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Consolidation of Deep Carpet Cleaner and Vacuum Cleaner: A Capstone Project to Investigate and Recommend Needed Improvements

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Abstract

A senior capstone project at Western Michigan University investigated shortcomings in combination vacuum / wet cleaning systems that purportedly remove dry debris and pet hair while performing wet cleaning of dirty surfaces. Having confirmed that these systems may promise more than they can deliver, the team explored the possibility of genuinely consolidating a vacuum cleaning system and a deep cleaning system. An effective consolidation would allow for the two methods of cleaning simultaneously, reducing process time and increasing customer satisfaction. Using a base model deep cleaner as a foundation, the team performed extensive testing to verify current lack of performance, and then followed the engineering design process to theorize, design, and test a proposed consolidation of the two functions and improvements. The use of computer aided design (CAD) and computational fluid dynamics (CFD) software allowed for accurate design creation and analysis. This multidisciplinary senior project drew on team members' experience and skills acquired in their undergrad programs while pushing them to proactively seek out as-yet unfamiliar software and techniques. Like all capstone project teams, a final formal presentation was required, and the team had to find a way to convey the highly technical nature of the project in a way that satisfied their engineering specialists, while still making the project relevant and interesting to the broad audience attending their presentation. The team feels the combination of exacting technical design and manufacturing skills, proactive research, and communicating specialized knowledge and findings to multiple audiences has well-prepared them for similar challenges to come in industry.

Introduction: Need for Project

Carpet is often a preferred option over hardwood or tile for several reasons, including reducing slips, softening falls, acoustic improvements, and improved thermal resistance [1]. Parents and pet owners are the main users for both vacuum cleaners and carpet cleaners due to the increased probability of stains, debris, and hair as a result of owning pets or having children. These two user groups desire simple and convenient cleaning options to allow their focus to remain on their children or their pets [2], [3].

After preliminary tests of these devices, it was apparent that carpet cleaners clogged often when the carpet was not vacuumed prior to use, a necessary step listed in the Bissell ProHeat manual. As a result, hair and debris became trapped in the brushes and large clumps of hair and dirt were left behind on the carpet after use. The desire for versatility as well as an expressed customer dissatisfaction due to current design limitations demonstrated a need to design a carpet cleaning solution capable of both vacuuming and deep cleaning; this was the impetus for this senior capstone design project. The proposed design must have all the current capabilities of a carpet deep cleaner with the added benefit of surface residue and debris removal.

Project scope and deliverables

Several design requirements were assessed during the redesign of the deep carpet cleaner. First, consolidation was achieved by incorporating a vacuum system alongside the current deep cleaner model. This was achieved by segregating both fluid and debris flow paths from intake to collection chamber. Baseline deep cleaner performance was analyzed using a current deep cleaner model, and the subsequent data was used to compare against the performance of the proposed solutions to determine design feasibility. Further considerations for the proposed design solution included prototyping the designed components, assessing manufacturability of the design, and determination of material selection.

Project objectives

Several tasks were required to create and implement a consolidated deep carpet cleaner/vacuum cleaner design. Market research and background information were collected around the functionality of both vacuum cleaners and deep carpet cleaners to obtain a better understanding of the two processes [4], [5], [6], [7]. Positive attributes from researched vacuum cleaning and deep cleaning systems were considered throughout the design process [8]. In addition, testing parameters were defined in order to analyze the functionality of the proposed design. Computer-aided design (CAD) models of both the baseline model, as well as all proposed solutions, were created and analyzed using computational fluid dynamics (CFD) software. Manufacturing options for prototyping the proposed design were also researched to produce physical examples of the designed components.

Deep Cleaner and Vacuum Cleaner Background

A vacuum cleaner is a household device that utilizes suction to remove surface debris, dirt, hair, and other loose particles from carpet, hardwood, or tile [9]. All particles removed from the surface are stored in either a bag or a compartment that can be emptied directly into the trash, reducing the amount of airborne dust and debris. Vacuum cleaners are a common household cleaning tool as they are intuitive, reliable, durable, and maneuverable.

How vacuum cleaners work

Modern vacuum cleaners are complex systems with many components, so it is essential to understand how these machines function before attempting to improve upon current models. The six essential components that make up a vacuum cleaner include the electric motor, the intake port, an exhaust port, a fan, a porous bag or collection chamber, along with the housing that holds all the components together [9]. These main components work together to produce a pressure drop as the air passes through the blades. Because pressure flows from high to low, suction is produced within the system as the lower pressure in the vacuum system drops below the environmental surrounding pressure. Air then flows through the intake port on its way through the system and to the exhaust port. Before reaching the exhaust port, the collected debris is filtered and held in a container for future disposal [9], [10]. Suction produced from vacuum cleaners is dependent upon the power of the electric motor and the passage provided for airflow. Understanding the functionality of a vacuum cleaner and its components provided insight on valuable design improvements during design creation and selection.

How carpet cleaners work

Carpet cleaning devices generally utilize water and cleaning solutions in conjunction with a brush to remove deep stains and loosen grime within dirty carpet. The water and solution containing the carpet debris is then suctioned by the carpet cleaner into a dirty water reservoir, which can be emptied.

