

Modular Sterile Cleanroom

Initial Design Report Template

Logan Bennett – Test Manager and Manufacturing Engineer

Michelle Borzick – Project Manager and Logistics Manager

Gia Neve – Financial Manager, Logistics Manager, Web Developer

Aaron Reynoza – CAD Engineer and Manufacturing Engineer

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Project Sponsor & Faculty Advisor: Dr. Timothy Becker

Instructor: Dr. David Willy

DISCLAIMER

This report was prepared by students as part of a university course requirement. While considerable effort has been put into the project, it is not the work of licensed engineers and has not undergone the extensive verification that is common in the profession. The information, data, conclusions, and content of this report should not be relied on or utilized without thorough, independent testing and verification. University faculty members may have been associated with this project as advisors, sponsors, or course instructors, but as such they are not responsible for the accuracy of results or conclusions.

EXECUTIVE SUMMARY

The "Modular Sterile Cleanroom" project aims to design an ISO Class 7 modular sterile cleanroom with a fan filter unit (FFU) to be used in the manufacturing of medical devices. The project will also convert a current cleanroom into a gowning room that connects to the designed cleanroom. The cleanroom will meet customer and engineering requirements related to modularity, capacity, and ISO Class 7 standards.

This report will outline the detailed project objectives as identified by the project client and sponsors. All course and client deliverables will be described in detail. The team will also set success matrices to measure the progress and outcome of the project.

Customer and engineering requirements will be created and detailed. A House of Quality will compare all customer and engineering requirements by weighing their importance within the overall design. The most important engineering requirements are those related to the customer requirement of meeting ISO Class 7 standards such as maintaining positive pressure, particle count, particle size, airflow, ceiling coverage, and Reynold's number.

Benchmarking of other modular cleanroom designs was researched to determine the advantages and disadvantages of different cleanroom subfunctions. The current cleanroom design is the most beneficial benchmark as the design team can test and manipulate it in person. Literature reviews were completed by each team member focusing on different design aspects. The literature reviews consist of peer reviewed journal articles, textbooks, manuals, and websites focusing on the subtopics of structural integrity/material connections, particle and flow requirements, cleanroom materials, and pressure/temperature requirements. All literature review sources served to help the team complete engineering analysis, mathematical modeling, and concept generation.

The engineering analysis and mathematical modeling was divided among structural, thermodynamic, and computational fluid dynamic (CFD) analyses. Structural analysis calculated frame connection shear forces to be used during the concept selection process. Thermodynamic analysis determined pressure requirements for the cleanroom design. CFD analysis determined the placement of FFUs on the cleanroom ceiling to also be used in the concept selection process.

Black box and functional models of the FFU and cleanroom will be used to identify subfunctions for the concept generation. The generated subfunctions frame connections, material connections, wall/ceiling material, fan number/location, and frame size are further developed into concept variants. Each concept variant advantage and disadvantage are used to create select criteria for each variant. The selection criteria are weighted and ranked to determine the best concept variant of each subfunction.

The final concept variants of each subfunction chosen are square tubing nylon frame connections, screws to connect the materials, all hard wall polycarbonate wall and ceiling materials, two centered FFUs, and a 12x8 frame size. The final concept was developed into a CAD model.

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1 BACKGROUND

The background of the project will be separated into the project description, deliverables, and success matrix. This section will act as a reference point for the project entirety to ensure the design team is meeting project objectives and deliverables.

1.1 *Project Description*

1.1.1 Project Title: Modular Sterile Manufacturing Cleanroom

1.1.2 Project Overview/Summary

The "Modular Sterile Cleanroom" project aims to facilitate the production of medical devices used in stroke treatment by establishing a specialized cleanroom environment. The project involves the design, construction, and testing of a filter-fan unit (FFU) and an extended modular curtained cleanroom area. The cleanroom must adhere to strict standards, ensuring a particle-free and sterile environment for the assembly of critical medical devices. The modular design allows for easy disassembly and reassembly, promoting flexibility and scalability in the manufacturing process.

1.2.3 Project Objectives

The project objectives include to develop and justify the following attributes, including but not limited to:

- FFU compatibility with both the cleanroom and gowning room, ensuring adequate airflow to maintain positive pressure within the cleanroom.
- Design the cleanroom to accommodate up to 6 workers per module, considering necessary equipment.
- Allocate approximately 10' x 10' floor space for each module, with provisions for up to two modules.
- Integrate the existing 3-person cleanroom with the newly designed cleanroom.
- Repurpose the current 3-person cleanroom as a gowning room to ensure compliance with sterile manufacturing protocols.
- Create a new floor plan incorporating assembly station and testing tables.
- Implement cleanroom compliant storage for gowning, emphasizing adherence to proper gowning procedures.
- Conduct airborne particle counts and adhere to specific cleanroom standards for thorough cleanroom validation.
- Document repeatable manufacturing and laboratory processes to ensure consistency and quality control in the production of medical devices.

1.2.4 Key Deliverables

The project will deliver a range of key documents and materials, including:

- Comprehensive literature review
- Detailed project proposal
- Final report highlighting the project's design, implementation, and testing phases.
- Engineering analysis report
- Cost estimate for the duplication of the cleanroom setup
- Detailed bill of materials
- Precise procedure for repeatable manufacturing processes
- Receipts for all project-related expenses
- Potential duplicates of the medical devices and cleanroom areas for future replication.

1.2.5 Sponsors/Client

The client/sponsor for the project is Timothy A. Becker and his company Aneuvus Technologies Inc. Aneuvus Technologies Inc (ATI) is a medical device company organized around bringing a new neurovascular device (PPODA-QT) to clinical trials and potentially to the marketplace for treatment of aneurysms.

1.2.6 Timeline

The project is set to span across two semesters, allowing for thorough research, meticulous planning, and comprehensive execution of the cleanroom development.

1.2.7 Budget

The project has a designated budget of \$10,000, which will be allocated to the necessary resources, equipment, and materials required for the design, construction, and testing phases of the cleanroom development.

1.2 Deliverables

1.2.1 Course Deliverables

Course deliverables are divided into presentations, reports, and prototypes.

1.2.1.1 Presentations

Presentation 1 introduces the project, includes benchmarks and research used to begin designing to the customer's requirement. Presentation 2 will include concept generation, along with calculations and analysis to identify the concepts that best fit the customer requirements, and an up-to-date budget and schedule. Presentation 3 introduces the 1st prototype, the questions the prototype answers, and describes in detail the final design that was selected.

1.2.1.2 Reports

Report 1 elaborates on the information shared in Presentations 1 & 2. Report 2 contains Report 1, as well

as elaborating on information shared in Presentation 3.

1.2.1.3 Prototypes

The first prototype will be a virtual prototype to figure out the required thickness of the polycarbonate walls, as well as the height of the walls off the ground. Pressure simulations using Solidworks and Ansys CFD analysis will be used. The second prototype will begin manufacturing of the cleanroom. The goal here is to test the structural elements of the design, as well as getting a jumpstart on manufacturing which will be completed in early 2024.

1.2.2 Client Deliverables

Client deliverables are reflective of the project's objectives and are separated into two cleanrooms. The goal of the initial cleanroom design is to create a modular, spacious, and affordable cleanroom for use by Dr. Becker and other stakeholders. Based on funding availability, the team will consider building a second cleanroom of the same size which can be attached to the first due to the design's modularity.

1.3 Success Metrics

To consider this project a success it must meet the project objectives, course deliverables, client deliverables, customer requirements, engineering requirements, and manufacturability. To confirm this has been achieved the team will complete manufacturing as early as possible in 2024. This will allow time to test the design's engineering requirements to be tested, complete the addition of a second cleanroom, as well as have the cleanrooms certified by a registered organization before the conclusion of the school year. Another benefit of beginning manufacturing early is that it provides time to correct any mistakes made during the design process.

2 REQUIREMENTS

Requirements of the design project are divided into customer and engineering requirements. Customer requirements are those general design requirements requested by the project's client. Engineering requirements are expanded customer requirements into quantifiable measurements and/or calculations that can be done to satisfy the customer requirements. A House of Quality will be generated to compare the customer and engineering requirements with each other as well as with other benchmarked designs.

2.1 Customer Requirements (CRs)

Based on the client's initial project requirements the team set the customer requirements as modular, transportable, spacious, ISO Class 7 compliant, and generator backup power. Modular refers to the finished cleanroom's ability to be disassembled and reassembled with ease. With a modular cleanroom comes a transportable one. The client requested a cleanroom that can be disassembled and transported if needed to other locations. The client also requested a spacious cleanroom with the ability to house at least six people. Since the cleanroom will be used for medical device manufacturing, it needs to be ISO Class 7 compliant to be certified at the end of the project. Lastly, the client would like a backup generator system to be incorporated in the design to maintain ISO Class 7 certificates when a power outage occurs.

