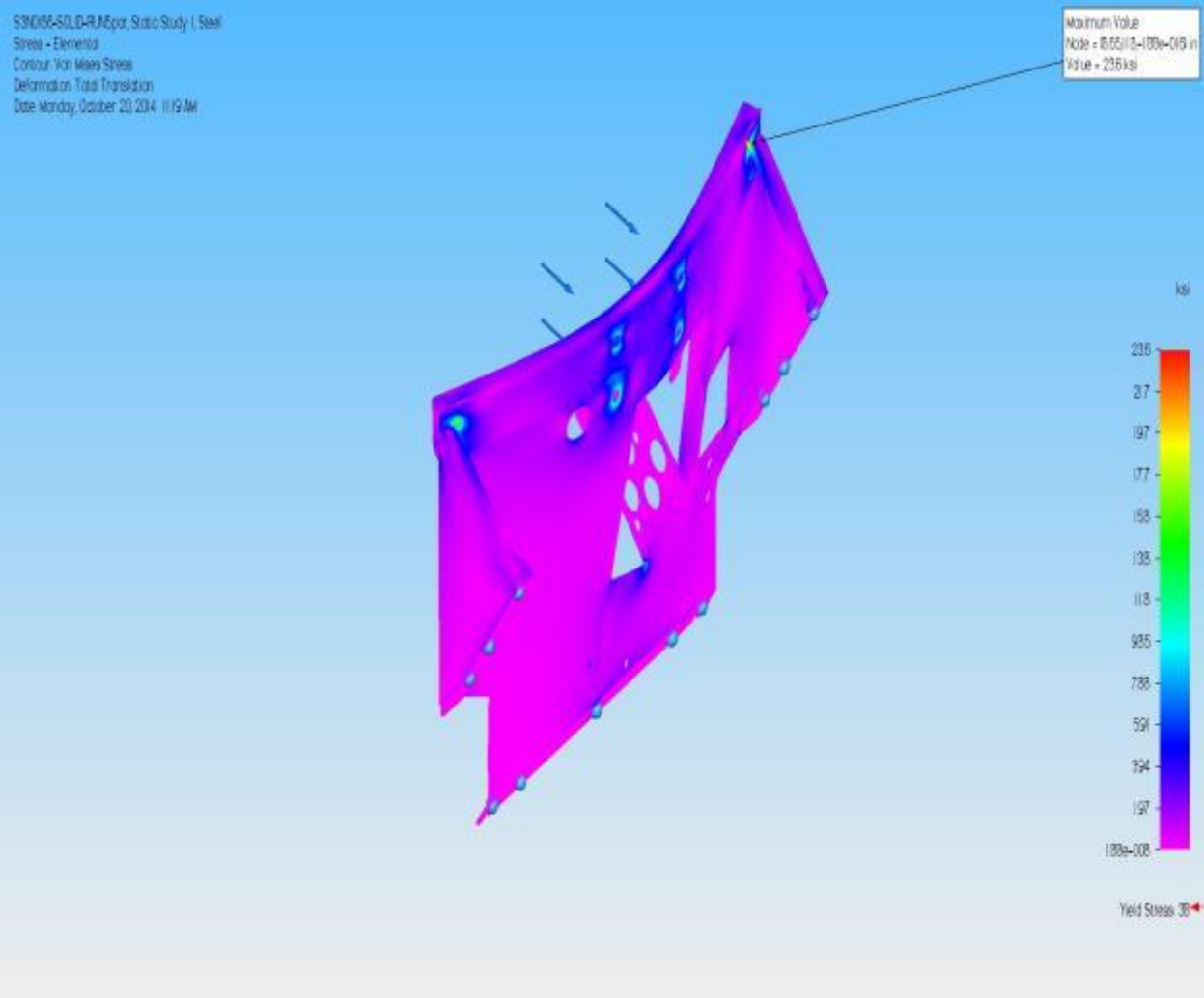


Treatment "ab" FEA Maximum Stress Diagram, Size 9 Mesh

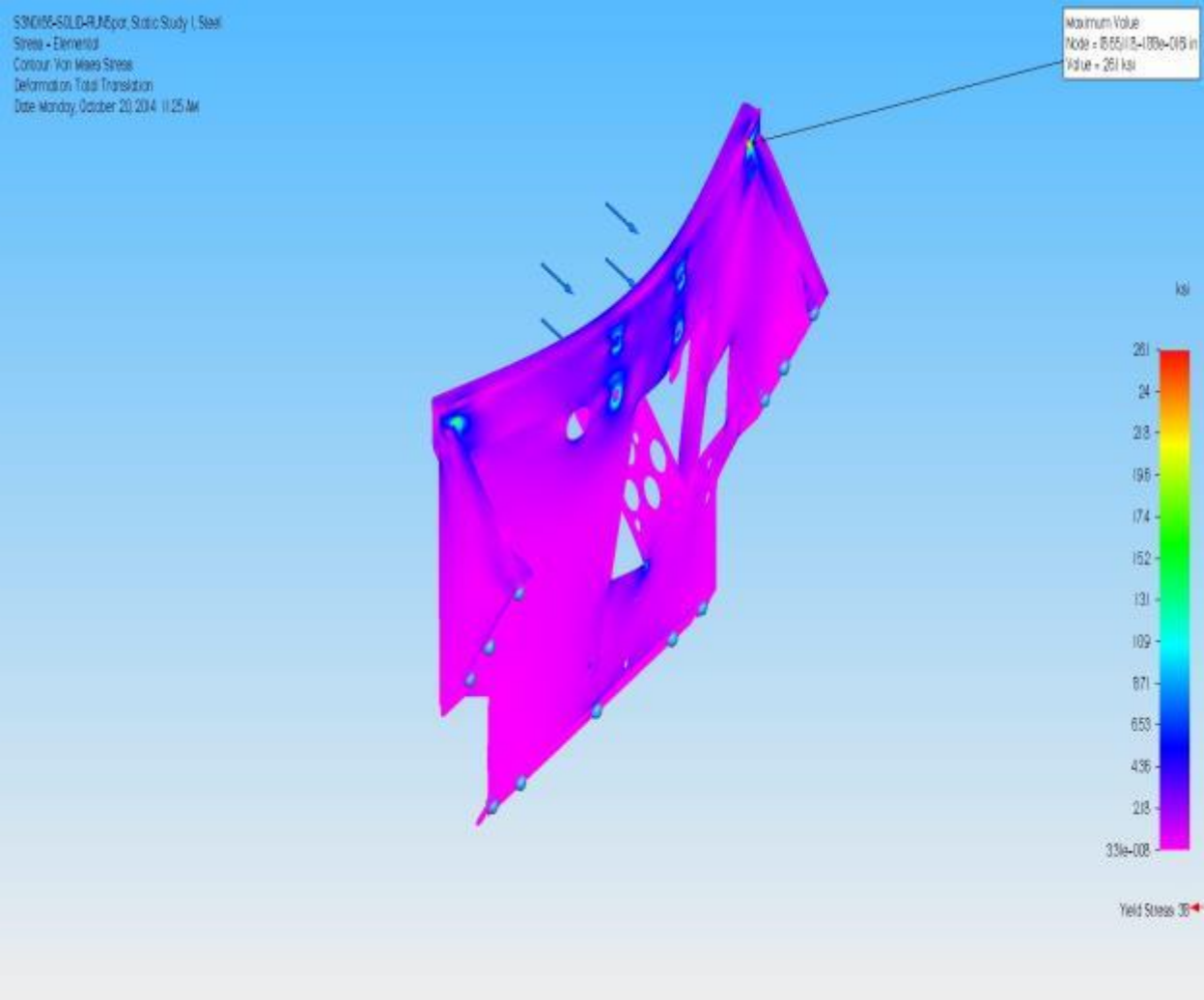




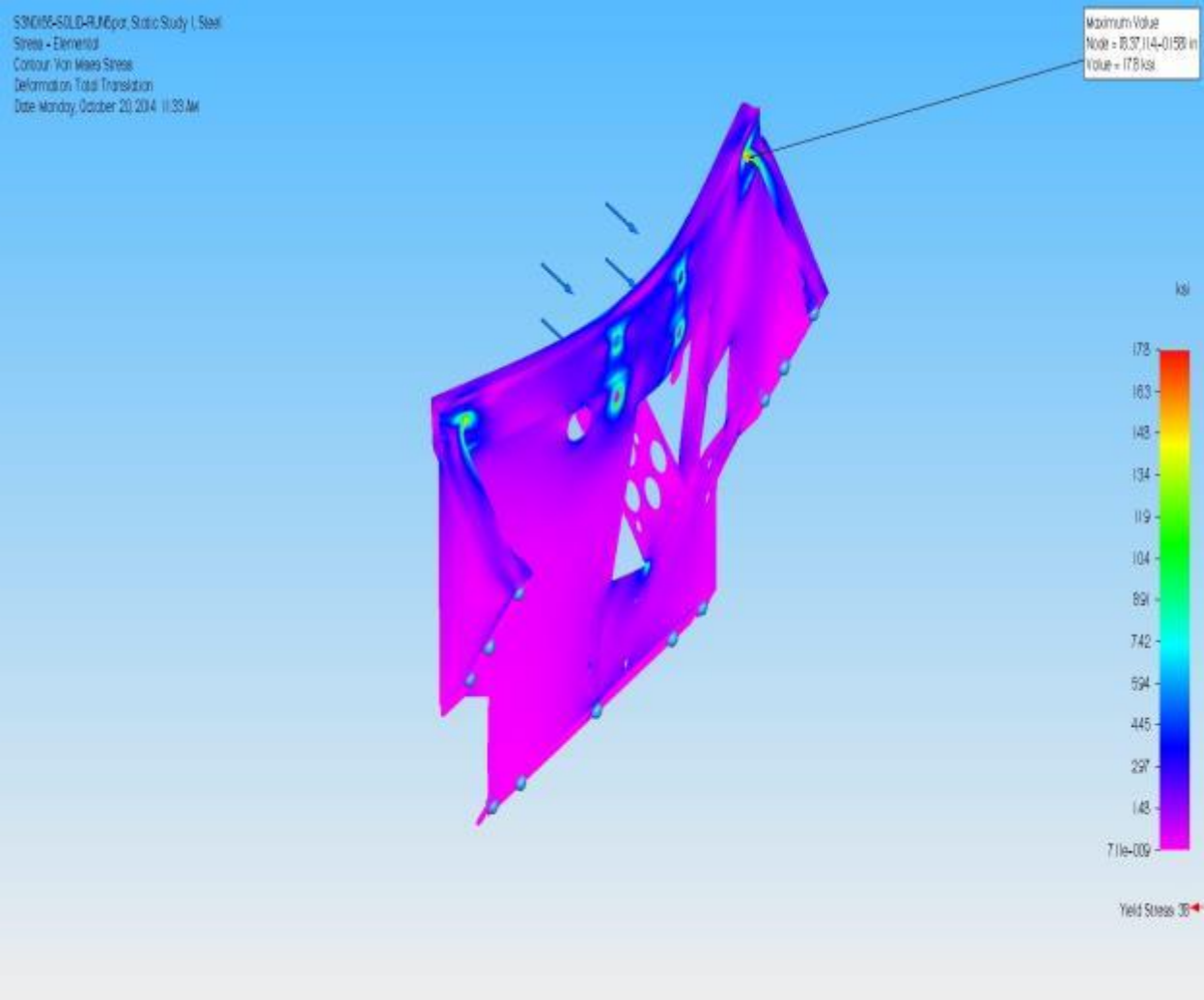