Carpet cleaners, also known as deep cleaners, are machines that operate under similar principles as vacuum cleaners. A fluid system consisting of a pump, a solution tank, a recovery tank, and sometimes a heating unit is integrated into the machine to provide suction and clean various surfaces [11].

Once a solution is applied, suction is created through the machine allowing for the collection of debris and the cleaning solution. Instead of passing through a filtration system or to a collection unit, the dirty water is deposited into the recovery tanks to be emptied after use.

Types of carpet cleaners

There are several types of carpet cleaners available in the current market. Each cleaner has its advantages and disadvantages for consumer comparison when selecting a cleaning device. Various carpet cleaners utilize different cleaning solutions, cleaning throughput times, and cleaning area coverage. Several cleaners are designed for generalized use and can be used for multiple applications, while other cleaners are highly specialized for specific applications [12]. Sufficient background material was gathered to determine basic functionality of both vacuum and deep carpet cleaners. With a good understanding of the current problem and how each type of system operates, brainstorming began for conceptual design solutions and a project plan was developed.

Methodology and Project Plan

Brainstorming took place to develop numerous potential solutions to solve the issues previously described. From this brainstorming, the three best proposed solutions were determined for consideration in further development through the design cycle. A Pugh matrix was developed to compare these proposals based on desired criteria collected from customer reviews and marketing research (Appendix A). After analyzing the Pugh matrix, it was determined that consolidating a vacuum cleaning system and deep cleaning system into one device was the best option. This proposed solution utilized two separate intakes for each system connected via a y-joint, allowing for a split flow path leading to a universal collection chamber (Figure 1).

Based on a moderate review, the Bissell ProHeat 2x Revolution Pet Pro model was selected for analysis of baseline performance. Reverse engineering was done to better understand crucial components for flow path development. Nine main assembly parts were determined as critical components, starting from the intake of the flow path at the head of the deep cleaner, internal cavities of the body, hosing components, and tubes that lead to the collection chamber. All components were precisely measured and documented for the necessary CAD work to be completed.

The first step in baseline model development was the creation of a representative CAD assembly. Inventor Professional 2020, a three-dimensional modeling software, was used to generate all CAD models throughout the project. To ensure the model was representative of the actual system, all critical dimensions were measured with calibrated instrumentation to ensure accuracy and precision in every measurement (Figure 2).

The creation of the representative baseline model within CAD was then used to develop potential design improvements within the deep cleaner device. All proposed design components were incorporated into the baseline model, including the addition of a two-intake device and a split flow path (Figure 3).