2.2 Engineering Requirements (ERs)

The engineering requirements selected by the design team were generated directly from the customer requirements. The first two customer requirements of modular and transportable are ease of construction-based requirements and will not be evaluated as engineering requirements. Instead, they will be considered during the design for manufacturing process. The customer requirement of spacious directly relates to the engineering requirement of room area. The minimum requirement for room area will be greater than the current cleanroom size of $48ft^2$. However, the design team aims to have an area closer to $100ft^2$ to account for the customer requirement of housing six people. The customer requirement of ISO Class 7 compliant encompasses six engineering requirements: positive pressure, particle count, particle size, airflow, ceiling coverage, and Reynold's number. These values will all be measured as one-sided constraints against the minimum standard requirements. The positive pressure different between the inside and outside of the cleanroom must be a minimum of 0.2 Pa [1]. Particle count and particle size must meet the strictest requirement of a maximum of 352,000 particles of size greater than $0.5\mu m$ [2]. Airflow must meet the minimum requirement of 0.051 m/s or 10 ft/s for the entire room [3]. Ceiling coverage must at least 15% coverage with FFUs [2]. Reynold's number must be less than 3500 to be considered transitional flow and less than 2300 to be considered laminar flow [4]. An initial power requirement estimate for all FFUs is 7200W. A full electrical load analysis will be performed on the cleanroom model in upcoming engineering analyses.

2.3 House of Quality (HoQ)

The team developed a House of Quality, shown in Appendix A, to compare the customer requirements with the engineering requirements. First, the customer requirements were given weights on a scale of 1 to 5. 1 represents less important and 5 represents more important. Then, the customer requirements were directly compared against the engineering requirements on a 1, 3, 6, or 9 ranking system. 1 showed a low correlation between the requirements, 3 and 6 a medium correlation, and 9 a high correction. Positive

numbers showed a positive correlation and negative numbers show a negative correlation. Cells left blank were identified as having no correlation. Based on the rankings of the customer and engineering requirements, the absolute and relative technical importance was calculated. Absolute technical importance was calculated by weighing the customer weight against the rankings. The relative technical importance was then determined based on the absolute technical importance ratings. Room Area ended up ranking the highest of the engineering requirements. This was because it was the only technical requirement with correlations to the modular and transportable customer requirements. The ISO Class 7 compliant requirements all ranked second and third. However, the design team will treat these requirements as more important than the room area going forward. The cleanroom cannot be certified regardless of room area unless it meets the ISO Class 7 requirements. The last ranking engineering requirement was the power requirement. Adding generator backup power is a low priority customer requirement and therefore will also be treated as the lowest priority engineering requirement.

3 Research Within Your Design Space

3.1 Benchmarking

3.1.1 Current Cleanroom Design (ISO 7):

The first cleanroom design featured in benchmarking is the current cleanroom design the team is to reimagine for this project located in **Figure 1**.



Figure 1: Current Cleanroom Design

This cleanroom is 6' x 8' in size and the frame consists of steel that is powder coated and welded together and is disassembles into two pieces. The wall material used here is a vinyl curtain covering the whole enclosure and is using magnetic adhesive strips as connectors. The design consists of one FFU, distributed by Terra Universal, Part no. 6601-24-H. The FFU is 2' x 4' in size, uses a HEPA filter, has top side filter replacement, and can be used up to ISO 5 applications. This cleanroom cost \$2000 to build.

3.1.2 Softwall Cleanroom (Clean Air Products) ISO 8-4:

The second cleanroom design in benchmarking is the Vertical Flow Soft Wall Portable cleanroom distributed by clean air products as shown in **Figure 2** below.



Figure 2: Clean air products' 4'x4' Cleanroom

The Vertical Flow Softwall Portable Cleanroom by clean air products features a modular cleanroom design that can be manufactured up to 12ft without adding any additional supports or hanging points. The design consists of a modular bolt-together design that simplifies initial assembly and future additions. All frame components are painted in a durable and cleanroom approved white powder coated finish. This design utilizes aluminum T-bars with polyurethane foam gaskets that form the ceiling grid. Included with transparent clear 40 mil flame retardant curtains attached to the frame with dual lock [5].

3.1.3 Hardwall Cleanroom (Clean Air Products) ISO 8-4:

The final cleanroom design for benchmarking is the Vertical Flow Hardwall Modular Cleanroom distributed by clean air solutions shown below in **Figure 3**.



Figure 3: Vertical Flow Hardwall Modular Cleanroom

The Vertical Flow Hardwall Cleanroom can distribute up to 34 ft and the interior height of 8ft up to 14 ft high. This design consists of a gasketed T-bar ceiling grid and offers an attractive design. The cleanroom is stated to be easily assembled and easily expandable/upgradable. The cleanroom is also offered as single pass or recirculating and allows for adjustable internal pressures up to 0.1 in W.C. The room can be distributed from class 100,000 to class 10 [5].

3.2 Literature Review

3.2.1 Structural Integrity/Material Connections – Logan Bennett

“Geometric and Structural Design of Foldable Structures” [6]

This paper details the strength and use of folding structures, which has value to this project as the goal is modularity and ease of assembly. This paper helped to remove foldable structures as an option as it showed the complexity and lack of strength of the scissor mechanism was not outweighed by any benefits.

“Connections in Steel Structures IV: Behavior, Strength and Design” [7]

This is a report publishing the proceedings of the “*Fourth International Workshop on Connections in Steel Structures*”. Specifically, the “Costs related to the connections” section helped to rule out certain connections that would be too expensive to justify, based on the minimum requirements for the connections. It also helped to rule out steel entirely due to the costs associated with powder coating.

“Analysis and experimental verification of the strength of telescopic booms for construction machinery” [8]

This journal was made specifically for telescopic booms of heavy machinery, however the conclusions reached were applicable to smaller fewer mechanical uses. This was used to narrow the options for our frame as well as the forced required to hold the frame steady using telescoping beams and columns was more than could be achieved easily and cheaply.

“Steel Connections – Types and Uses,” [9]

This is a web page that gives brief descriptions of different commonly used steel connections. Though the final design uses aluminum, the information here is applicable to aluminum as well as steel. The webpage was used to make sure all options for connections were considered before moving forward with the final design.

“Beam Designer” [10]

This webpage calculates maximum stress, moments, and shear for customizable beam conditions, including mounting style, moments of inertia, load distribution, and material. This was primarily used to confirm calculations made by hand regarding the load placed on the ceiling beams used to hold up the FFUs.

“Machinery’s Handbook, 25th ed.” [11]

This book contains material strengths, as well as equations used to design the structural elements of the frame. It also provides advice on factors of safety and where certain materials are best utilized. It helped to settle on the aluminum frame.

“Magnet pull force: Measure strength of magnet: Magnets holding power” [17]

A quick guide describing the mechanics of magnetic fasteners. This information will be used in the concept generation to determine the validity of magnets as a connection material.

3.2.2 Particle Count and Flow Requirements – Michelle Borzick

“Air Flow Rates” – Clean Rooms West [3]

The Clean Rooms West website provides measurable values for the average airflow across the entire cleanroom, air changes per hour, and ceiling coverage requirements for an ISO Class 7 cleanroom. The standard for airflow across the entire room in 0.051-0.076 m/sec or 10-15 ft/min. The average air changes per hour is 60-90. The average airflow requirements will be used to compare measured airflow in the cleanroom during the construction phase to ensure the cleanroom standards are being maintained.

“Cleanroom ISO 7 Specifications” – Clean Air Products [2]

The Clean Air Products website breaks down quality and standard requirements for all ISO classes of cleanrooms. The most valuable information for the design team from this website is the particle count requirements for the ISO Class 7 cleanroom shown in **Figure 4** below. The particle count requirements as well as the air flow requirements from the previous sources will be used in the Fluid Analysis to help determine cleanroom size and FFU placement. The air flow velocities and changes per hour requirements will be used to simulate air flow with different FFU placements. The particle count requirements will be tested once the initial cleanroom has been built.

ISO Class	Fed-Std 209E Class	Maximum Number of Particles in Air (Particles per cubic meter)				
		Particle Size				
		≥ 0.1µm	≥ 0.2µm	≥ 0.3µm	≥ 0.5µm	≥ 1µm
ISO 1		10	2			
ISO 2		100	24	10	4	
ISO 3	(Class 1)	1,000	237	102	35	8
ISO 4	(Class 10)	10,000	2,370	1,020	352	83
ISO 5	(Class 100)	100,000	23,700	10,200	3,520	832
ISO 6	(Class 1,000)	1,000,000	237,000	102,000	35,200	8,320
ISO 7	(Class 10,000)				352,000	83,200
ISO 8	(Class 100,000)				3,520,000	832,000

Figure 4: Cleanroom Particle Count Requirements

“Designing Air Flow Systems” [12]

This manual describes the types of air flows, types of air systems, pressure losses in an air system, fan performance specifications, and pressure calculations. First, the laminar and turbulent flow areas of an air system are described. Laminar flow is seen parallel in the centers of air systems and turbulent flow is seen perpendicular to the center and parallel to the outer edges of the system. Because of the mixed laminar and turbulent flows, most systems fall into a transitional flow category. This information will be used to determine what locations to calculate flow type in. Next the manual describes how pressure loss occurs in air systems. The pressure can be broken down into component pressure losses, dynamic pressure losses, and frictional pressure losses. The component pressure losses in the team’s cleanroom would be the known pressures of the FFUs. Dynamic pressure losses will be negligible because the cleanroom structure will not change shape or direction as pipes do. Frictional pressure losses will be present on the cleanroom walls but will also be considered negligible. These pressure losses will be accounted for when simulating the air flow of the cleanroom.

“Analysis and experiments on the characteristics of airflow and the air cleanliness protection region under fan filter units in cleanrooms” [13]

This peer reviewed article from the journal *Sustainability* explores how to reduce the amount of air supply required for cleanrooms using FFUs. To determine how to reduce air supply, the research team experimented using three different FFU sizes and four air supply velocities. The resulting airstream velocities and particulate concentrations were measured. The experimental methods will be studied by the team to help design experimental studies on the build cleanroom for FFU placement.

