NATIONAL TECHNICAL UNIVERSITY OF ATHENS

POLYTECHNIC SCHOOL

DEPARTMENT OF MECHANICAL ENGINEERING

HEAT TRANSFER LABORATORY

Energy-Efficient Cooling Strategies for Optimizing Data Center Thermal Management Systems

DIPLOMA THESIS

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JANUARY 2025

ATHENS

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Acknowledgments

This thesis was conducted in the Heat Transfer Department of the School of Mechanical Engineering at the National Technical University of Athens (NTUA) during the 2024-2025 academic year.

I would like to express my sincere gratitude to my thesis supervisor, Professor Christos Tzivanidis, for providing me the opportunity to work on this research project. His expert guidance, straightforward feedback, impartial support, and unwavering willingness to assist me throughout the process were invaluable. Professor Tzivanidis' insightful direction and prompt availability to address any issues that arose significantly contributed to the successful completion of this work.

I am also deeply grateful to my family, Mr. George Kotsalis, Ms. Anna Metaxa and Mr. Socrates Chalkias for their steadfast support during my studies, both academically and personally. Their constant encouragement and understanding were a source of motivation that enabled me to overcome challenges and remain focused on my educational pursuits.

Abstract

The rapid growth in data center energy consumption, driven by expanding cloud computing and digital services, has made cooling system efficiency a critical challenge. This thesis presents a comprehensive analysis of thermal management and energy optimization strategies for data center cooling, focusing specifically on 1U rack server configurations. Through advanced computational fluid dynamics (CFD) simulations using ANSYS Discovery, the study investigates the complex relationships between airflow dynamics, temperature distribution, and energy consumption under various operating conditions. The research methodology incorporates detailed 3D modeling of server components, mesh optimization, and simulation of multiple operational scenarios including baseline, energy-saving, peak load, and stress test conditions. The investigation encompasses comprehensive thermal and fluid dynamic analyses, examining temperature distributions, airflow patterns, pressure gradients, and heat transfer characteristics across different server components. This multi-faceted approach enables thorough evaluation of cooling system performance and identification of optimization opportunities. Results demonstrate that optimal cooling efficiency is achieved with moderate flow rates (3-5 m/s) combined with ambient inlet temperatures around 25°C, yielding maximum component temperatures of 45.2°C while maintaining minimal pressure drops of 15.1 Pa. This configuration represents a significant improvement in energy efficiency compared to higher-velocity alternatives, which show diminishing returns despite increased power consumption. The study reveals critical relationships between fan speeds, thermal performance, and energy consumption, providing valuable insights for optimizing data center cooling strategies. The findings provide evidence-based guidelines for data center operators and server manufacturers, establishing a framework for balancing thermal performance with energy efficiency. Through detailed analysis of component-level cooling effectiveness and system-wide thermal behavior, the research identifies key factors influencing cooling system performance and energy consumption. The study validates its findings against industry standards, including ASHRAE guidelines and manufacturer specifications, ensuring practical applicability of the recommendations. The research concludes with recommendations for future cooling system optimizations and identifies promising directions for continued investigation. These include the development of hybrid cooling systems, integration of AI-based control strategies, advanced heat sink designs, and implementation of predictive maintenance approaches. The comprehensive analysis and recommendations contribute to the ongoing advancement of energy-efficient cooling solutions for modern data center infrastructure.