Treatment "c" FEA Maximum Stress Diagram, Size 8 Mesh



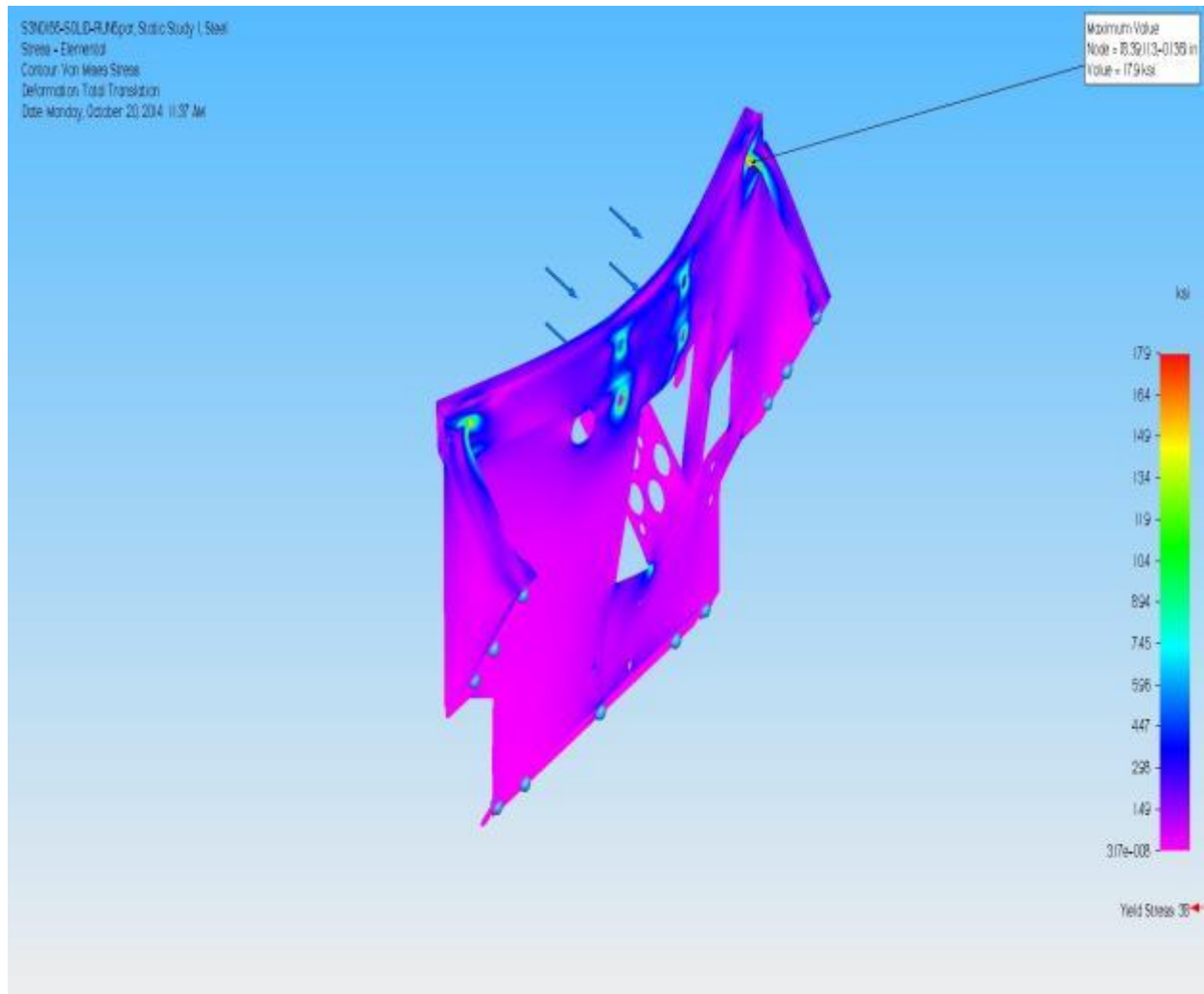
Treatment “c” FEA Maximum Stress Diagram, Size 9 Mesh