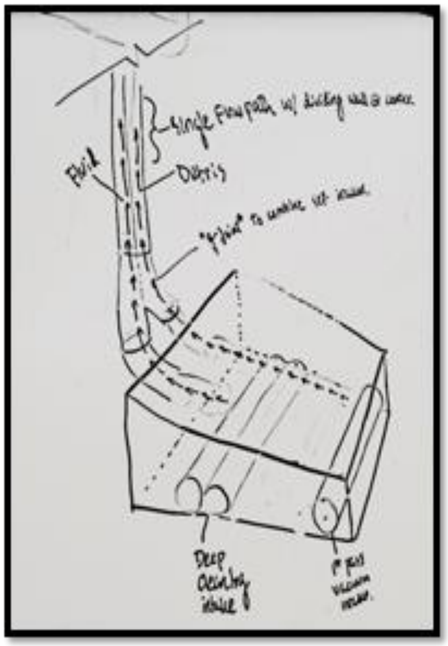

Figure 1. *Initial Concept Sketch*

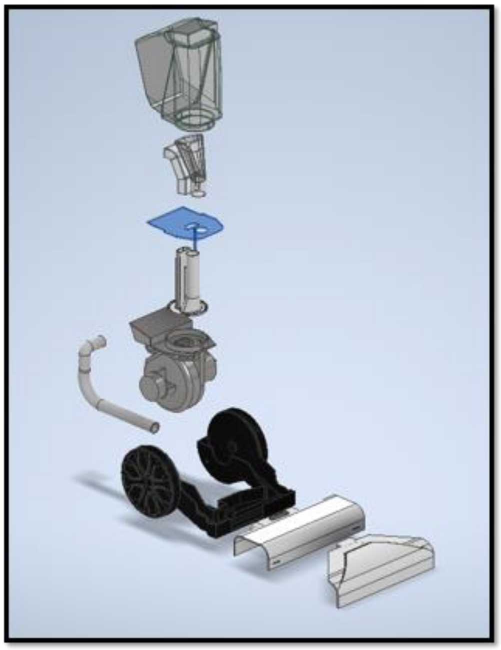

Figure 2: *Baseline Exploded View*

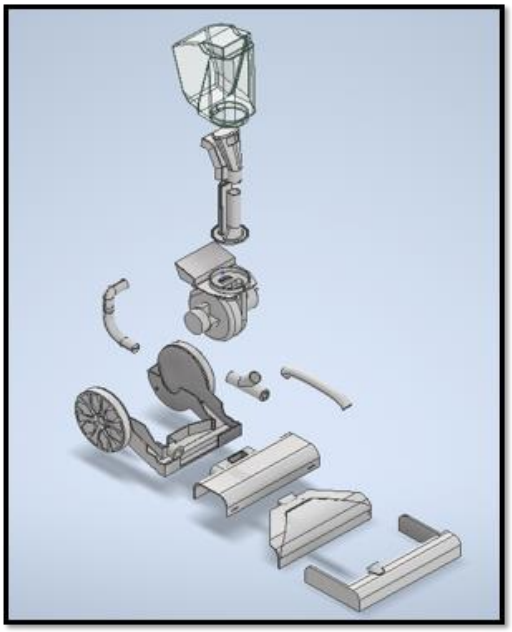

Figure 3: *Proposed Solution Exploded View*

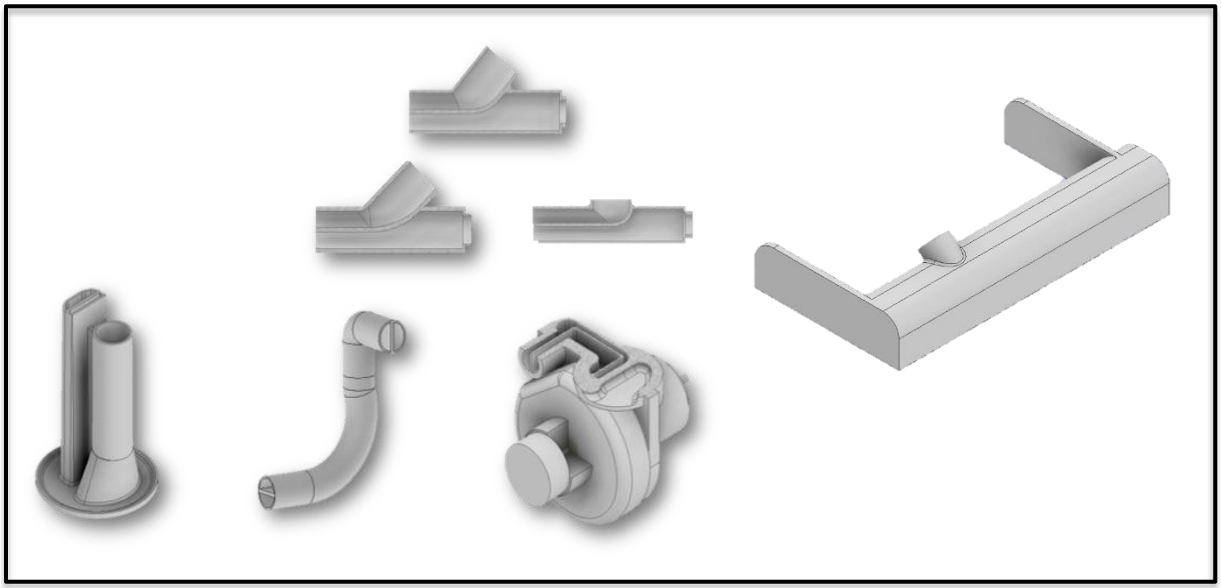

Figure 4: *Detailed Proposed Components*

Several design changes were implemented within the existing baseline design (Figure 4). Once all the CAD geometries were created and accurately represented the physical models, Computational Fluid Dynamics (CFD) analysis was initiated.

Computational Fluid Dynamics (CFD) Analysis Setup

Computational fluid dynamics analysis served as the best option to quickly analyze and interpret the performance of both baseline and proposed solution designs. Before diving into analysis, it was necessary to define which CFD program would best fit the needs of the project, the group decided on Ansys for its CFD capabilities. For an internal flow analysis, it was required that an inlet and an outlet be defined within CAD geometry. The flow path of the system was defined using the generated CAD model and an input velocity was specified at the inlet location. Fluid dynamic simulations could then be run based off of these set parameters and various fidelity settings or computing accuracy. Based on five selected critical points shown below (Figure 5), the CFD results could then be reported and analyzed.