1. Introduction

Data centers form the backbone of modern digital infrastructure, but their growing energy footprint presents significant environmental and economic challenges. Cooling systems, which typically consume 40% of total data center energy, represent a critical opportunity for efficiency improvements. While various cooling technologies exist, optimizing their performance requires deep understanding of the complex thermal and fluid dynamics within server systems. This thesis addresses this challenge through systematic investigation of cooling strategies for 1U rack servers, combining advanced computational modeling with practical engineering considerations. The research employs ANSYS Discovery software to simulate various cooling scenarios, enabling detailed analysis of temperature distributions, airflow patterns, and heat transfer characteristics. This computational approach allows for comprehensive evaluation of different cooling strategies without the expense and limitations of physical testing. The investigation encompasses multiple operational scenarios, from baseline conditions to stress tests, providing insights into system behavior across the full spectrum of data center operations. By examining the interplay between airflow rates, inlet temperatures, and component thermal responses, the study identifies optimal configurations for energy-efficient cooling while maintaining reliable system performance. The research methodology incorporates detailed component modeling, advanced mesh generation techniques, and sophisticated fluid dynamic simulations to ensure accurate representation of real-world conditions. Building on established thermal management principles and industry best practices, the study explores innovative approaches to server cooling optimization. The analysis considers not only the thermal performance of individual components but also the systemic effects of different cooling strategies on overall energy efficiency. This holistic approach enables identification of practical solutions that balance cooling effectiveness with operational costs.

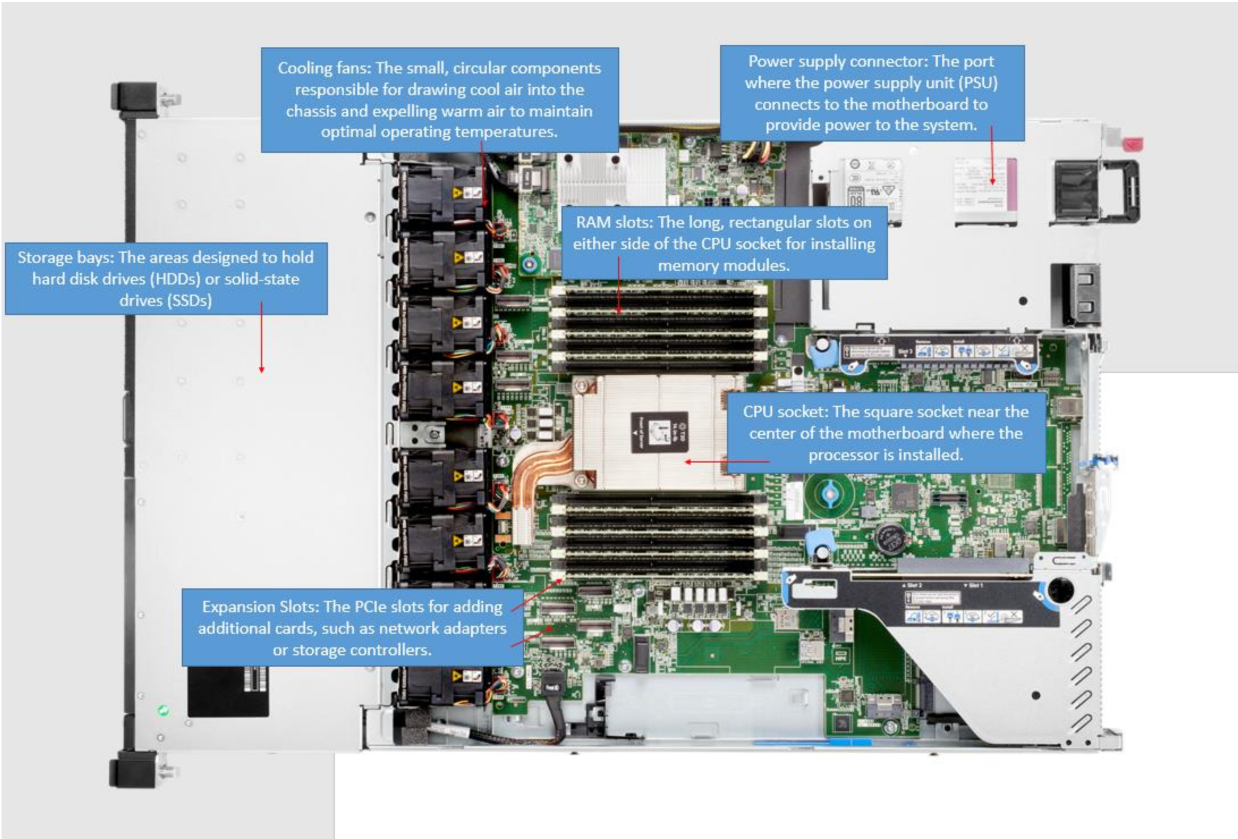


Figure 1. *Internal components of a 1U rack server / HPE ProLiant DL325 Gen10 Plus v2 [22]*