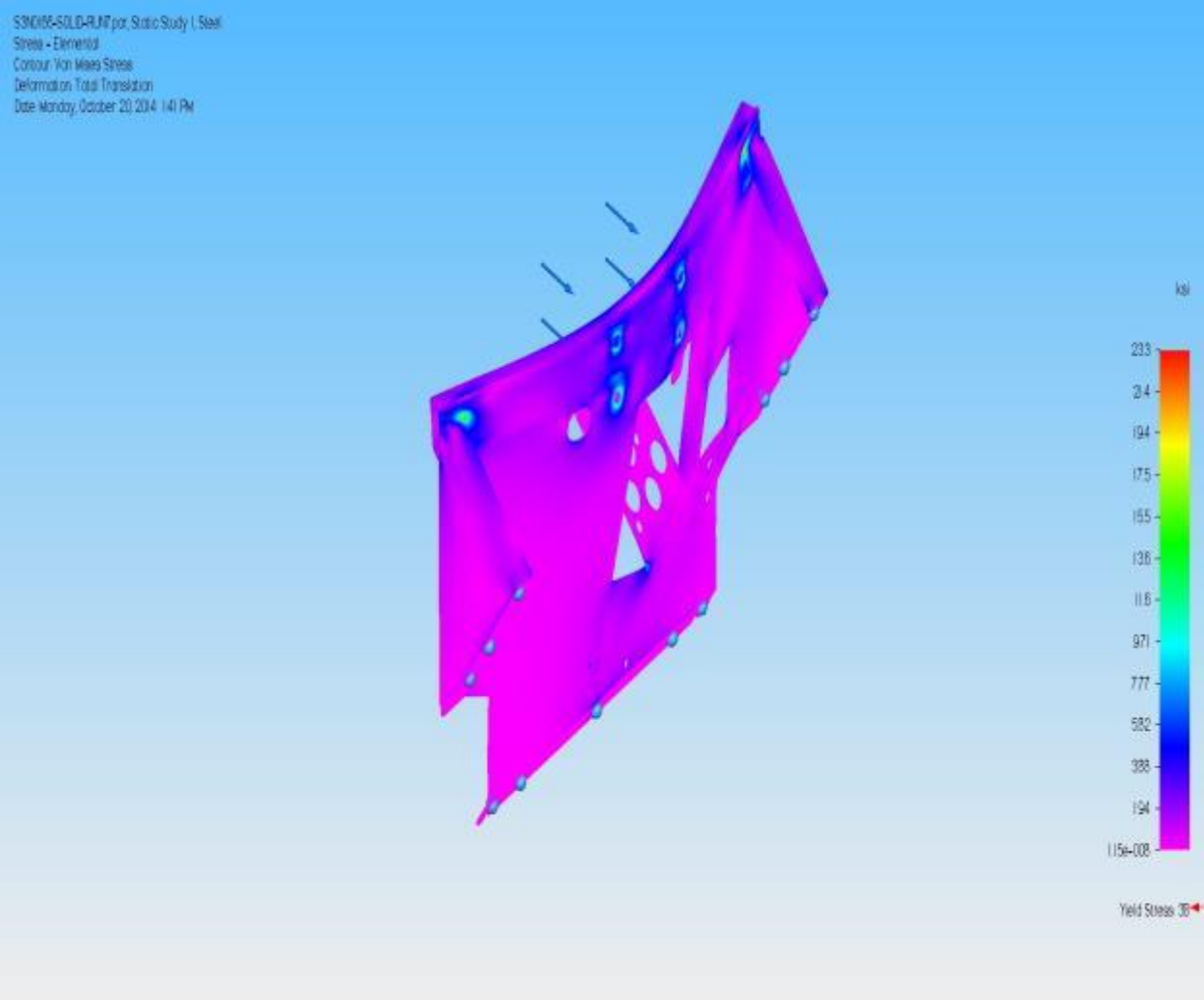
Treatment "ac" FEA Maximum Stress Diagram, Size 8 Mesh



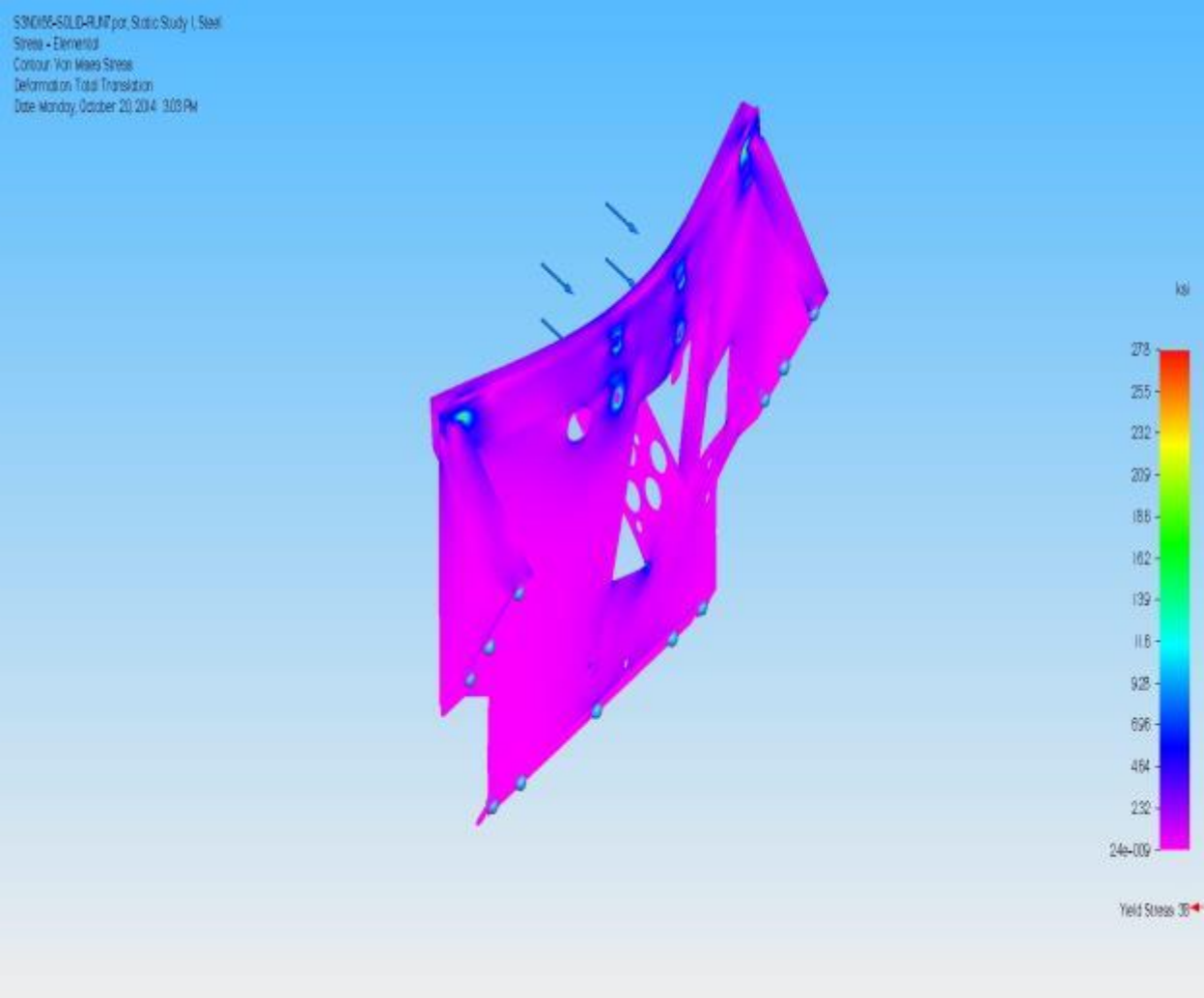
# Treatment "ac" FEA Maximum Stress Diagram, Size 9 Mesh



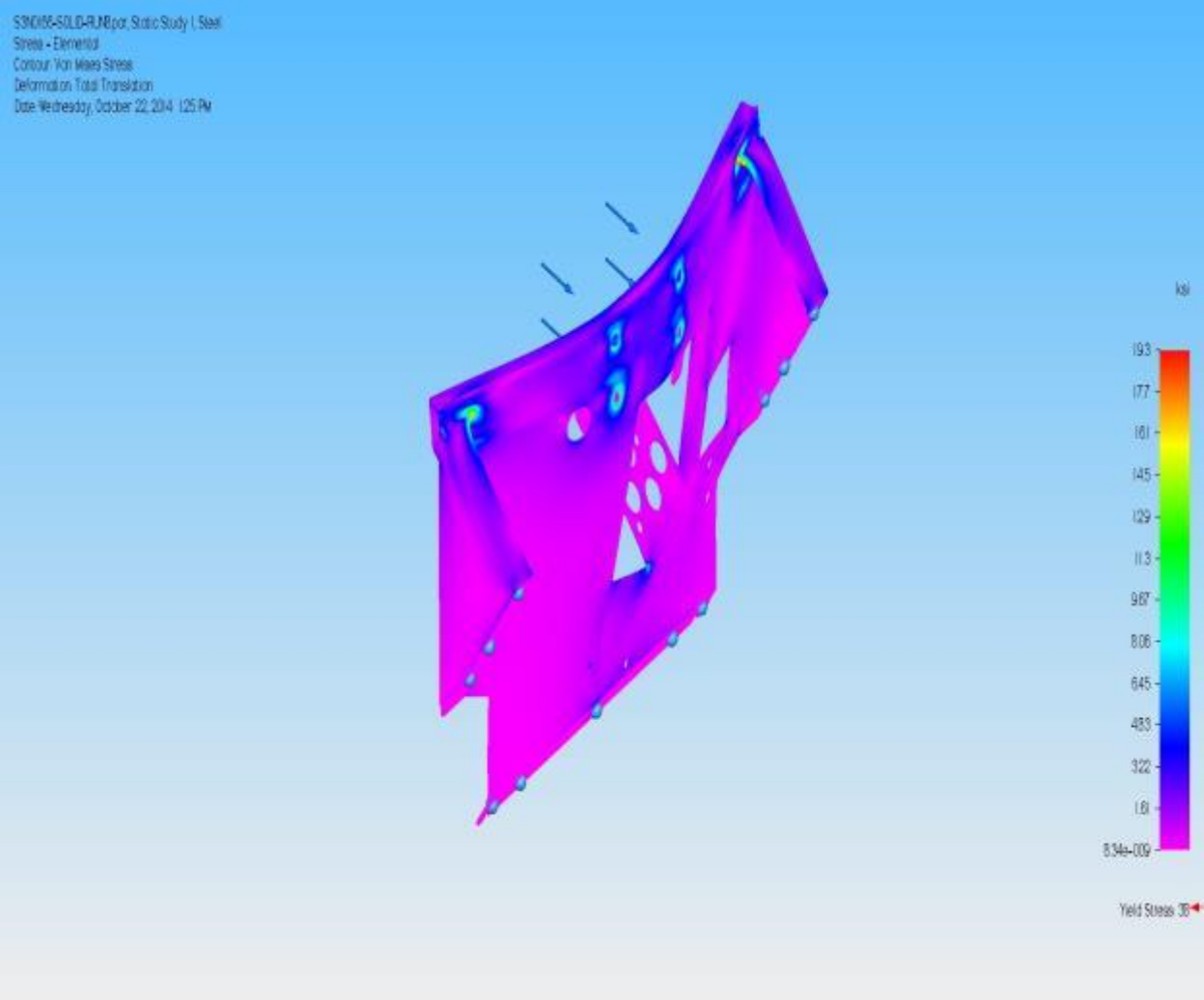
Treatment “bc” FEA Maximum Stress Diagram, Size 8 Mesh