“Impact of the speed of airflow in a cleanroom on the degree of Air Pollution” [14]

This peer reviewed article from the Journal of Applied Sciences studied how different fan velocities impacted the particulate concentrations of a cleanroom. The same FFU was tested on different speeds and particle counts were taken at various locations in the cleanroom. Like the previous study, the experimental methods of the experiment will be studied to help determine the best experimental methods for upcoming particle count experiments.

“Experimental investigation of particle dispersion in cleanrooms of electronic industry under different area ratios and speeds of fan filter units” [15]

This peer reviewed article from the Journal of Building Engineering studied the impact of reducing air supply volume of FFUs to save energy. They performed experiments on three different FFU speed ratios, four particle source locations with 16 subzones, and two FFU area ratios. The study found that air supply volume could be reduced by almost half while maintaining particle removal requirements. They also found that reducing the FFU area ratio negatively impacted the particle removal and that regardless of air speed the particle removal away was decreased for areas away from directly under the FFU. Like the previous studies, this experiment will be considered to design a velocity and particle count experiment on the design team’s cleanroom.

Introduction to Fluid Mechanics [4]

The Introduction of Fluid Mechanics textbook will be used to find equations for laminar/turbulent flow and air flow principles. Equations for Reynolds number and Bernoulli’s Principle will be used in calculations to determine if the cleanroom airflow is laminar or turbulent and if pressure gradients are maintained appropriately.

3.2.3 Cleanroom Materials – Gia Neve

“Modular Softwall Cleanrooms: Cleanroom design,” [19]

This website provided a large amount of information on the design of soft wall cleanrooms and the advantages associated with them. This website contributed and was used to aid the concept selection process when deciding between soft wall designs opposed to a hard wall design.

“Materials Science and Engineering” [20]

This textbook was used to supply the team with helpful equations for understanding how a material acts under stress and strain. While the team did not end up needing to do much else with this source, it could still become relevant in the future when constructing our virtual prototype one.

“Clean Room Design: Minimizing Contamination Through Proper Design” [21]

This book provided detailed guidance on all aspects of cleanroom airflow, the mechanics of airflow, and how contamination is carried through the room. This book mapped the effect of human interference on unidirectional airflow and the potential of contamination. The main area of this book that was used was the laminar flow section used when deciding what flow patterns are needed for our design.

"Softwall Cleanrooms," [5]

This is a website for clean air products which had numerous explanations and definitions used within our report. This website goes into detail on the differences between soft wall and hard wall cleanrooms and their specific applications. This was used greatly when finding benchmarks and the concept selection for hard walls vs soft walls. Because Clean Air Products are a distributor of cleanrooms, this provides the team with valuable insight to how much premade cleanrooms can cost, which impacted our design heavily.

"FS209E and ISO Cleanroom Standards," [22]

This source is a document containing valuable information on ISO cleanroom standards and how to obtain them. This document is very useful as Terra Universal (the distributor of this document) is the company that distributes the FFUs the team plans to use for our cleanroom design.

“Comparison of Conventional Cleanrooms” [23]

This source is a report that goes into heavy detail about the fundamentals of a cleanroom, cleanroom standards, cleaning procedures, modular cleanrooms, filtration, etc. The only use of this book thus far has been to understand the cleanroom classes and designs that best fit the team's need, however, this report will remain as a very useful tool as the testing and monitoring stages of the design begin.

"Cost-effective Clean Room Designs," [24]

This paper looks at the underlying principles of cleanroom technology and explains how the associated stringent requirements can be met in the most cost-effective way possible. This paper provided good insight on what parts of our design can be made more cost-effective and what is worth spending more money on for better quality assurance.

3.2.4 Pressure and Temperature Requirements – Aaron Reynoza

“FUNDAMENTALS OF ENGINEERING THERMODYNAMICS” [25]

In this textbook, it provides a table that states the characteristics of air based on a few properties. The difference between the cleanroom and the environment. It is important to use this resource because it will allow the team to get air properties in a timely manner. This textbook also gives information of water, which will be helpful when the cleanroom environment gets humid.

“Characterization of minienvironments in a cleanroom: Design characteristics and environmental performance,” [26]

From the article, it describes the ways to maintain pressurization for a positive pressure and negative pressure in a minienvironment. A minienvironment has a strict regulation to be labeled as a clean environment. While different from a cleanroom, the article does give information on what the minimum pressure difference. Based on our customer requirements, the pressure in the cleanroom will be a positive pressure. To maintain an effective cleanroom, the minimum pressure that is required is 0.2Pa.

“Maintaining Area or Room Pressurization in Manufacturing and Healthcare” [1]

On the website, the article talks about the importance of pressurization in the cleanroom. The website also gives a value on the amount of air changes required to be a clean environment. The amount of air changes is 20 ACH (Air Changes per Hour). Based on the description of the cleanroom, it is important to keep a positive pressure cleanroom is because it does not allow outside particles to go inside the cleanroom.

“The development of fan filter unit with flow rate feedback control in a cleanroom,” [27]

The article is about the importance of an adjustable flow rate for the filter fan unit. It states that it is important to control the flow rate because it will make the cleanroom air supply stable. It is also important to control the air velocity of the filter fan unit because it can also affect the amount of air changes.

“Humidity and the Ideal Gas Law,” [28]

The website article describes the relationship between Humidity and the Ideal Gas Law. The articles stats that when the air gets humid, it will have an increase element of H₂O which will change the properties. Based on the provided chart, if the humidity percentages increases, the moister content of air also increases. This is important for the team because it gets humid in Flagstaff which will affect the cleanroom.

“Analysis Thermodynamic Analysis of Air Conditioning System of Clean Rooms,” [29]

The article describes the effects of an Air Conditioning System inside the cleanroom. The researchers analyzed an air conditioning system by its exergy generation, and the thermodynamic efficiency. The article describes that during hot and humid days, the coefficient of exergy increases while during cold days, the coefficient of exergy decreases. The information provided will inform the team on the effects of an air conditioning unit of a cleanroom.

Mathematical Modeling

3.2.1 Structural Analysis – Logan Bennett

3.3.1.1 Frame Connections Shear Force Analysis

To identify the amount of shear force and torsion force being applied to the connections, a shear flow analysis must be made. The Shear flow analysis can determine the maximum shear and torsion force that can be applied to a frame. For this calculation, A 4x8 ft frame will be used to do the calculation, since this design will be common for our cleanroom. The force being applied to the frame will be the weights of the two filter fan units which will be applied to the single frame. This will calculate the worst-case scenario for the frame since all the weight will only act on the frame instead of multiple ones. Throughout this section will show the process of doing the shear flow analysis.

$$\tau_{max} = \frac{VQ}{It} \quad (1)$$

The first step of calculating the shear flow is to find the Moment of Inertia location of the 4x8 feet frame using the 1.5x1.5-inch extruded aluminum. Since the frame is a rectangle, the location of the Moment of Inertia will be in the center of shape. With the given dimensions, the team were able to find the Moment of Inertia location of the frames shown in **Figure 5**.

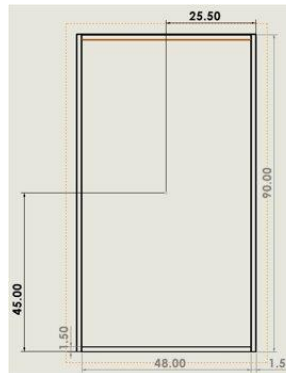


Figure 5: Location of Moment of Inertia in Frame

The next step will be finding the first moment area of the frame which is done by choosing a section of the beam and using its properties to generate a solution. The beam properties that is useful is it the length, height, and the distance from the frame moment of inertia to the local Moment of Inertia.

$$Q = (48in) * (1.5in) * (44.25in) = 3186 in \quad (2)$$

For the maximum shear stress, the only force that will act on the frame will be the weight of the filter fan unit. The total weight of the Filter fan unit is 100 lbm, which is 3.02 lbf when converting the mass into a force.

$$V_{max} = 3.02 \text{ lbf} \quad (3)$$

To calculate the moment of inertia, the team would have to use the specific rectangle MOI equation. Since the frame is not a complete rectangle, the moment of inertia will use the outside dimensions, and subtract it from the inside dimensions.

$$I = \frac{51(90)^3}{12} in^4 - \frac{48(87)^3}{12} in^4 = 6523.75in^4 \quad (4)$$

The last variable that needs to be solve is the width across the section, which is solved by dividing the

beam width by 2.

$$t = \frac{1.5 \text{ in}}{2} = 0.75 \text{ in} \quad (5)$$

With all the variables, the Max torsion that the frame will experience will be 1.96 Psi.

$$\tau_{\max} = 1.96 \text{ psi} \quad (6)$$

3.3.2 Thermodynamics Analysis – Aaron Reynoza

3.3.2.1 Pressure and Temperature Requirements

It is important to maintain an air positive pressure difference in the cleanroom so it can have a sterile environment. To prove that the cleanroom will work, the Ideal Gas Law equation will be used to calculate the pressure difference based on the properties inside and outside the cleanroom.

$$pv = \frac{mRT}{M} \quad (7)$$

Table 1: Table of Variables

Variable	Description
p	Pressure (psi)
v	Volume (ft^3)
m	Mass(lb)
R	Universal Gas Constant ($\frac{ft \cdot lbf}{Rmol \cdot R}$)
T	Temperature (R)
M	Molar mass ($\frac{lb}{lbmol}$)