2. Server Cooling Methods and Fan Cooling

Effective thermal management is essential for maintaining the reliability and performance of data center servers. The primary goal is to ensure that critical components, such as processors and memory modules, operate within their specified temperature ranges. Several cooling methods are employed in data centers, each with its own advantages and limitations.

a. Air Cooling: Air-cooling is the most common method, relying on fans to circulate cool air through the server and dissipate heat. Server fans are strategically placed to draw cool air from the front, pass it over heat-generating components, and exhaust warm air at the rear. Air-cooling is relatively simple, cost-effective, and easy to maintain. However, its effectiveness can be limited by factors such as high heat density, inefficient airflow management, and environmental conditions.

b. Liquid Cooling: Liquid cooling systems use water or other coolants to remove heat from server components. This can be achieved through various techniques, such as cold plates, immersion cooling, or direct-to-chip liquid cooling. Liquid cooling offers higher heat transfer efficiency compared to air cooling, enabling better performance and higher rack densities. However, it comes with increased complexity, cost, and maintenance requirements.
c. Hybrid Cooling: Hybrid cooling combines air and liquid cooling methods to balance their advantages. For example, air-cooling can be used for general server cooling, while liquid cooling targets high-heat-density components. Hybrid cooling allows for flexibility in design and can provide a more cost-effective solution compared to full liquid cooling.

Among these methods, fan cooling remains the most widely adopted due to its simplicity, compatibility with existing server designs, and lower implementation costs. However, as power densities continue to rise and efficiency becomes increasingly critical, advanced fan cooling techniques and alternative cooling methods are being explored