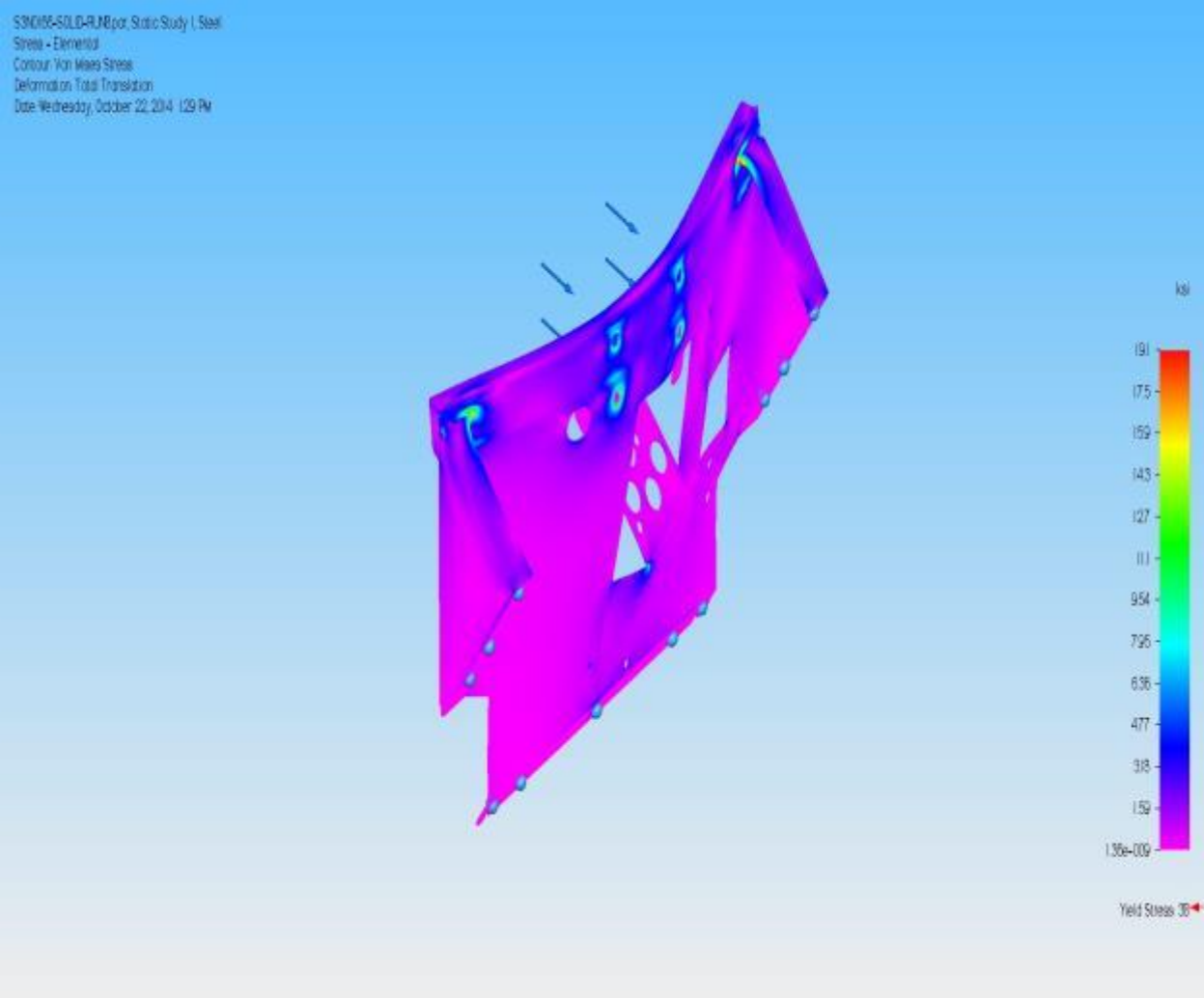
Treatment "bc" FEA Maximum Stress Diagram, Size 9 Mesh



Treatment “abc” FEA Maximum Stress Diagram, Size 8 Mesh



Treatment “abc” FEA Maximum Stress Diagram, Size 9 Mesh





## Appendix VIII – Statistical Analysis Results: Max Stress

### Factorial Regression: Max Stress versus Radius, Flange, Holes

#### Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	7	211544375	30220625	4.74	0.022
Linear	3	192111875	64037292	10.04	0.004
Radius	1	191130625	191130625	29.97	0.001
Flange	1	30625	30625	0.00	0.946
Holes	1	950625	950625	0.15	0.710
2-Way Interactions	3	14026875	4675625	0.73	0.561
Radius*Flange	1	8850625	8850625	1.39	0.273
Radius*Holes	1	225625	225625	0.04	0.855
Flange*Holes	1	4950625	4950625	0.78	0.404
3-Way Interactions	1	5405625	5405625	0.85	0.384
Radius*Flange*Holes	1	5405625	5405625	0.85	0.384
Error	8	51025000	6378125		
Total	15	262569375			

#### Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2525.50	80.57%	63.56%	22.27%

#### Coded Coefficients

Term	Effect	Coef	SE Coef	T-Value	P-Value	VIF
Constant		22106	631	35.01	0.000	
Radius	-6913	-3456	631	-5.47	0.001	1.00
Flange	-88	-44	631	-0.07	0.946	1.00
Holes	-488	-244	631	-0.39	0.710	1.00
Radius*Flange	1487	744	631	1.18	0.273	1.00
Radius*Holes	237	119	631	0.19	0.855	1.00
Flange*Holes	1113	556	631	0.88	0.404	1.00
Radius*Flange*Holes	-1163	-581	631	-0.92	0.384	1.00

#### Regression Equation in Uncoded Units

$$\text{Max Stress} = 22106 - 3456 \text{ Radius} - 44 \text{ Flange} - 244 \text{ Holes} + 744 \text{ Radius*Flange} + 119 \text{ Radius*Holes} + 556 \text{ Flange*Holes} - 581 \text{ Radius*Flange*Holes}$$