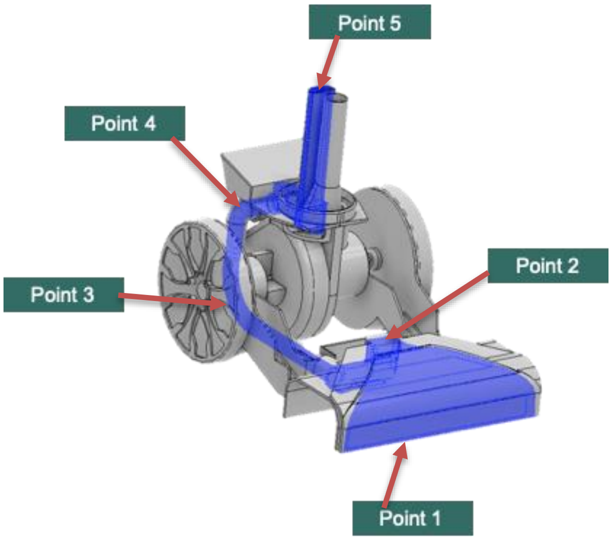

Figure 5: *Baseline Pressure Locations*

Computational Fluid Dynamics (CFD) Analysis Results

The results of the analysis indicated where design improvements could be made to increase device effectiveness for the proposed system solution. The resulting values from this CFD analysis indicated which design allowed for maintaining fluid performance while consolidating two systems into one. The following section, outlines the results from both baseline, and proposed solution analysis. Specific data correlating to baseline and each proposed design iteration is located in appendix F. CFD conducted for the baseline and selected proposed solution model, provided results for pressure readouts at points 1 through 5 as shown in Appendix F. Fringe plot and streamline plot results shown below in figure 6: Baseline CFD, Figure 7: Proposed Fluid, and Figure 8: Proposed Debris display an array of colors throughout the flow path.

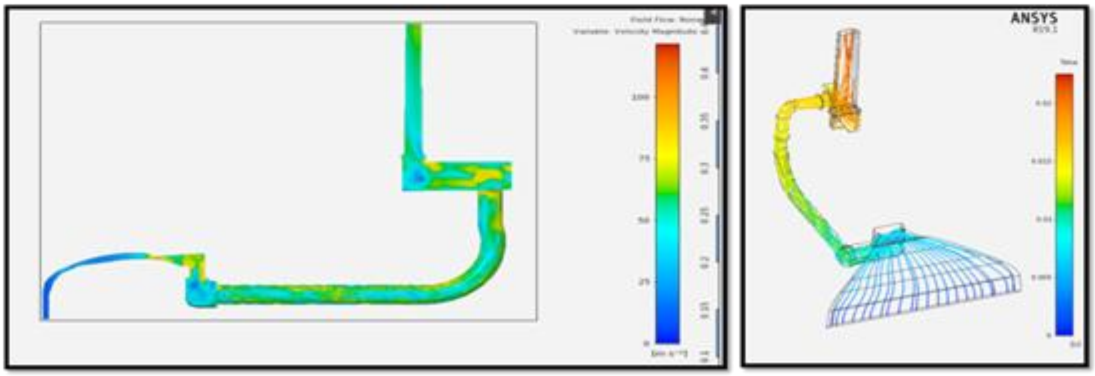

Figure 6: *Baseline CFD*

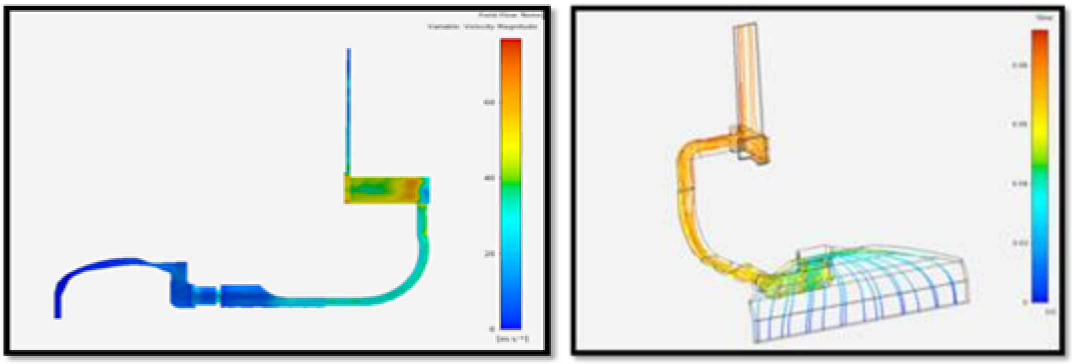

Figure 7: *Proposed Fluid*

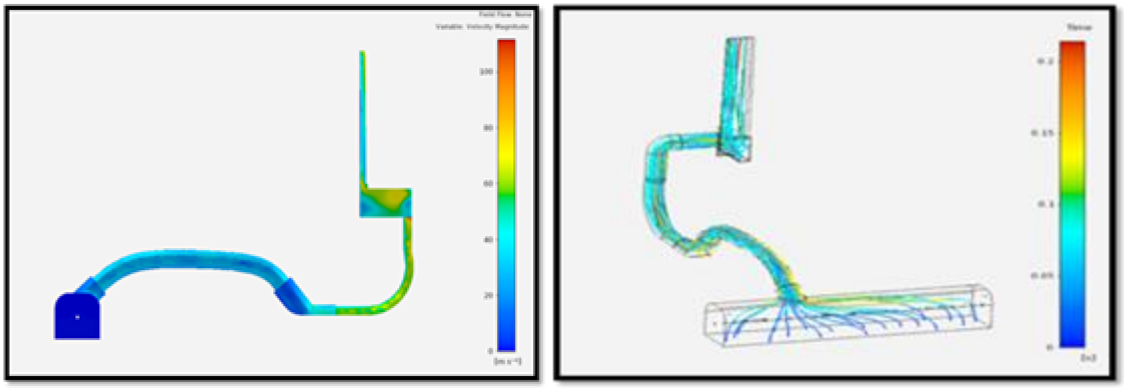

Figure 8: *Proposed Debris*

These colors represent higher and lower velocity readouts by warmer and cooler colors respectively. These results were compared to validate that consolidation of a deep cleaning and vacuum system, while retaining baseline flow performance, was possible.