Before doing calculations of the pressure difference, the team has got information about the variables and assumption. The given variables were gathered from the location of the cleanroom and the Thermodynamics textbook(A#).

$$p1 = 30.5(\text{inHG}) = 14.98(\text{psi}) \quad (8)$$

$$v1 = 444564.1(\text{ft}^3) \quad (9)$$

$$T1 = 70(F) = 529.67(R) \quad (10)$$

$$R = 1545\left(\frac{ft \cdot lbf}{lbmol}\right) \quad (11)$$

$$M = 28.97\left(\frac{lb}{lbmol}\right) \quad (12)$$

The outside properties of the air will help determine the mass of the air since the team did not acquire the tool to measure. After rearranging the Ideal Gas Law to solve for mass, the team has calculated 3394.74 lb.

$$m = \frac{pvM}{RT} \rightarrow m = 3394.7(\text{lb}) \quad (13)$$

To be able to solve the pressure of the cleanroom, a few assumptions will be made. The Assumption that the team will make is the air mass of the environment will be the same as the cleanroom, and the inside temperature will be 50F. This will help simplify the Ideal Gas Law by adding value to the air properties of the cleanroom.

$$v2 = 720ft^3 \quad (14)$$

$$T = 50(F) = 509.67(R) \quad (15)$$

$$R = 1545\left(\frac{ft \cdot lb_f}{lbmol}\right) \quad (16)$$

$$M = 28.97\left(\frac{lb}{lbmol}\right) \quad (17)$$

$$m = 3394.74(lb) \quad (18)$$

Rearranging the Ideal Gas Law Equation to solve for pressure, The value that the team calculated will be 889.97 Psi.

$$p = \frac{mRT}{vM} \rightarrow p = 899.97(psi) \quad (19)$$

With both pressures labeled, the pressure difference that the cleanroom will have is 874.99psi, which converted to pascals, will be 6.03 MPa.

$$p2 - p1 = (899.97 - 14.98)(psi) = 874.99(psi) = 6.03(MPa) \quad (20)$$

3.3.3 Fluid Dynamics Analysis – Michelle Borzick

3.3.3.1 Fan Number Requirements

The fan number requirement was determined by the ISO Class 7 minimum standard requirement of 15% for ceiling coverage ratios. The ceiling coverage was calculated using a simple area ratio shown in Equation 21.

$$Ceiling\ Coverage = \frac{Area\ FFUs}{Area\ Cleanroom\ Ceiling} \quad (21)$$

The ceiling coverage with only one FFU is 8.33% (22) which does not meet the standard requirement. The ceiling coverage with two FFUs is 16.67% (23) which does meet the standard. Therefore, the team moved forward with a two FFU configuration.

$$Ceiling\ Coverage\ 1\ Fan = \frac{2x4}{12x8} = 8.33\% \quad (22)$$

$$Ceiling\ Coverage\ 2\ Fans = \frac{2(2x4)}{12x8} = 16.67\% \quad (23)$$

3.3.3.2 Computational Fluid Dynamics Analysis

A Computer Fluid Dynamic (CFD) analysis was completed to determine the best ceiling configuration of the two FFUs. An Ansys Fluent CFD analysis was completed using a simplified model of the 12x8 cleanroom. Simulations for two different fan configurations were completed, one with the two fans mirrored and centered on the ceiling and one with the two fans in the corners of the ceiling. The simulation was run using the velocity output of the fans set to 0.4572 m/s or 90 ft/min as specified by the WhisperFlow FFU specifications [30]. The simulation output was set to 0.2 Pa as specified by the cleanroom pressure standard [1]. The simulations output Reynold's numbers for the streamlines created for the different configurations. The streamline results for the centered fans is shown in Figure # and for

the cornered fans in Figure #. The centered fans had a Reynold's number of 3441.3 representing transitional flow and the cornered fans had a Reynold's number of 3703.6 representing turbulent flow. Additional CFD simulations will be done to determine the impact of different fan speeds on the airflow.

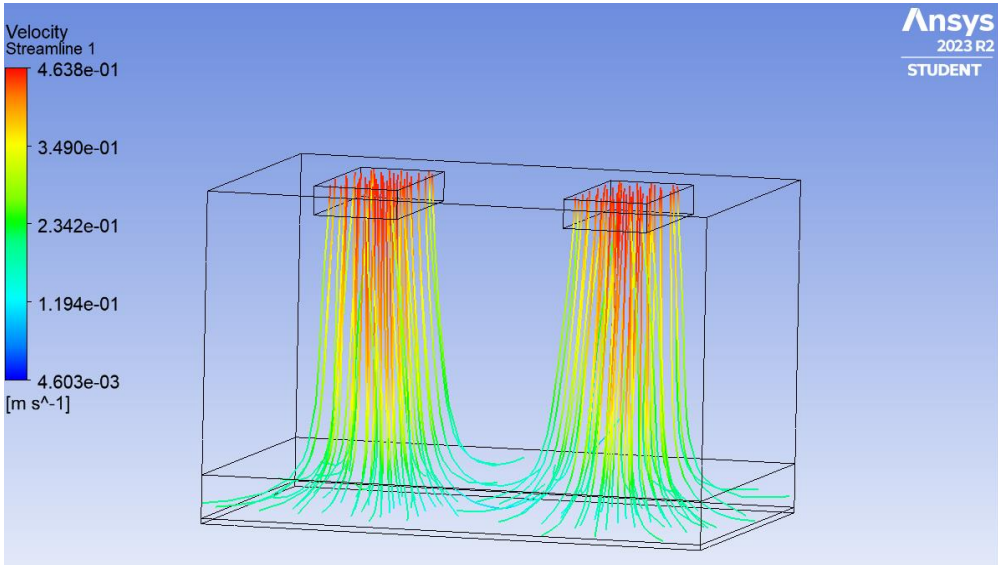


Figure 6: Centered Fans Streamline Simulation

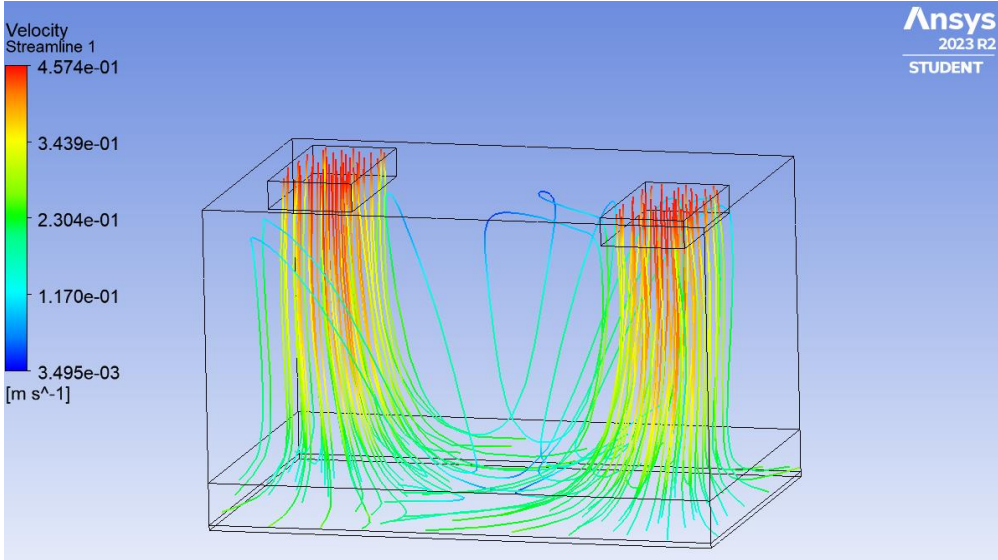


Figure 7: Cornered Fans Streamline Simulation

4 Design Concepts

4.1 Functional Decomposition

A functional model and black box model were created to begin the concept generation portion of design. A black box model for the FFU and cleanroom were made to understand how the FFU and cleanroom uses material, energy, and signals to maintain function. The black box model for the FFU is shown in **Figure 8**. The FFU black box model was used to understand how a FFU maintains positive pressure and acceptable particle count. The FFU for the cleanroom shown in **Figure 9** was used to understand what roles the cleanroom structure itself plays in maintaining positive pressure and particle count. This design project will not be designing a FFU therefore it will be essential for the design team to understand all interactions between the FFU and cleanroom.

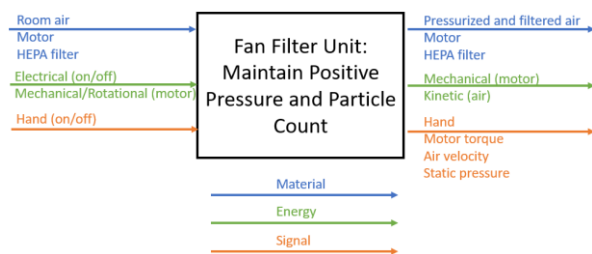


Figure 8: FFU Black Box Model

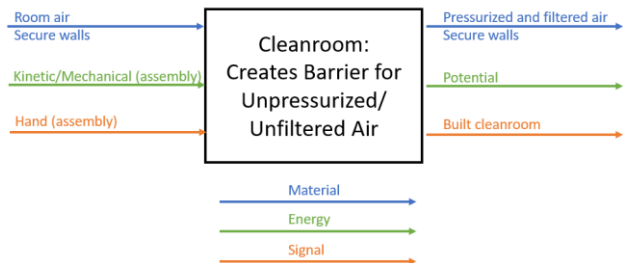


Figure 9: Cleanroom Black Box Model

The material, energy, and signal inputs and outputs from the black box models were used to construct one functional model. The functional model (**Figure 10**) was used to understand which aspects of the FFU create positive pressure and filtered air and how those functions interact with the cleanroom.