#### Alias Structure

Factor	Name
A	Radius
B	Flange
C	Holes

#### Aliases

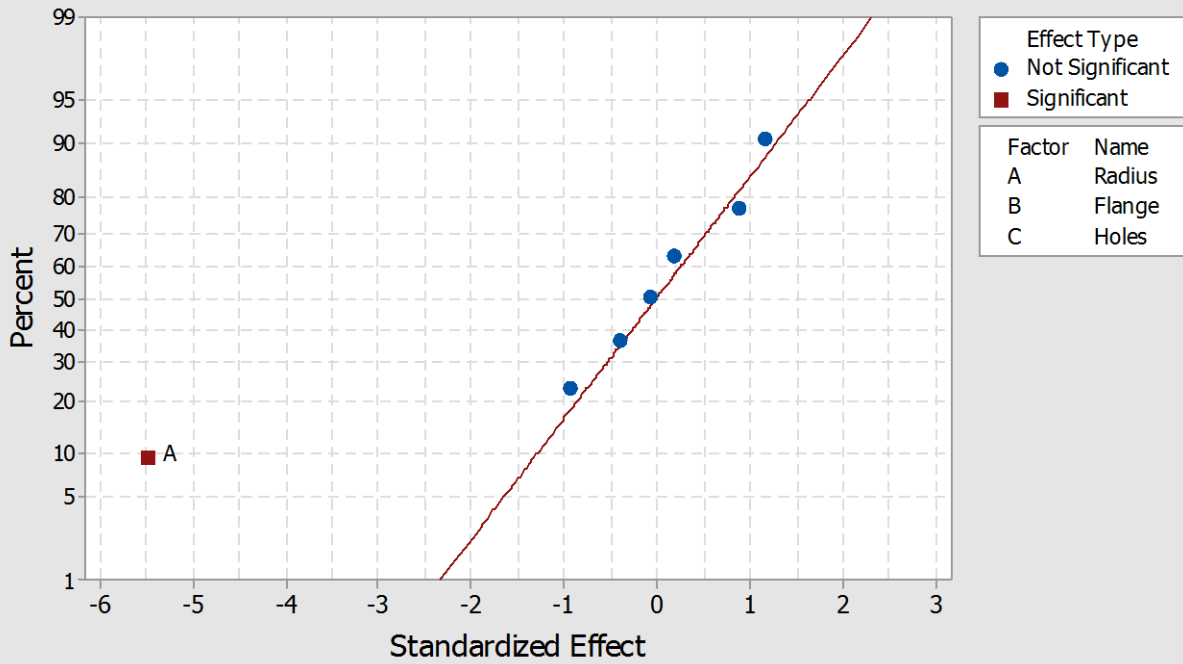
I  
A  
B  
C  
AB  
AC  
BC  
ABC

#### Fits and Diagnostics for Unusual Observations

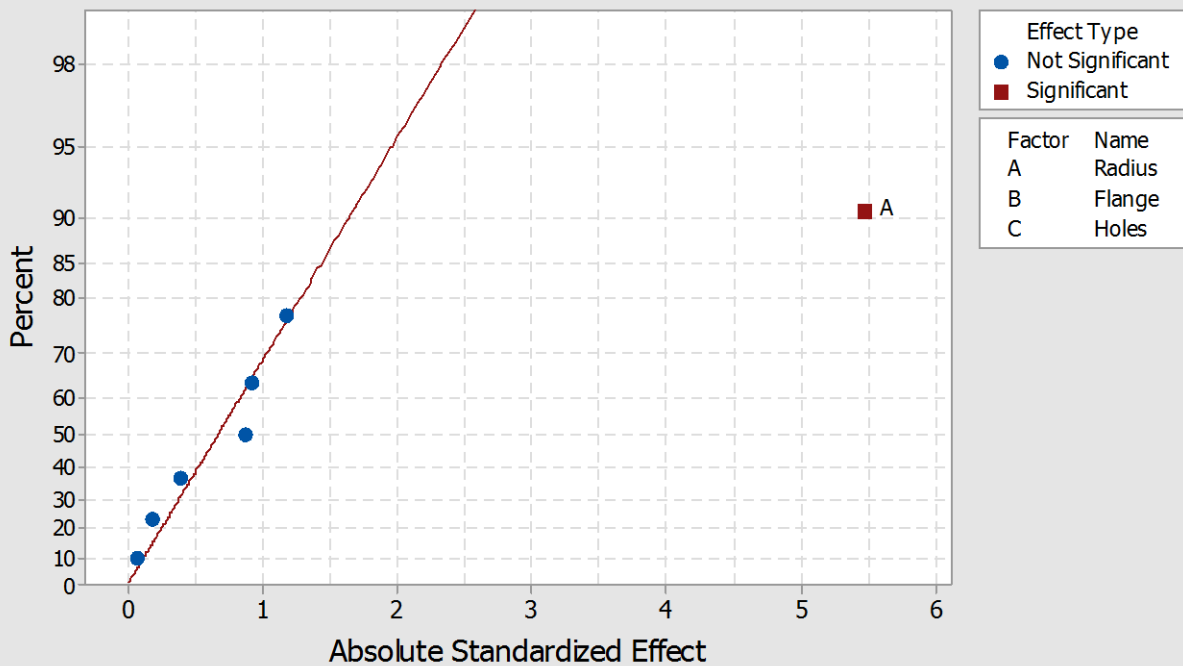
Obs	Stress	Fit	Resid	Std Resid	
1	23700	27850	-4150	-2.32	R
9	32000	27850	4150	2.32	R

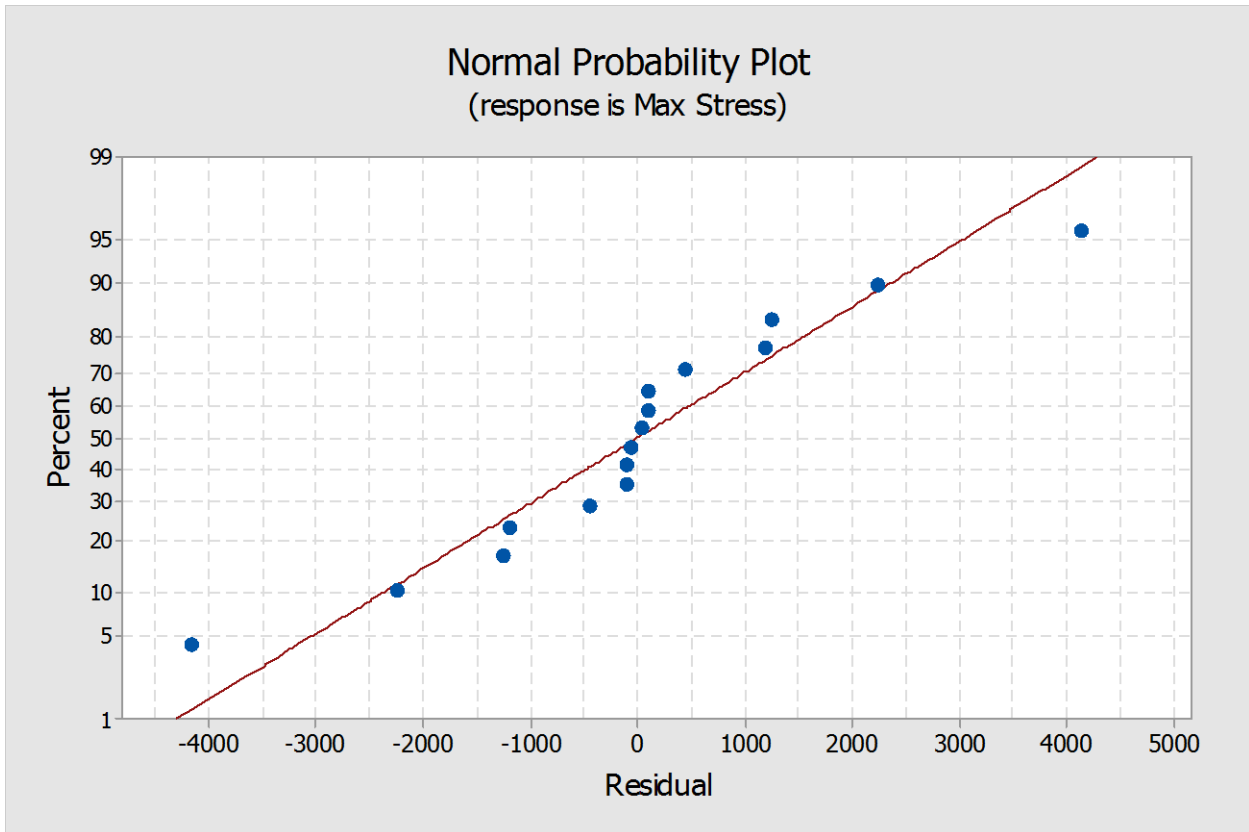
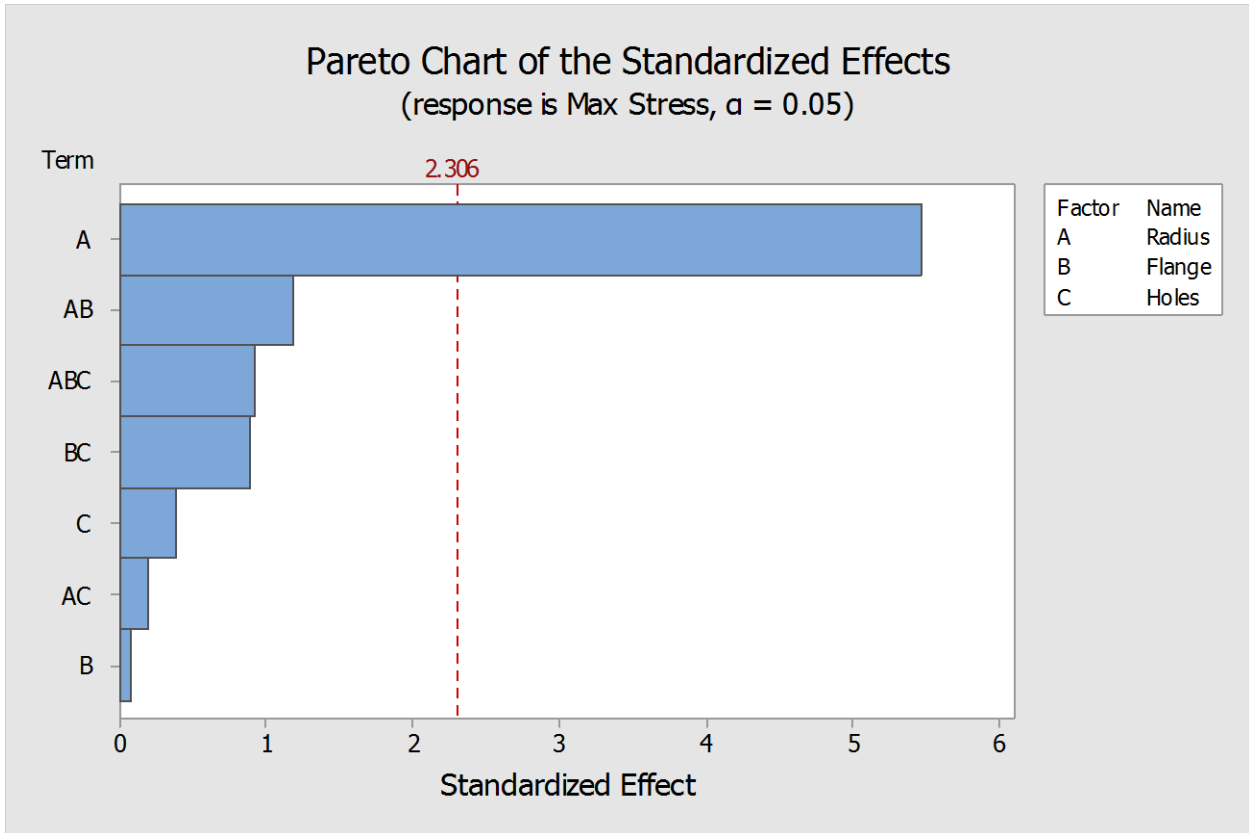
R Large residual