The probed point results from the CFD analysis in both baseline and proposed solutions, provided a visual and numerical representation of analysis data. Appendix F shows a superposition of both results, indicating variance in points 1 through 5. This graph shows pressure drop from points 1 to 5, validating our CFD setup representing a vacuum created at point 5. It was important that these results were as accurate as possible, and representative of the physical system. Data collected from the CFD analysis was used to support the design proposal in the end.

Project Team: Challenges and Successes

The senior capstone design project ideally presents challenges for students to put their knowledge to work, and this one certainly did that. Our design team was four students from different majors, working over two semesters to design a solution to a problem. Within the roughly 32 weeks, the cross-functional team not only applied their academic learning, but learned new technologies, software, and engineering practices. Our capstone experience also places great emphasis on professional development, particularly in areas of communication, teamwork, project management, and lifelong learning.

At the start of this project, we had little insight as to what the learning curve might look like. It was understood that this project was going to be demanding of our technical knowledge as well as problem-solving skills, and that our group would encounter setbacks or roadblocks. We didn’t anticipate, however, having to teach ourselves complex computer software and how to utilize testing devices with little to no experience prior to use. A majority of time spent on this project was, in fact, conducting studies to check results obtained from Computational Fluid Dynamics (CFD) software or validating pressure probe readouts. Early on in the design process, the team had to identify the ideal approach to reverse engineering, specifically what CAD program to use and why. After establishing what system to use, Inventor 2020, the team moved to modeling and eventually testing of designs. To do this, the CFD program most compatible with the selected CAD program had to be chosen. The fluent workbench, provided by ANSYS, allowed for an analysis of the current and proposed design from a fluid dynamics perspective. Many hours were spent looking at data generated from this workbench, and determining whether or not it was accurate and/or useful. Once the team was sure that we had a good understanding of the CFD program, hard input data from the deep cleaner model had to be obtained. This data was gathered through the use of a pressure differential manometer, a gauge that measured the pressure drop in the vacuum created by the deep cleaner. This device required a brief training to ensure proper use, provided by a professor from a different department. Even after the training, there were some discrepancies in obtained data based on who was operating the device and probe orientation. The final data set was an average across all probe orientations while utilizing three different operators.

Development and Application of Professional Skills

At different periods throughout the two semesters, the team was required to present their work to a variety of audiences. This experience strengthened not only their public speaking abilities but also their professionalism and proved to be extremely important, because no information is useful if the audience does not understand the material presented. The group had to appropriately present their information based on the audience to ensure an understanding of the material was gained. Audiences ranged anywhere from weekly technical meetings with the project advisor, to monthly progress reports to university peers and faculty, and finally, in a formal presentation open to the public, consisting of young students, peers, faculty, family, and members of industry.

After investing all of the technical background, testing, analysis, and CAD work necessary for this project, the team members were comfortable discussing project details to any level of audience, diving into further detail for technically inclined audiences or simplifying complex aspects of the project to assist general audiences. Ultimately the group was able to logically present a summary of the project to a general audience showing the importance of the project and how deliverables were met while still answering technical questions from engineering experts.

Working in engineering teams was also a challenge many of the senior design groups faced throughout the process of developing their projects. For this project some of the key factors that were essential to the success of the project were staying organized, developing regular and consistent communication, and structuring a reasonable plan for completing each task necessary for this project. To be successful in all of these areas, the team utilized some skills and practices developed throughout their time in university.

For example, in many of the CAD classes students took, there was a high emphasis on file structure, saving convention, and general organization of folders and files. Because this team had four members contributing numerous CAD files, Excel charts and tables, research materials, formal documentation, and endless simulation data, staying organized while file sharing and saving was essential for the retrieving data at later stages of the project. This is not only a good practice to establish before getting into the workplace but helped this team stay organized with the massive amount of files accumulated throughout the 32-week project.

Learning and applying project management skills and techniques was also necessary to not only stay on task but to ensure necessary tasks were completed and crucial deadlines were met. A clear scope statement was followed by a realistic schedule: a Gantt chart listing critical tasks and deadlines that needed to be met in order to complete the project to fruition and on time.

Part of meeting these deadlines was staying in constant communication with the entire team. Because each member of this team also had other coursework and employment commitments, the four engineering students, course advisor, and technical advisor all kept communication through email and weekly meetings where meeting minutes were maintained. The students themselves had a running group text conversation set up to enable constant communication and shared resources were accessed through Google drive. Utilizing the online platform was important so that all members of the team had constant access to any data, information, or resources necessary while working independently. With so many other commitments pulling the group away from each other, this established communication was necessary for staying organized and on task to complete the project.