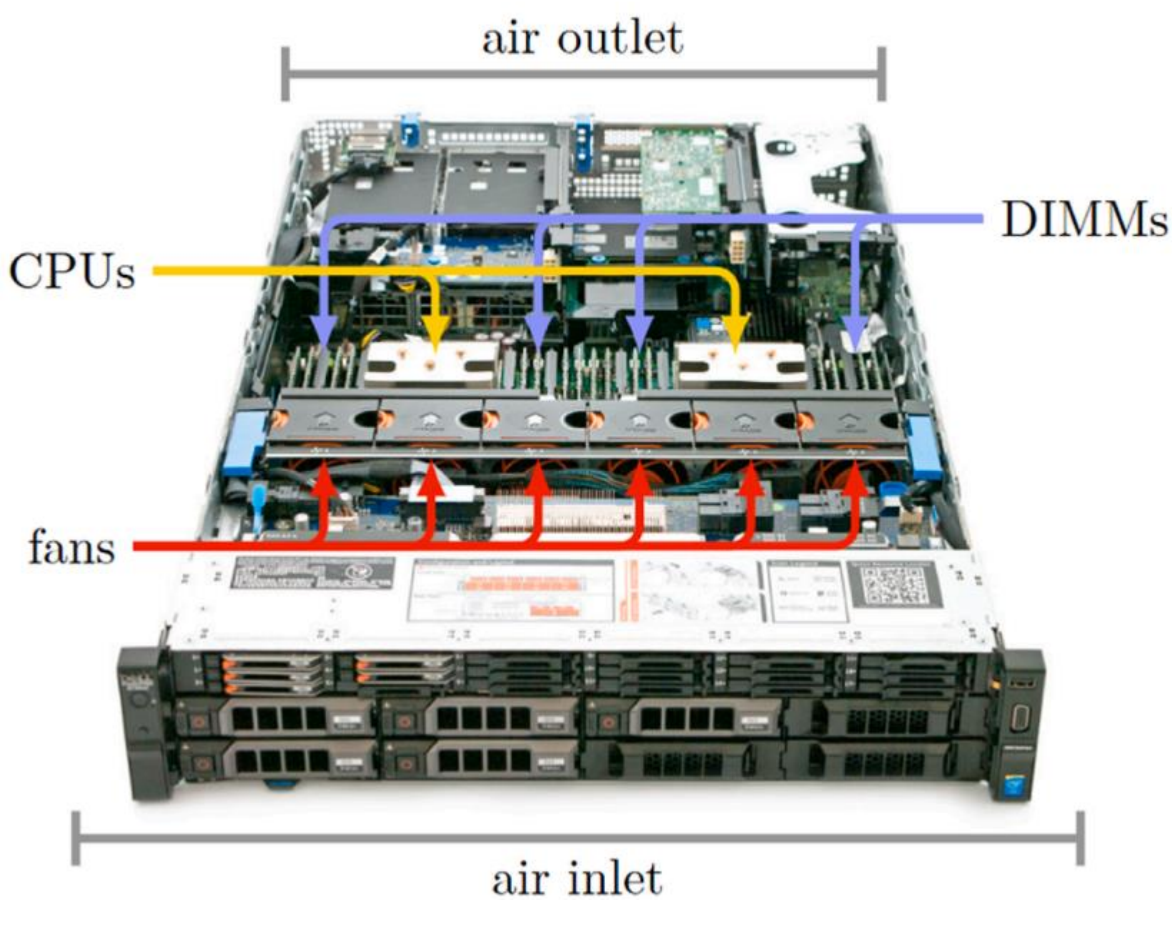


Figure 2. *Air Cooling in a Server / Dell R730xd Power-Edge server [23]*

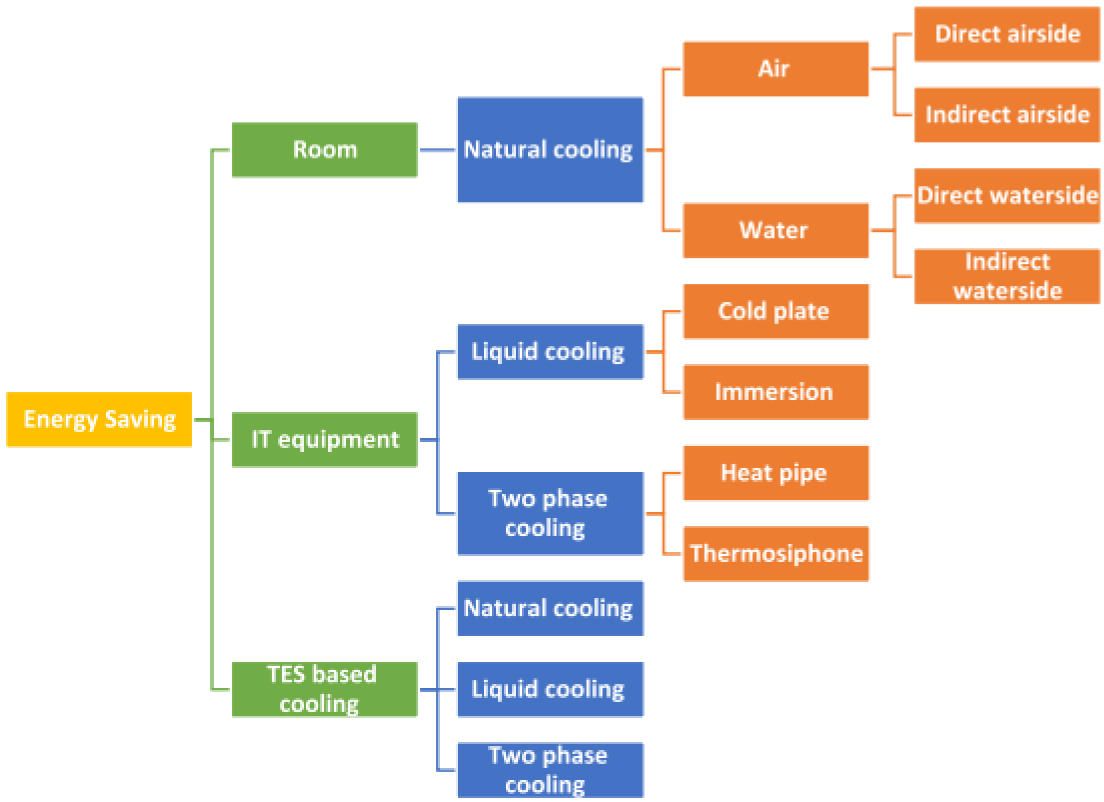


Figure 3. *A summary of some energy-saving cooling solutions for data centers [24]*