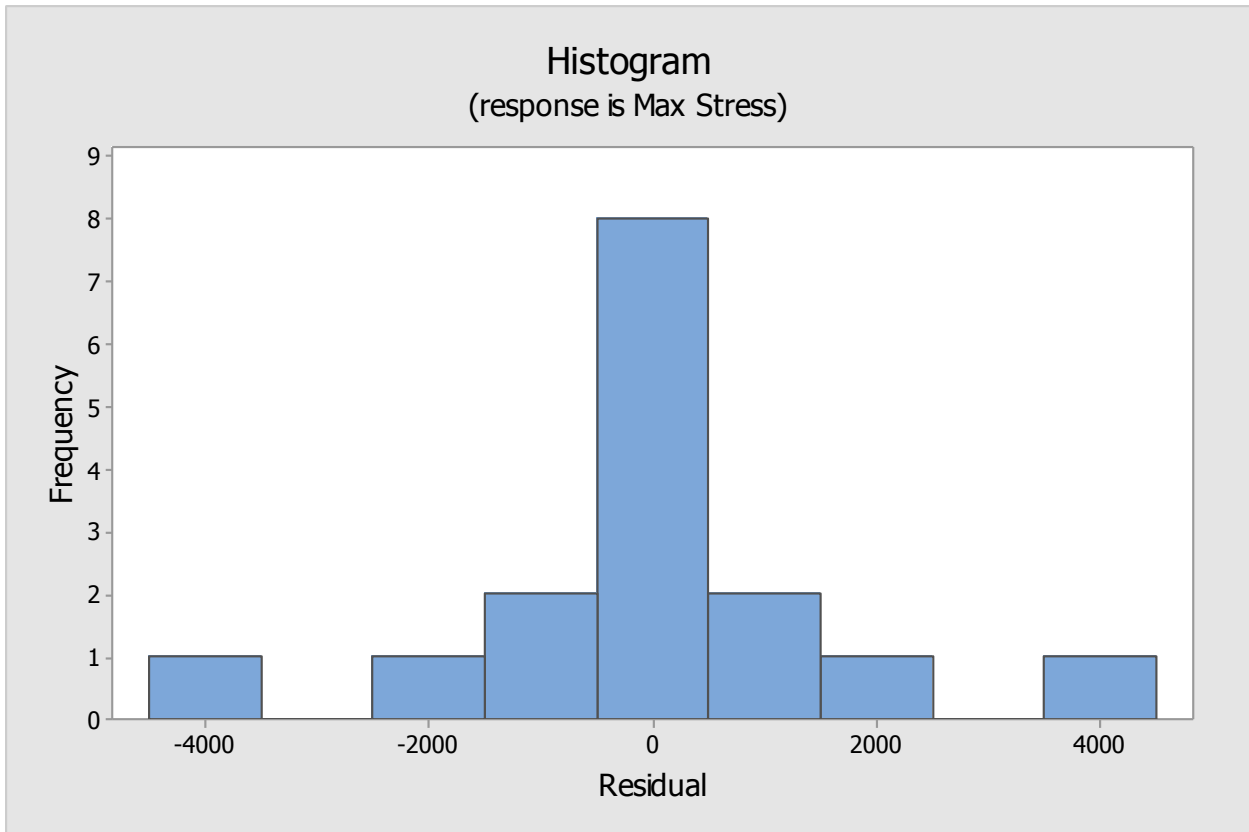
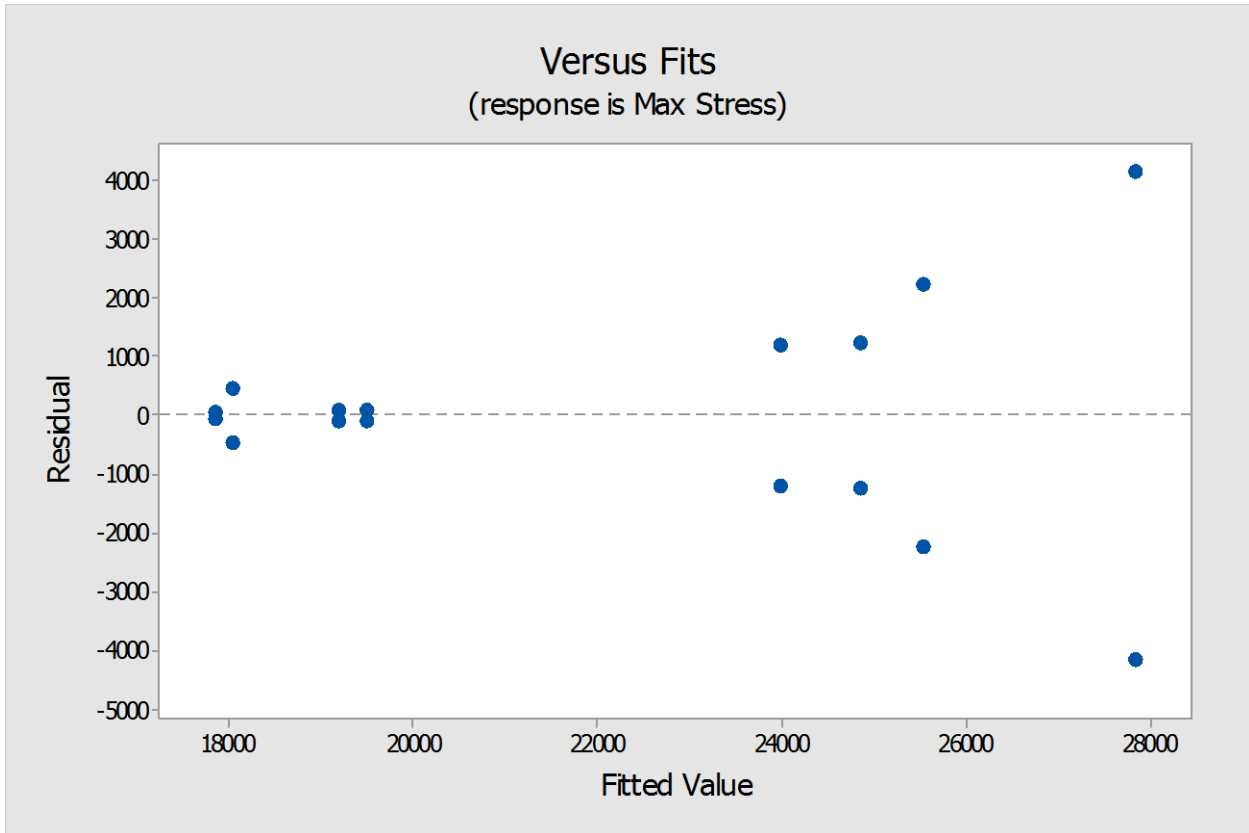
Normal Plot of the Standardized Effects  
(response is Max Stress,  $\alpha = 0.05$ )