After four years of developing technical and broad engineering concepts and practices, we were able to combine our specific talents and gained knowledge to complete all of the necessary tasks for the completion of this project. With a diverse set of skills across four group members and by utilizing the tools outlined above, our group was able to complete most of the goals our project set out to accomplish. Our group was also able to present the sum of two semesters worth of work to a wide variety of people to show the importance of our project and all of the work that went into producing the results we obtained. This project was a great way to finish our undergrad experience and provided the development necessary to prepare us for projects to come once we start working in the workplace with similar team set ups and projects.

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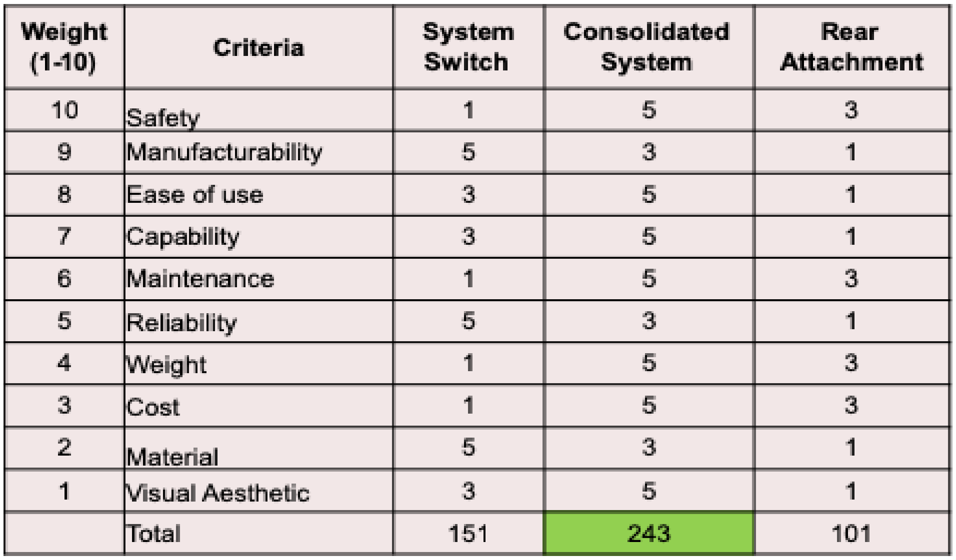
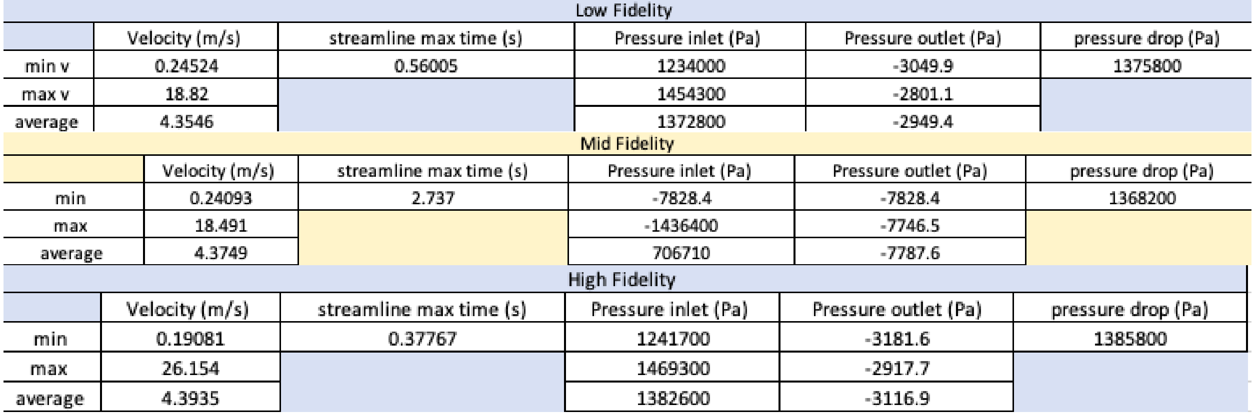
Appendices

Appendix A. Pugh Matrix utilized for design selection, with design criteria weighted from least important to most important.



Weight (1-10)	Criteria	System Switch	Consolidated System	Rear Attachment
10	Safety	1	5	3
9	Manufacturability	5	3	1
8	Ease of use	3	5	1
7	Capability	3	5	1
6	Maintenance	1	5	3
5	Reliability	5	3	1
4	Weight	1	5	3
3	Cost	1	5	3
2	Material	5	3	1
1	Visual Aesthetic	3	5	1
	Total	151	243	101

Appendix B. Data recorded from the fidelity toggle study for CFD analysis.