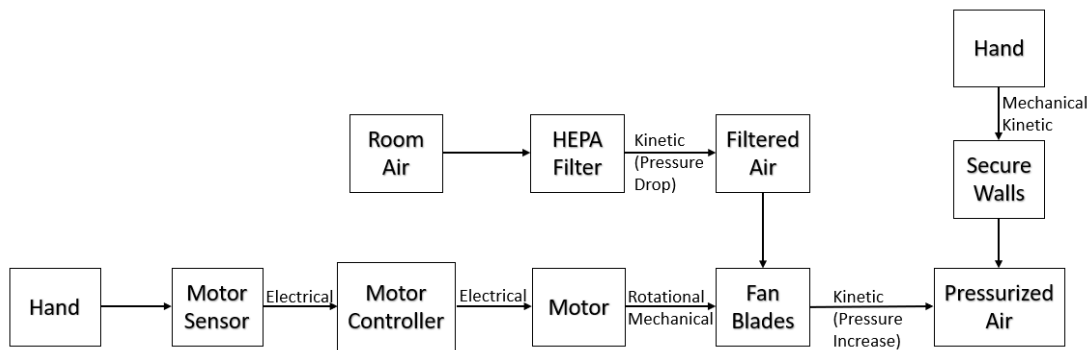


Figure 10: FFU and Cleanroom Functional Model

Concept Generation

To determine the important subfunctions and concept variations of the design, the team created a morphological matrix of all important subfunctions to the design with all concept variations possible. The morphological matrix is shown in **Table 2**. The subfunctions chosen were frame connections, material connections, wall/ceiling material, fan number/location, and frame size. Concept variants were brainstormed and all recorded.

Table 2: Morphological Matrix

Subfunctions	Concept Variants			
Frame Connections	Square Tubing Nylon Connectors 	T-Slots (80/20) 	Welded 	Screwed Joints 
Material Connections	Magnets 	Adhesive 	Slide in Frames 	Screws 
Wall/Ceiling Material	All Vinyl Soft Wall 	All Polycarbonate Hard Wall 	Polycarbonate Walls with Vinyl Ceiling 	Vinyl Walls with Polycarbonate Ceiling 
Fan Number/Locations	1 Centered Fan 	2 Off-Center Fans 	2 Corner Fans 	
Frame Size	10x10 	12x8 		

A detailed summary table of all advantages and disadvantages for each subfunction are shown in Appendix B. All concept variants of each subjunction will be discussed in detail in the following sections. Each concept variant will then be compared in a decision matrix to determine the final design concept that will be used as that subfunction in the final design.

4.1.1 Frame Connections

Frame connections are the components which the beam will be connected to create a frame. The 4 frame connections that will be used are the Nylon Square tubing connectors, 80/20 Specific T-Slotted connections, screwed joints, and welding. Based on the mathematical modeling of the frame connections, it must handle the maximum shear stress of 3.02 lbf and a torsion stress of 1.96 PSI. For the customer requirement the frame connections must be affordable, can be assembled, disassembled, and have modularity.

4.1.1.1 Nylon

With the square nylon tubing connectors, the advantage of this frame connection allows modularity. To assemble the frame with nylon connectors, the user must insert these components between the beam and then secure it by hitting it with a rubber mallet. This will allow the user to create many designs of the frame while not interfering with other parts. Since the nylon connectors are inserted by a mallet, The modularity also comes with good stability because the rough textures on the nylon connector allow friction between the beams which makes them stationary. One last advantage of square tubing connectors is the material. With the material nylon, buying or manufacturing these connectors will be cheap which goes with the customer requirement of being affordable [35]. Along with some advantages comes at a cost of disadvantages. The material Nylon has Modulus of Elasticity is 4.50×10^5 psi [34], which means that this material is the weakest to handle shear and torsional stress compared to other frame connections. Another disadvantage is that for the number of beams required to connect, a unique tube connector design must be used which will increase the number of unique parts required which will increase the price. One last disadvantage that comes with the nylon connector is optional, but if the customer wants to hide the connections, the beams must be altered by machining which will cost money.

4.1.1.2 T-Slots

With T-slot connections, they offer a variety of connection types which only applies to the T-slotted extruded aluminum. Since this connection has many ways to connect the beams, one of the advantages of T-Slot connections is that they become modular. The connection types vary from screw-ins, gusset brackets, triangle plates, and anchoring which all works with the T-Slotted Aluminum [29]. Another advantage with this connection type is that they have a strong connection between the beams which will increase the stability of the frame. A disadvantage that comes with T-Slots connections is that it is expensive to use. Based on the specific connection, the price range for the T-Slots connections can be between 3 dollars to 20 dollars. Another disadvantage is that it requires an extra number of components just to use the T-Slots, which will decrease the ease of building the frames and increase the price. One last disadvantage is that it's not effective against external forces, because to use these connectors, an adapter has to be used which slides in the T-Slot gaps and has a possibility of sliding.

4.1.1.3 Welding

One of the most common frame connections that can be used is welding. One of the advantages of welding is that this connection does not need extra components when creating the frame, which reduces the number of parts required to assemble. Another advantage of welding is that it creates permanent fixtures and because of this, it allows the aluminum frame to be stable [33]. One last advantage that comes with welding is that it creates strong connections between frames, which adds to the stability to the frame. With these advantages, come with many disadvantages which go against the customer and engineering requirements. One issue that can happen is that the quality of the work will affect the stability of the frames. When reviewing the previous cleanroom for this project, the group noticed that the welding quality was not good which created an unstable frame. Another disadvantage to welding is that it does not allow the cleanroom to be modular, which goes against the customer's requirements. One last disadvantage of welding is that it is expensive, the reason is that the price for welding aluminum is more than the price of steel [32].

4.1.1.4 Screwed Joints

One last frame connector is screwed joints for square tubing, while is similar to the 90/20 T-Slot bars, these connections do require machining for these connections to work. One advantage of these connectors is that they are inexpensive since a lot of these parts are available to purchase. Another advantage of these connections is that they are easy to assemble and disassemble because the only tool required to install these screwed joints is a screwdriver. One last advantage is that these screw joint parts can be replaced in a cheap and timely manner, which keeps maintenance cost to the minimum. Some of the disadvantages of the screwed joints is that they require machining of the beams to use these connections, which will increase the cost. One other disadvantage is they take up space so that it interferes with other parts which decreases the options of modularity. One last disadvantage of screwed joints is that they require a lot of extra parts to be used properly, which does make it harder to assemble and disassemble.

4.1.2 Material Connections

Material connections are the method used to attach the walls to the frames. The 4 styles analyzed were magnetic, adhesive, slide-in, and bolts/washers. The main requirements are that the style of connection must be capable of holding the full weight of the walls, and that the seals can be made to be airtight.

4.1.2.1 Magnetic

Magnetic connections are what are used in the current cleanroom (which will be converted into a gowning room). After 3 years of use, the plastic deformations in the soft walls have caused the magnetic strips from the current cleanroom to no longer hold the walls to the frame. However, this would not be a problem with a hard walled design. Due to this the biggest requirement of this option is that it can hold up the weight of hard polycarbonate walls. The strongest magnetic strips were found to have a magnetic pull force of only 30.3lbf [17], and since the walls will be attached vertically, that translates to 10.84lbf of friction holding the walls up [16]. This technically meets the requirement of for 9.5lb walls, but just barely. This method of material connection would need to be used in conjunction with another.

4.1.2.2 Adhesive

Adhesives come in many forms, but for this analysis high strength structural glue was used. A major drawback of adhesives with regards to this design is that it is a permanent connection. Since modularity is a major goal of this project this almost immediately takes this option off the board. To make sure all options were considered fully, a strength calculation was still done, and the strongest adhesive found [17] far exceeds the required strength of the material connections. So be exact, the surface area allotted to the adhesives would theoretically be able to hold 45kips.

4.1.2.3 Slide-in-Frame

This would work due to the geometry of t-slotted frames. The t-slots have a slot that is generally used for connection hardware; however, it also runs the length of the beam and would create a perfect slot for the walls to sit. This would make the design highly modular, as no machining is required on the frame or the walls. The major drawback of this option is that t-slotted frames are required. The walls would be held up by an insert 2 friction-based inserts per wall tile and would be able to hold 17.5 kips, far exceeding the required strength.

4.1.2.4 Bolts/Nuts

The final option is bolts and washers, this is the simplest and most commonly used of the 4 options. Holes are drilled into the frame and wall material, and the walls are attached with nuts and bolts. Using standard bolts that can be bought extremely cheaply from any hardware store, it was found with only 5 bolts per

wall tile this method could hold 21.9 kips, again, far exceeding the required strength. A layer of foam or rubber between the wall and the frame would also make this airtight. The only major drawback of this design is the required machining; however, members of this team have access to mills and very little machining is required.

4.1.3 Wall Material

The cleanroom's wall material encompasses the external enclosure or structural components that define the spatial boundaries. While the client has not stipulated explicit customer requirements, a comprehensive comparison between soft wall and hard wall applications is imperative to discern the optimal modular design solution. The objective of the design deliberation is to achieve a cost-effective and durable wall configuration that simultaneously aligns with the client's aesthetic preferences and functional requirements.