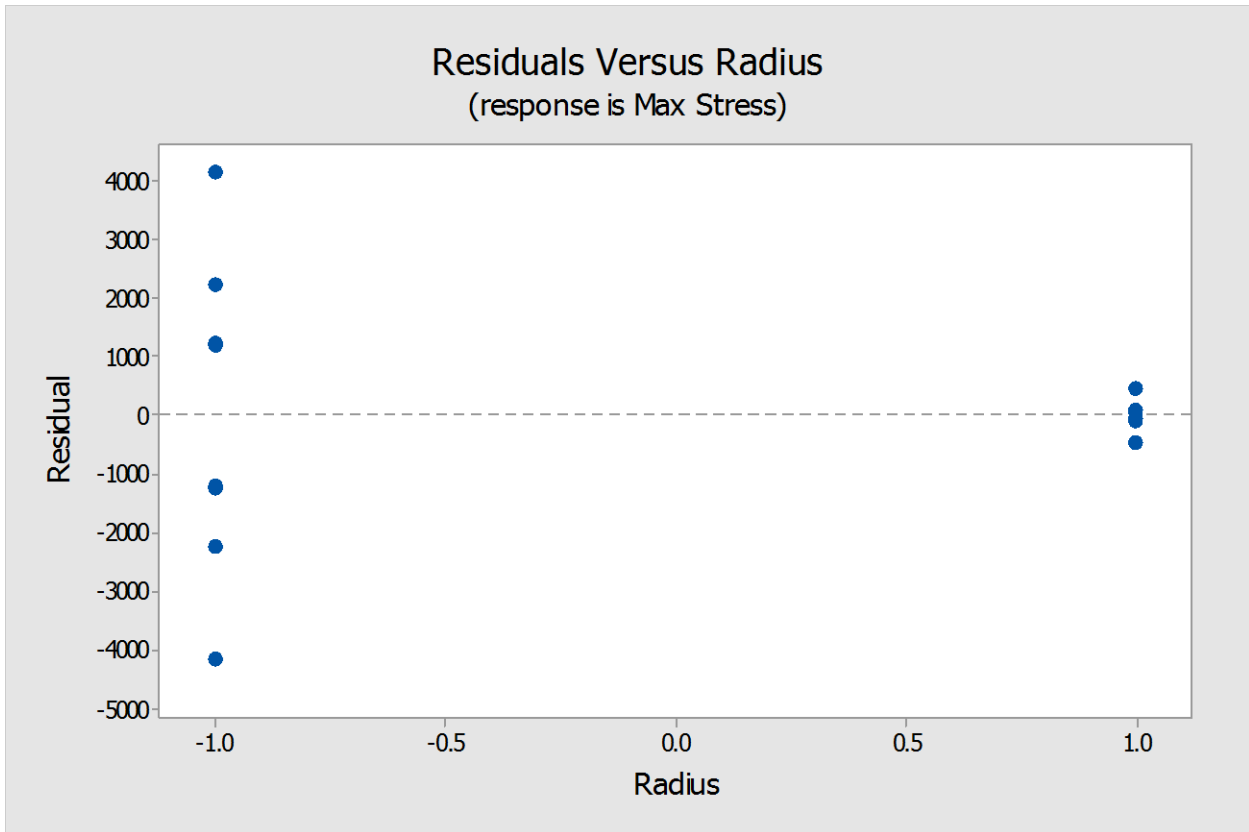
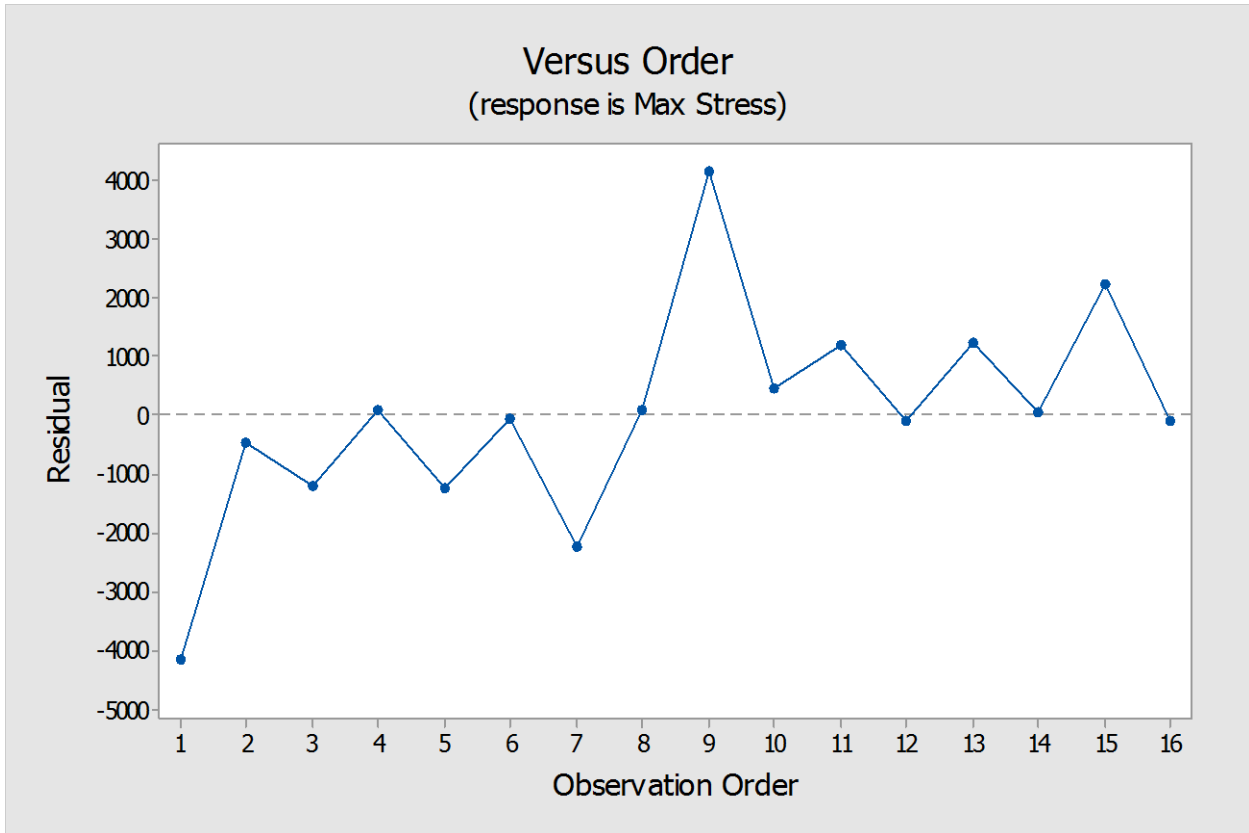


Half Normal Plot of the Standardized Effects  
(response is Max Stress,  $\alpha = 0.05$ )