Low Fidelity

	Velocity (m/s)	streamline max time (s)	Pressure inlet (Pa)	Pressure outlet (Pa)	pressure drop (Pa)
min v	0.24524	0.56005	1234000	-3049.9	1375800
max v	18.82		1454300	-2801.1	
average	4.3546		1372800	-2949.4	

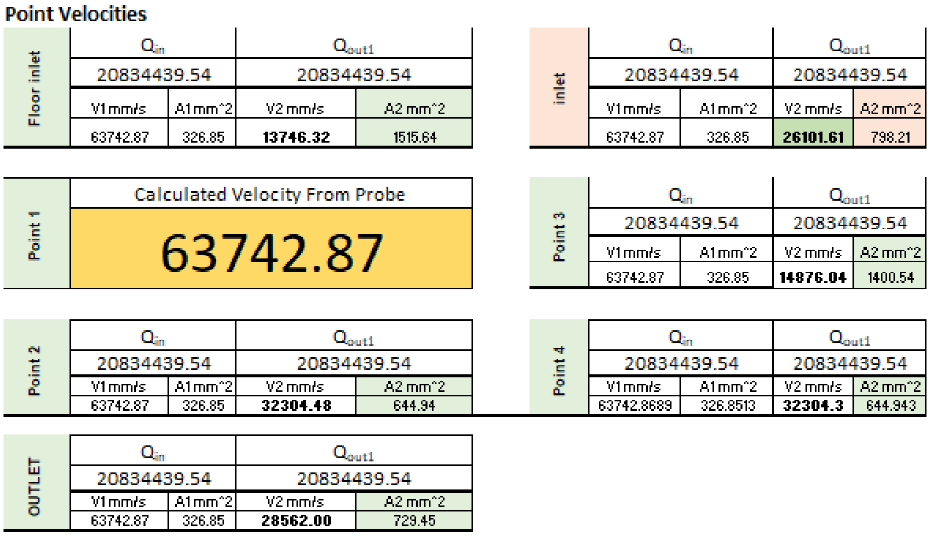
Mid Fidelity

	Velocity (m/s)	streamline max time (s)	Pressure inlet (Pa)	Pressure outlet (Pa)	pressure drop (Pa)
min	0.24093	2.737	-7828.4	-7828.4	1368200
max	18.491		-1436400	-7746.5	
average	4.3749		706710	-7787.6	

High Fidelity

	Velocity (m/s)	streamline max time (s)	Pressure inlet (Pa)	Pressure outlet (Pa)	pressure drop (Pa)
min	0.19081	0.37767	1241700	-3181.6	1385800
max	26.154		1469300	-2917.7	
average	4.3935		1382600	-3116.9	

Appendix C. Calculation of velocities at various points, given the derived velocity described in the methodology section.



Point Velocities

	Q_{in}		Q_{out1}	
Floor inlet	20834439.54		20834439.54	
	V1 mm/s	A1 mm^2	V2 mm/s	A2 mm^2
	63742.87	326.85	**13746.32**	1515.64

	Q_{in}		Q_{out1}	
inlet	20834439.54		20834439.54	
	V1 mm/s	A1 mm^2	V2 mm/s	A2 mm^2
	63742.87	326.85	**26101.61**	798.21

Point 1	Calculated Velocity From Probe
	63742.87

	Q_{in}		Q_{out1}	
Point 3	20834439.54		20834439.54	
	V1 mm/s	A1 mm^2	V2 mm/s	A2 mm^2
	63742.87	326.85	**14876.04**	1400.54

	Q_{in}		Q_{out1}	
Point 2	20834439.54		20834439.54	
	V1 mm/s	A1 mm^2	V2 mm/s	A2 mm^2
	63742.87	326.85	**32304.48**	644.94

	Q_{in}		Q_{out1}	
Point 4	20834439.54		20834439.54	
	V1 mm/s	A1 mm^2	V2 mm/s	A2 mm^2
	63742.8689	326.8513	**32304.3**	644.943

	Q_{in}		Q_{out1}	
OUTLET	20834439.54		20834439.54	
	V1 mm/s	A1 mm^2	V2 mm/s	A2 mm^2
	63742.87	326.85	**28562.00**	729.45

Appendix D. Flow rate ratios representing various percentages of baseline flow rate.

Intake velocities 60/45					
Vacuum inlet area	16169.102				
Vacuum outlet area	166.935				
Deep clean Inlet area	2212.525				
Deep clean oulet area	90.073				
Vacuum Probed half	180.023				
Deep clean probed half	180.023				
Baseline Q (mm^3/2)	20834439.5				
Deep Clean Q (54%)	11250597.3	in	5084.958	out	124905.3