4.1.3.1 Soft Wall Materials

Soft wall enclosures typically focus primarily on how easily portable they are. The portable design allows for easy assembly, disassembly, storing, cost effective, and temporary applications. The soft wall design would consist of a vinyl curtain material to be draped over the frame of the room and attached using an adhesive or magnets. This was how the current cleanroom was designed as seen in **Figure 11**. However, while being cheap to manufacture, the quality is also of cheap caliber. The vinyl used in these applications tend to off gas a large amount of VOC's into the air for an extended amount of time. Off-gassing is the release of a dissolved, trapped, or absorbed gas in a material, while VOC's are volatile organic compounds.

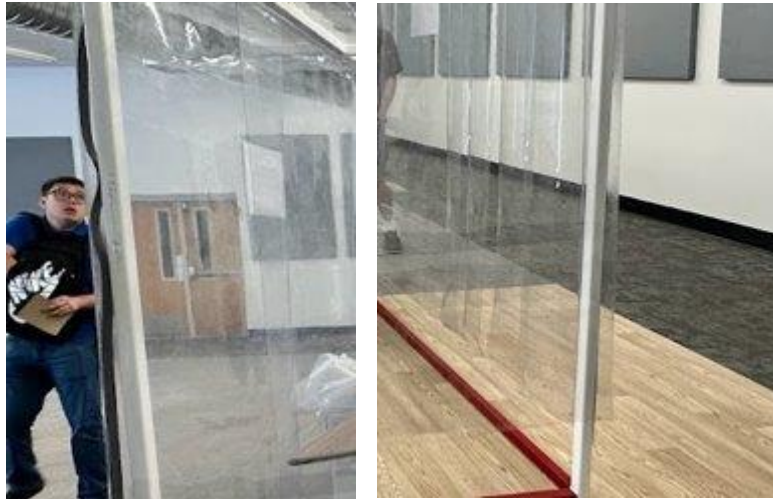


Figure 11: Current Cleanroom Design

4.1.3.2 Hard Wall Materials

While Hard Wall Materials tend to be more expensive, and less modular than soft wall designs, they provide a more structurally sound enclosure. Hard wall construction also allows for increased volumes of internal air pressure, which can help minimize dirty air from entering the room. This type of design using a polycarbonate material provides a better and more consistent performance. Also, compared to a soft wall construction, the life span of a rigid wall material is much more extensive. For example, the current

design the team is reimagining (located in **Figures 12 and 13**), is constructed of soft vinyl curtains attached to the frame with adhesive magnetic strips. This design is already deconstructing after only 4 years since its completion, as shown in Figure #, the curtains are no longer straight and have warped a bit. The adhesive from the magnetic strips have also spread causing the strips to peel off. A rigid application would eliminate the warping of the walls and the use of magnetic strips all together.



Figures 12 and 13: A closer look at the effects of time on the current soft wall cleanroom

4.1.4 Frame Size

The frame size of the cleanroom is the actual dimensions of the cleanroom. The client requested a 10' x 10' or 100 sq/ft sized enclosure that can house up to 6 people at once as the current cleanroom is only 6' x 8' in size. When researching potential materials for the cleanroom walls, polycarbonate sheets became the standard to use if following through with a hardwall design. These sheets come in 4 feet long by 8 feet tall sheets which impacted the design of the frame size. This led to the consideration of a 12' x 8' concept.

4.1.4.1 10' x 10'

The 10' x 10' design's main advantage is that it is a direct request from the client. However, when taking into consideration the rigid sheets' dimensions, the 10' x 10' design would produce material waste as the lengths are not evenly divisible by 4.

4.1.4.2 12' x 8'

The 12' x 8' design was constructed with the idea of eliminating material waste and providing a more aesthetically pleasing design while still being cost effective. The 12' x 8' design meets these criteria, but the only drawback is that the 12' x 8' is slightly smaller than the 10' x 10' at 96 sq/ft.

4.1.5 Fan Number/Location

The last subfunction is the FFU number and location. The airflow, pressure, and particle count of the cleanroom are dependent on selecting the appropriate FFU number and placing them in the best locations to maintain the cleanroom's airflow, pressure, and particle count requirements per the ISO Class 7

standards. Fan number options for the cleanroom included one fan or two. Fan location is mainly dependent on ceiling frame structure and airflow. If one FFU is used, it will need to be centered in the ceiling. However, if two FFUs are used there are different options to balance the fans in the frame structure while also considering the distribution of airflow in the room for different fan configurations.

4.2 Selection Criteria

4.2.1 Frame Connections

The selection criteria for the wall material are as follows listed from highest to lowest importance: cost, modularity, yield strength, stability, interference, small quantity, and ease of use. Cost is weighted at 50% and references the total cost of all frame connection components required for the 12x8 design. Modularity is weighted at 15% and refers to the design's customizability measured in number of possible designs. Yield strength is weighted at 10% and refers to highest amount of stress the material can handle without permanent deformation measured in MPa. Stability is weighted at 10% and is how stable the frame can be without movement measured by displacement of the frame. Interference is weighted at 5% and describes if the connection pieces will interfere with each other or other structural members. Small quantity is weighted at 5% and refers to the number of parts required for all frame connections. Lastly, ease of use is weighted at 5% and refers to the how easily the design can be assembled and disassembled.

4.2.2 Material Connections

The selection criteria for the wall material are as follows listed from highest to lowest importance: durability, modularity, strength, seal tightness, and aesthetics. Durability is weighted at 25% and is the expected lifespan of the connection material measured in years. Modularity is weighted at 25% and is the ease of assembly, disassembly, transport, and reorientation of the design. Strength is next weighted at 20% and refers to the wall weights the connection can hold measured in lbs. Seal tightness is next and refers to the gas loss measured in in^3/s . Lastly, aesthetics is weighted at 10% and is the subjective opinion of the client and design team.

4.2.3 Wall Material

The selection criteria for the wall material are as follows listed from highest to lowest importance: cost, customer preference, VOCs, and longevity. Cost is weighted at 30% and refers to how cost effective the design is including all wall and ceiling materials for one 12x8 cleanroom. Customer preference is weighted at 30% and is the subjective preference of the client. VOCs is weighted at 20% and refers to how much off-gassing the material produces and for how long. Lastly, longevity is weighted at 20% and refers to the life span of the design considering disassembly, transport, and reassembly.

4.2.4 Frame Size

The selection criteria for the wall material are as follows listed from highest to lowest importance: manufacturing ability, cost, customer preference, and aesthetics. Manufacturing ability is weighted at 40% and refers to how easy the design is to manufacture while accounting for waste. Cost is weighted next at 35% and considers how cost effective the design is. Customer preference is weighted at 20% and is the subjective preference of the client. Aesthetics is weighted at 5% and refers to how pleasing the design is

to look at and will be another subjective measurement determined by the client and design team.

4.2.5 Fan Number and Location





The selection criteria for the fan number and location are as follows listed from highest to lowest importance: particle count, flow distribution, structural load, and cost. Particle count is weighted at 40% and refers to the number of particles in the room measured in particles per cubic meter. Flow distribution is weighted at 35% and encompasses the output velocity and Reynold’s number of the air in the cleanroom. Structural load is weighted at 20% and refers to the stability of FFU weights on the ceiling structure. Cost is weighted last at 5% and refers to the total cost of the FFUs and material configurations of the ceiling structure.

4.3 Concept Selection

4.3.1 Frame Connections

The advantages and disadvantages of the different frame connection concept variants were compared in **Table 3**. The square modular tubing is very modular, inexpensive, and high in stability. However, it has decreased yield and shear strengths and requires specific designs that cannot be modified after purchase. T-slots are also very modular and allow for a plethora of different connection designs but are more expensive than other options. Welded parts do not require extra connection pieces but have poor modularity. Screwed joints are inexpensive, easily replaced when damaged, and very modular. However, screws require extra milling of the wall material and may require additional connection materials. The advantages and disadvantages were weighed in a decision matrix to choose a concept variant.

Table 3: Frame Connections Advantages and Disadvantages

Frame Connections	Advantages	Disadvantages
 <p>Square Tubing Nylon Connectors</p>	<ul style="list-style-type: none"> -Very modular -Inexpensive -Allows strong structure stability 	<ul style="list-style-type: none"> -Requires altering frame -require specific design for different types of connections -weak connection material for yield and shear strength
 <p>T-Slots (80/20)</p>	<ul style="list-style-type: none"> -Very modular -Allows many connection types - Strong connections between frames 	<ul style="list-style-type: none"> -Expensive - Requires many components for connections -Not effective against external forces
 <p>Welded</p>	<ul style="list-style-type: none"> -Creates permanent fixtures -No extra components required - Allows for strong connections 	<ul style="list-style-type: none"> -Does not allow modularity -Expensive -Quality of weld can affect stability
 <p>Screwed Joints</p>	<ul style="list-style-type: none"> -Inexpensive -Parts are replaceable - Can be assembled/disassembled easily. 	<ul style="list-style-type: none"> -Requires milling for frame and joint -Takes up space which effects other parts -Require many components for connections

In the decision matrix below (**Table 4**), the team left out the frame connections of welding because it does not follow the customer’s criteria of being modular. After scoring each criterion, the team has concluded that the square nylon tubing connector will be the best option for frame connections.