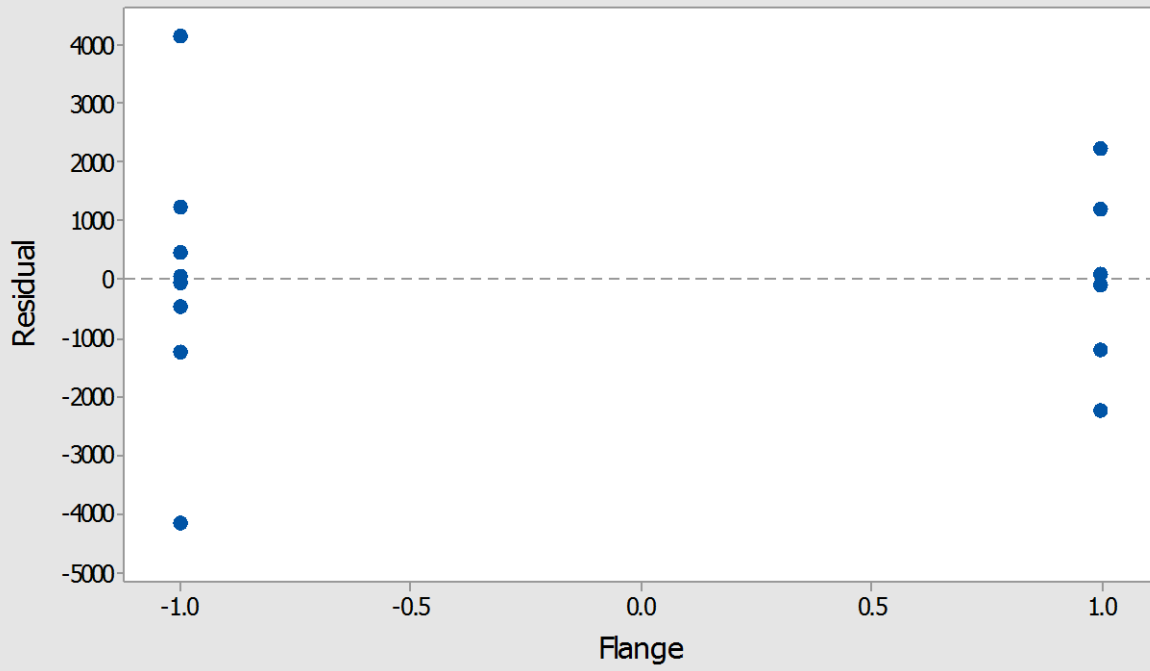




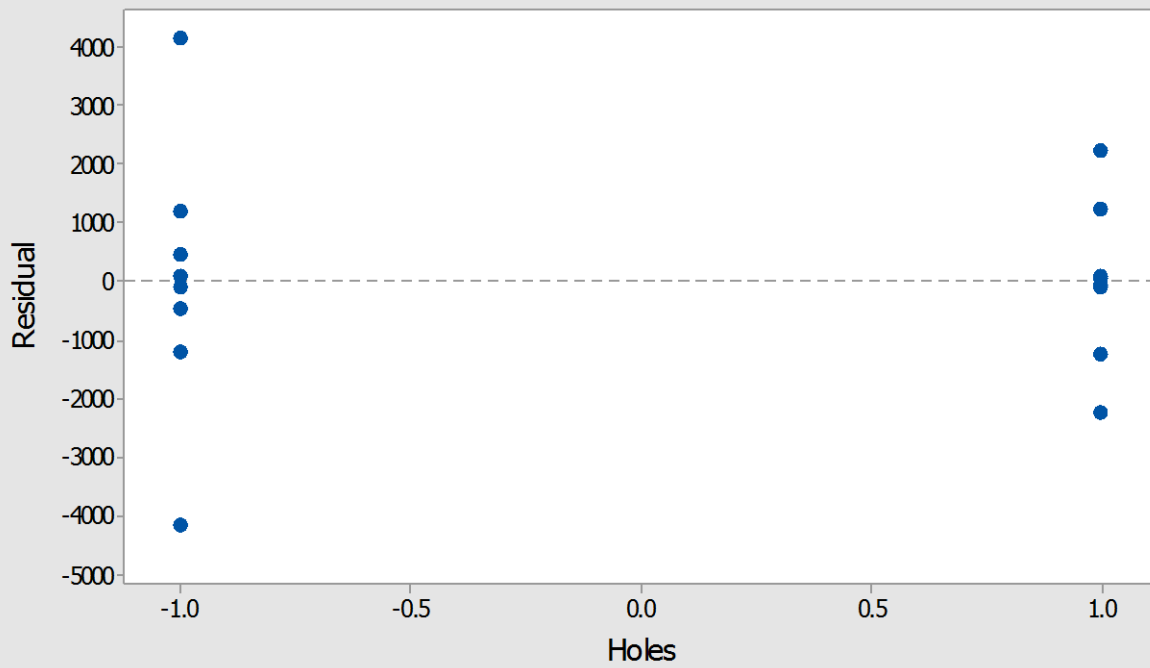




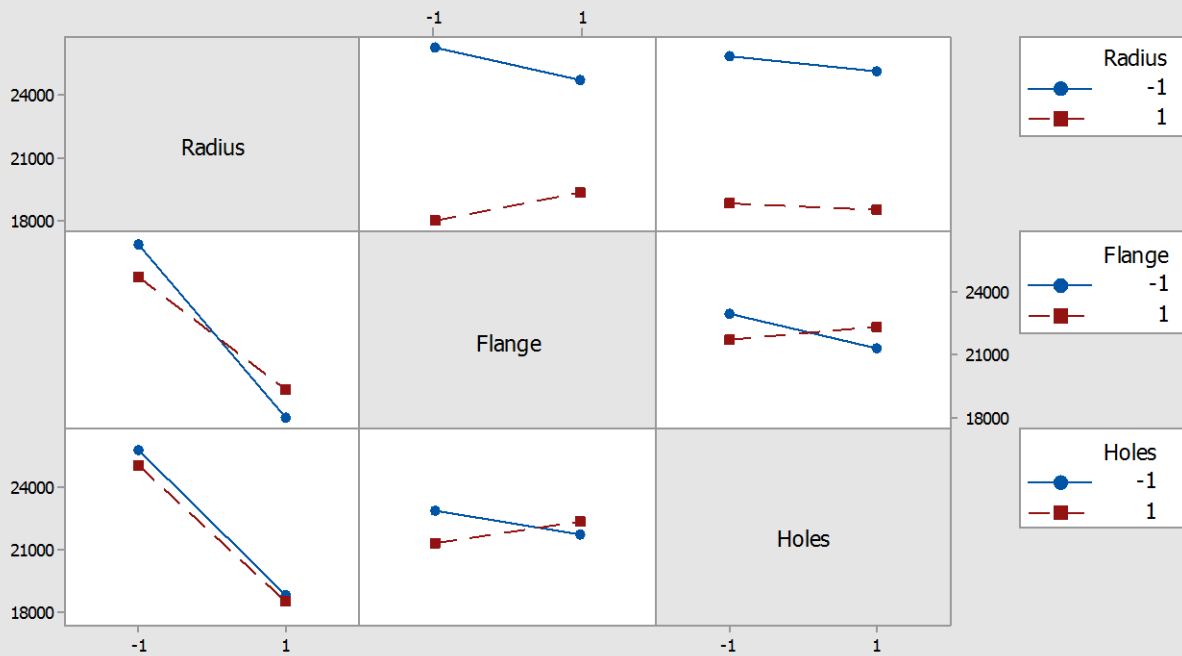
Residuals Versus Flange  
(response is Max Stress)



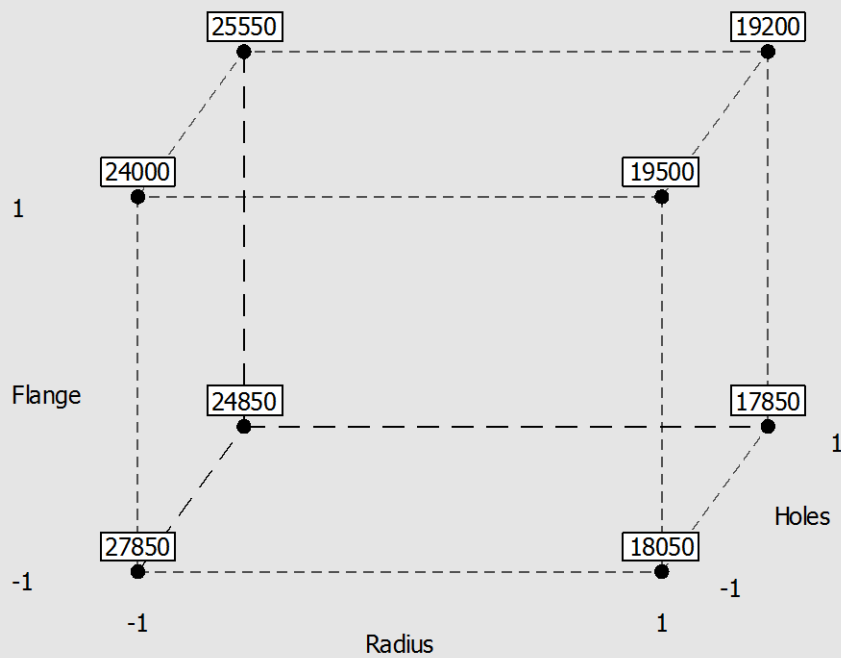
Residuals Versus Holes  
(response is Max Stress)



Interaction Plot for Max Stress  
Data Means



Cube Plot (fitted means) for Max Stress



## Response Optimization: Max Stress

### Parameters

Response	Goal	Lower	Target	Upper	Weight	Importance
Max Stress	Minimum		17600	32000	1	1

### Solution

Solution	Radius	Flange	Holes	Max Stress	Fit	Composite Desirability
1	1	-1	1	17850		0.982639

### Multiple Response Prediction

Variable	Setting
Radius	1
Flange	-1
Holes	1

Response	Fit	SE Fit	95% CI	95% PI
Max Stress	17850	1786	(13732, 21968)	(10717, 24983)