Presure Readout

Deep Clean		Vacuum		Diff.
2	-19973	2		

Deep Clean Q (10%)	2083443.95	in	941.65894	out	23130.616

Presure Readout

Deep Clean		Vacuum		Diff.
2	-849.94	2		

Deep Clean Q (20%)	4166887.9	in	1883.3179	out	46261.231

Presure Readout

Deep Clean		Vacuum		Diff.
2	-3046.2	2		

Deep Clean Q (22%)	4583576.69	in	2071.6497	out	50887.355

Presure Readout

Deep Clean		Vacuum		Diff.
2	-3636.4	2		

Deep Clean Q (25%)	5208609.875	in	2354.1474	out	57826.539

Presure Readout

Deep Clean		Vacuum		Diff.
2	-4559.5	2		

Deep Clean Q (30%)	6250331.85	in	2824.9768	out	69391.847

Presure Readout

Deep Clean		Vacuum		Diff.
2	-6467.1	2		

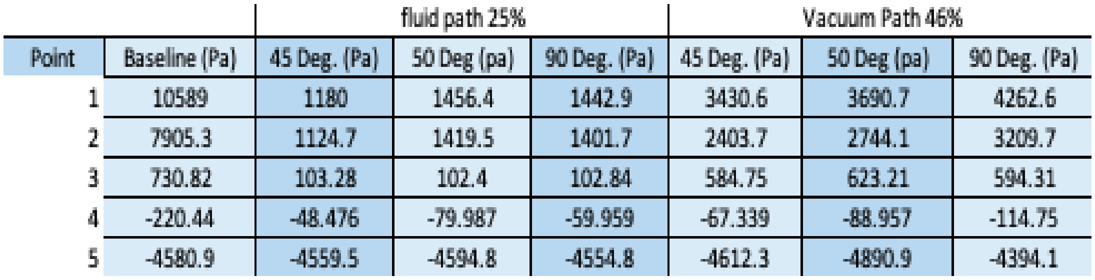
Deep Clean Q (90%)	18750995.55	in	8474.9305	out	208175.54

Presure Readout

Deep Clean		Vacuum		Diff.
2	-50751	2		

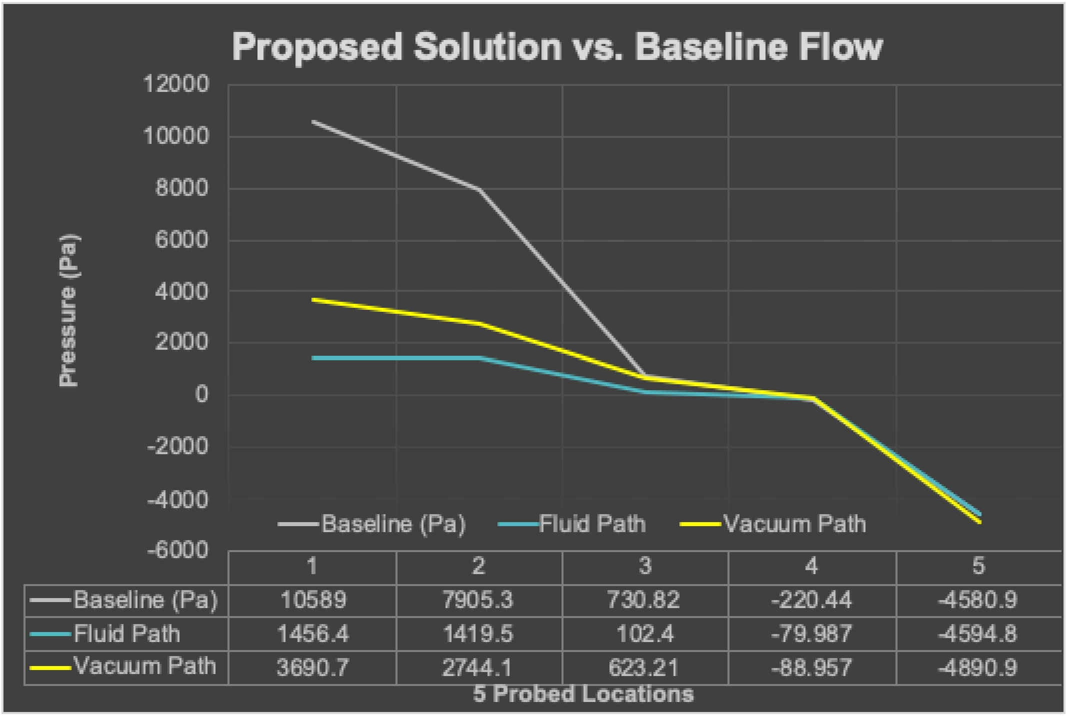
The main parameter compared is the pressure reading at “point 5” at the collection chamber. The desired pressure value of -4580.9 Pa was used to determine the flow rate percentage. The chosen flow rate percentage for the deep cleaning flow path was 25%, as it resulted in the closest point five pressure reading to original baseline value.

Appendix E. Pressure data supporting the selection of Y-joint angle.



		fluid path 25%			Vacuum Path 46%		
Point	Baseline (Pa)	45 Deg. (Pa)	50 Deg (pa)	90 Deg. (Pa)	45 Deg. (Pa)	50 Deg (pa)	90 Deg. (Pa)
1	10589	1180	1456.4	1442.9	3430.6	3690.7	4262.6
2	7905.3	1124.7	1419.5	1401.7	2403.7	2744.1	3209.7
3	730.82	103.28	102.4	102.84	584.75	623.21	594.31
4	-220.44	-48.476	-79.987	-59.959	-67.339	-88.957	-114.75
5	-4580.9	-4559.5	-4594.8	-4554.8	-4612.3	-4890.9	-4394.1

Appendix F. Superimposed pressure plots for baseline and proposed solution flow paths.



	1	2	3	4	5
Baseline (Pa)	10589	7905.3	730.82	-220.44	-4580.9
Fluid Path	1456.4	1419.5	102.4	-79.987	-4594.8
Vacuum Path	3690.7	2744.1	623.21	-88.957	-4890.9