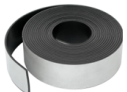


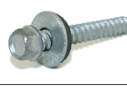
Table 4: Decision Matrix for Frame Connections

Selection Criteria	Weight (%)	CV 80/20 T-Slot		CV Square tubing Connector		CV Screw Joints	
		Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Modularity	15	3	.45	3	.45	2	.30
Price	50	1	.50	3	1.50	2	1.00
Yield Strength	10	2	.20	1	.10	3	.30
Stability	10	1	.10	3	.30	3	.30
Interference	5	3	.15	3	.15	1	.05
Small quantity	5	1	.05	3	.15	1	.05
Ease of Use	5	2	.10	3	.15	2	.10
Total	100	13	1.55	18	2.80	14	2.1

4.3.2 Material Connections

The advantages and disadvantages of the material connections are listed in **Table 5**. Magnets are inexpensive but can degrade over time, leave residue on the frame, and disconnect with slight wall shifting. Adhesive is also inexpensive but causes/collects particulation, off-gassing, can degrade over time, leave residue on the frame, and disconnect with slight wall shifting [18]. Slide in frames are higher modular and create strong connections but are only applicable with t-slot frames. Lastly, screws are inexpensive, create strong connections and are highly modular but could cause cracking or tearing of the wall material if not installed well.

Table 5: Material Connection Advantages/Disadvantages

Material Connections	Advantages	Disadvantages
 <p>Magnets</p>	- Inexpensive	- Adhesive connection degrades over time - Adhesive residue on frame - Shifting of vinyl/polycarbonate panels could cause disconnection
 <p>Adhesive</p>	- Inexpensive	- Particulation - Off-gases - Strength degrades over time - Shifting of vinyl/polycarbonate panels could cause disconnection - Collects particulates
 <p>Slide in Frames</p>	- High modularity – easy to assemble and disassemble - Strong connection	- Only works with t-slots. Would have to modify other frame material to accommodate
 <p>Screws</p>	- Inexpensive - Strong connection - High modularity – easy to assemble and disassemble	- Could cause tearing of vinyl/cracking of polycarbonate panels

While slide-in-frame is the decision made here, the cost of using t-slots over square tubing tipped the scales in favor of screwed in hardware. The difference was only found in the aesthetic criteria as well, which was the criteria with the lowest weight demonstrated below in **Table 6**.

Table 6: Decision matrix for material connections

Selection Criteria	Weight (%)	Magnets		Adhesive		Screws		Slots	
		Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Durability	25	1	0.25	2	0.5	3	0.75	3	0.75
Modularity	25	2	0.5	1	0.25	3	0.75	3	0.75
Strength	20	1	0.2	2	0.2	3	0.6	3	0.6
Seal Tightness	20	2	0.4	2	0.2	3	0.6	3	0.6
Aesthetics	10	1	0.1	2	0.2	2	0.2	3	0.3
Total	100		1.45		1.35		2.9		3.0

4.3.3 Wall Material

The selection process for the wall material started with a comparison of the advantages and disadvantages between the two designs as described in **Figure 14**. As shown, the advantages of the soft wall design are only that it is inexpensive while the hard wall design provides less air leakage, longer life span, and has a more professional appearance. It is also stated that the hard wall design is client preferred, this was not specifically stated at the beginning of the project but was later mentioned by the client as not necessary but preferred. The disadvantages state the soft wall expels VOC's, increases potential air leakage, has a decreased life span, and could potentially become less modular over time. Moreover, the disadvantages of the hard wall application are only that it is a more expensive design choice.



Wall/Ceiling Material	Advantages	Disadvantages
Vinyl Soft Wall Ceiling 	- Inexpensive	- Contains VOCs - Increased air leakage - Deteriorates over time - Less modular than polycarbonate
Polycarbonate Hard Wall Ceiling 	- Client preferred - Less air leakage - Longer life span - More professional appearance	- More expensive

Figure 14: Advantages vs Disadvantages between soft wall and hard wall designs

To be able to accurately weigh the selection criteria, a cost analysis of both designs was completed. To purchase enough vinyl to cover one unit of our cleanroom, it would cost around \$200. For the Hard wall application, the largest sheets of polycarbonate found were to be 4ft long by 8 ft tall at 1/16 of an inch thick, distributed by ePlastics. With this size in mind, to cover all walls and ceiling and not considering doors or holes within the enclosure, it was calculated that the team would need to purchase 13 panels for one unit. As stated on the ePlastics website, as you purchase more individual units of a product, the overall price drops. This breakdown is shown in **Table 7**. At 13 units, the team can expect each sheet to cost \$67.41, adding to a total of \$876.33. accounting for shipping and taxes, the total price comes out to \$1,296.96, and for budgeting purposes the team can round this to a closing price of \$1,300.

Table 7: Price of Polycarbonate sheets per unit quantity supplied by ePlastics.

Quantity	1 – 2	3 – 9	10 – 19	20 – 29	30 – 49	50 +
Price	\$82.08	\$76.13	\$67.41	\$63.84	\$60.27	\$54.32

Now that there is a cost understanding between the designs, a decision matrix can be constructed as shown below in **Table 8**.

Table 8: Wall Material Decision Matrix


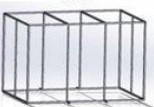
Selection Criteria	Weight (%)	Hard Wall (Polycarbonate)		Soft Wall (Vinyl)	
		Score	Weighted Score	Score	Weighted Score
Cost	30	2	0.15	3	0.9
Customer preference	30	3	0.9	1	0.3
VOCS	20	2	0.4	1	0.2
Longevity	20	3	0.6	2	0.4
Total	100		2.05		1.8

Each each selection criteria are weighted with an associated score. While the softwall design dominates in cost effectiveness, it falls short in customer preference, VOCs, and longevity, leading to the hardwall design becoming the best choice for the design.

4.3.4 Frame Size

The Selection process for the frame sizing also incorporates the use of an advantages vs disadvantages table shown in **Table 9**. It states that the 10' x 10' designs only advantage is that it was a direct customer request, while the 12' x 8' design is evenly spaced resulting in less material waste, uses the same material requirements as the 10' x 10' design, and has a symmetrical design that is more aesthetically pleasing. The disadvantages associated with the 10' x 10' are that because of the uneven spacing of the supports caused by the polycarbonate sheet sizing, the design requires material cutting and material waste. The only disadvantage of the 12' x 8' design is that it is slightly smaller, coming in at 96 sq/ft instead of the 100sq/ft given by the 10' x 10' design.

Table 9: Frame size Advantages Vs Disadvantages

Frame Size	Advantages	Disadvantages
<p>10x10</p> 	<ul style="list-style-type: none"> - Direct customer request - Total area of 100 square feet of floor space 	<ul style="list-style-type: none"> - Unevenly spaced support beams will require additional material cutting
<p>12x8</p> 	<ul style="list-style-type: none"> - Evenly spaced bars will require no material cutting - Uses same material requirements as 10x10 - Symmetrical design requires less assembly time 	<ul style="list-style-type: none"> - Less total area - 96 square feet of floor space

To being weighing each selection criteria, another cost analysis was conducted that compares the cost of framing, connectors, and wall material for each design.

4.4.4.1 10' x 10' Frame Size

Framing

To be able to construct an accurate cost analysis of the framing, inventory of all the lengths of 80/20 square aluminum tubing will be used to construct this design is necessary. Those are as follows:

- 18: 47" Beams
- 12: 87" Beams
- 8: 20" Beams
- 8: 18.5" Beams
- 4: 8.5" Beams
- 1: 53" Beam

Using the square Aluminum tubing with part no. 9700 costing \$0.49 per inch, the sum is \$1,262.00. After tax and shipping the final cost is \$1,649.39.

Connectors

The connectors to be used within the design are distributed from Esto connectors. The parts list consists of the following:

- 14: 1.5" Straight Base Connectors
- 4: 1.5" 4-Way Cross Connectors
- 20: 1.5" 3-Way Tee Connectors
- 8: 1.5" 3-Way Corner Connectors

The total cost of the connectors comes out to \$431.82.

Wall Material

The wall material cost for both frame sizes is the same, coming out to about \$1,300.

4.4.4.2 12' x 8' Frame Size

Framing

To be able to construct an accurate cost analysis of the framing, inventory of all the lengths of 80/20 square aluminum tubing that will be used to construct this design is necessary. Those are as follows:

- 29: 46" Beams
- 10: 87" Beams
- 4: 22" Beams
- 2: 22.5" Beams

Using the square Aluminum tubing with part no. 9700 costing \$0.49 per inch, the sum is \$1,262.69. After tax and shipping the final cost is \$1,661.14.

Connectors

The connectors to be used within the design are distributed from Esto connectors. The parts list consists of the following:

- 10: 1.5” Straight Base Connectors
- 6: 1.5” 4-Way Cross Connectors
- 10: 1.5” 3-Way Tee Connectors
- 8: 1.5” 3-Way Corner Connectors

The total cost of the connectors comes out to \$305.53.

Wall Material:

The wall material cost for both frame sizes is the same, coming out to about \$1,300.

All cost calculations are summarized in **Table 10**.

Table 10: Cost Analysis of Frame designs

	12’ x 8’	10’ x 10’
Framing	\$1661.14	\$1649.39
Connectors	\$305.53	\$431.82
Wall Material	\$1300	\$1300
Total Cost:	\$3266.67	\$3381.21

When deciphering the data, it is apparent that the framing cost of the 12’ x 8’ design is slightly larger than the 10’ x 10’, however, the 10’ x 10’ design requires more connectors because of its uneven design, resulting in a higher total cost. With this in mind, the decision matrix was used to produce the most optimal design. This is shown in **Table 11** below. It is apparent from the table that the 12’ x 8’ design is the winner and will be what the team moves forward with for the final design phase.




Table 11: Frame Size Decision Matrix

Selection Criteria	Weight (%)	12x8		10x10	
		Score	Weighted Score	Score	Weighted Score
Cost	35	3	1.05	2	.7
Manufacturing ability	40	3	1.2	2	.8
Customer preference	20	3	.6	3	.6
Aesthetics	5	3	.15	2	.1
Total	100		3		2.2

4.3.5 Frame Number and Location

For the concept selection of the FFU number and location, first the advantages and disadvantages of all concept variants were listed in **Table 12**. The advantages of the single centered fan include that it is less expensive and creates less turbulent air flow than two fans. However, as was determined in the engineering analysis, a single FFU does not allow the cleanroom design to meet ISO Class 7 standards and was thus ruled out of the design options. The remaining concept variants for two fans both meet ISO Class 7 standards and are more expensive than one fan.

Table 12: Fan Number/Locations Advantages and Disadvantages

Fan Number/Location	Advantages	Disadvantages
1 Centered Fan 	- Less expensive	- Does not meet ISO7 filter fan unit ceiling coverage requirement
2 Off-Center Fans 	- Meets ISO7 filter fan unit ceiling coverage requirement	- More expensive than 1 fan
2 Corner Fans 	- Meets ISO7 filter fan unit ceiling coverage requirement	- More expensive than 1 fan

Since the one FFU design does not meet standards, it was not considered in the decision matrix shown in **Table 13**.

Table 13: Fan Number/Location Decision Matrix

Selection Criteria	Weight (%)	2 Fans Off-Center		2 Fans Cornered	
		Score	Weighted Score	Score	Weighted Score
Cost	5	2	0.1	2	0.1
Flow Distribution	35	3	1.05	2	0.7
Structural Load	20	2	0.4	3	0.6
Particle Count	40	3	1.2	3	1.2
Total	100		2.75		2.6

The cost of both designs is the same for the two fans and ceiling materials. The flow distribution was better in the centered fans designed as shown in the CFD simulations. The structural load of the concept variant with the fans on the corners was stronger than with the fans in the middle as shown in the structural analysis calculations above. Both designs were equally efficient in meeting particle count requirements since they both utilize two identical fans of equal filtering capacity. With the weighted criteria considered, the highest scoring concept variant is the two centered fans.

4.4 Computer-Aided Design

After each team member chose their highest rated concept generation; the team then decided to combine all design to create a final CAD model located in **Figures 14** and **15**. The final design of the cleanroom will be an 8x12x7.5 feet cubed with polycarbonate walls that is mounted by screws. For the roof of the cleanroom, a two-fan design will be located off-center with Nylon Square tubing holding the 1.5x1.5 in beams together. While the CAD model is subject to change, it does help the team to visualize the final design and have an idea of how it will look like.

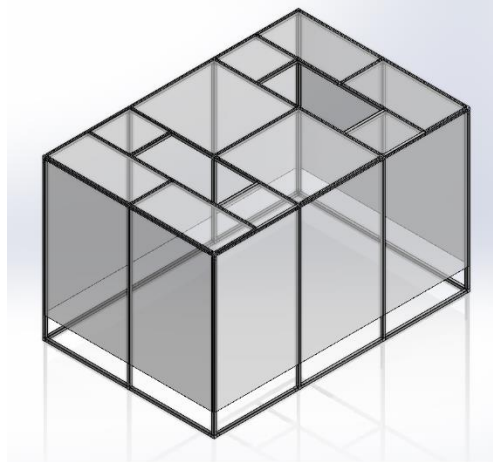


Figure 14: Final CAD Model of a 8x12x7.5 ft Cleanroom

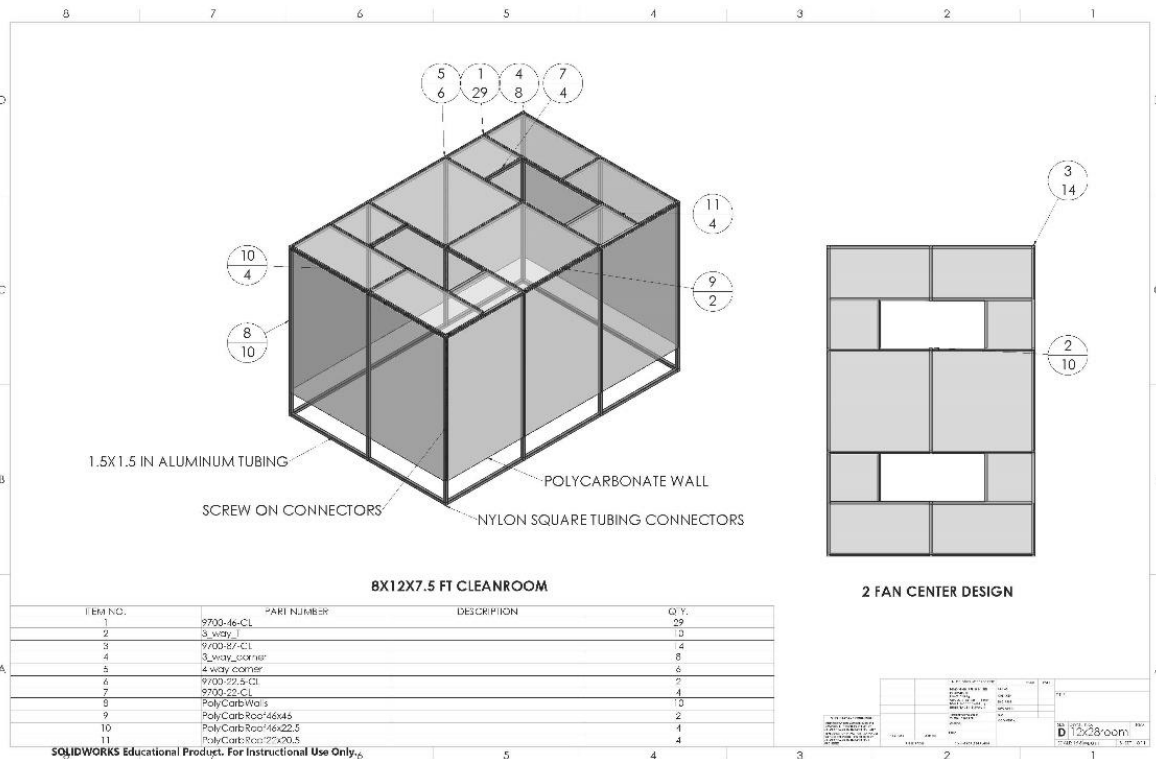


Figure 15: Final CAD Model BOM With Engineering Notes

5 CONCLUSION

The objective of the design project is to create a sterile environment to produce medical devices by designing and constructing a cleanroom. This will be achieved by a filtered fan unit that provides a positive pressure difference inside the cleanroom. The design goals for the cleanroom are to make it an ISO Class 7 cleanroom while being modular, affordable, easy to assemble, and disassemble. This is achieved by using multiple engineering techniques to narrow down our design requirements. The design requirements for the project include having laminar flow, strong frame connections, good frame support, positive pressure difference, optimized fan placement, strong material connections, affordability, and modularity.

The group has concluded that the design will include beams of 1.5x1.5-inch aluminum tubing, two filter fan units located off-center of the cleanroom, an 8x12x7.5 feet cleanroom, and attaching polycarbonate walls with screws. The team has learned a lot from doing extensive research on this project and are on track of on being able to produce this design.

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7 APPENDICES

7.1 Appendix A: House of Quality

System QFD		Project: Modular Sterile Manufacturing Clean Room													
		Date: 9-18-23													
1	Room Area	6													
2	Positive Pressure	6	6												
3	Particle Count	6	6	9											
4	Particle Size	6	6	9	3										
5	Airflow	6	6	3	3										
6	Ceiling Coverage	9	6	9	9	6									
7	Reynold's Number	6	3	1	1	9	6								
8	Power Requirement	1	3	3	3	3	1	3							

Customer Requirements		Weight	Room Area	Positive Pressure	Particle Count	Particle Size	Airflow	Ceiling Coverage	Reynold's Number	Power Requirement	Customer Opinion Survey				
											1 Poor	2	3 Acceptable	4	5 Excellent
1	Modular	5	3									C		AB	
2	Transportable	3	3									C	AB		
3	Spacious	4	9	-1	-1	-1	-1					A		C	B
4	ISO Class 7 Compliant	5	3	9	9	9	9	9	6	1				A	BC
5	Generator Backup Power	2	1	1	1	1	1		1	9	ABC				
Engineering Requirement Units			ft ²	Pa	particles/ m ³	µm	m/s	N/A	N/A	W					
Engineering Requirement Targets			1 77 48	3 43 0.02	3 43 352,000	3 43 0.5	3 43 0.051	2 45 15%	4 32 2300	5 23 7200					
Absolute Technical Importance			1 77 48	3 43 0.02	3 43 352,000	3 43 0.5	3 43 0.051	2 45 15%	4 32 2300	5 23 7200					
Relative Technical Importance			1 77 48	3 43 0.02	3 43 352,000	3 43 0.5	3 43 0.051	2 45 15%	4 32 2300	5 23 7200					

Figure A.1: Modular Cleanroom House of Quality