3. Server Fan Cooling Design Considerations and Factors Influencing Effectiveness

The layout, design, and various factors play crucial roles in the effectiveness of server fan cooling. Key considerations and factors include:

3.1. *Fan Placement and Configuration*

- Aligning fans with component layout to ensure proper airflow over heat-generating components
- Minimizing airflow obstructions and ensuring clear airflow paths from inlet to exhaust
- Balancing fan pressure and airflow to achieve efficient cooling while minimizing power consumption
- Optimizing the number, size, and placement of fans within the server to maximize airflow distribution and heat removal

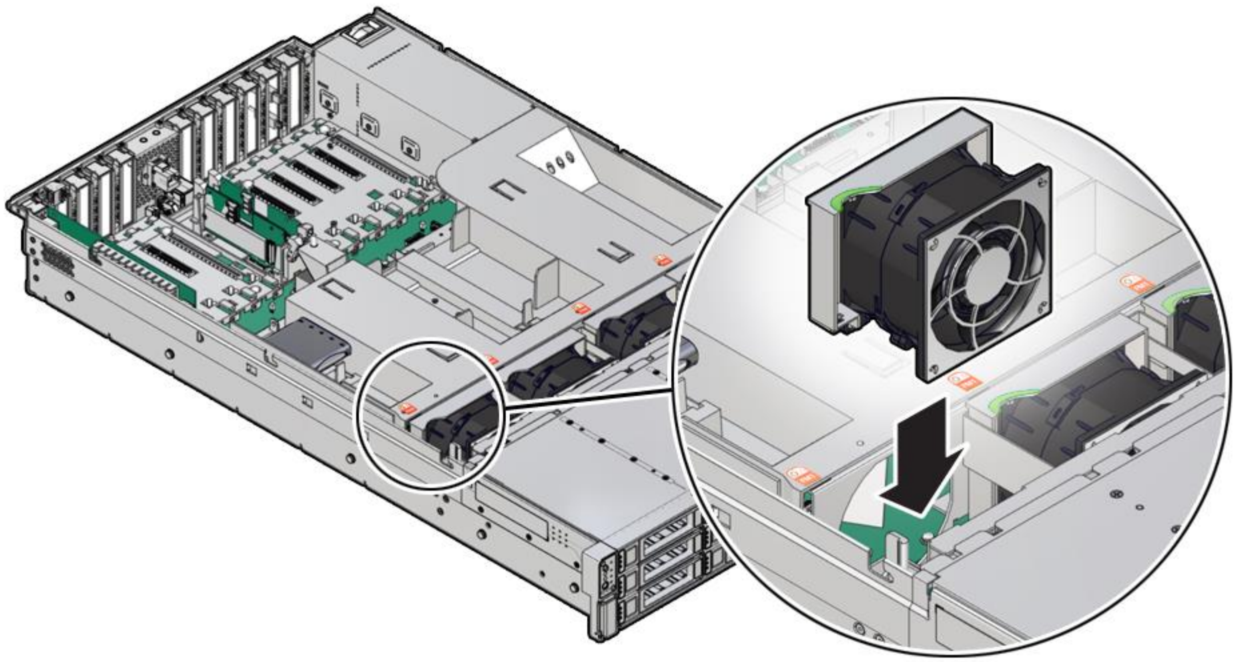


Figure 4. *Server Cooling Effectiveness Factors [25]*

3.2. <u>*Fan Speed Control*</u>

- Utilizing temperature-based control to adjust fan speeds based on real-time temperature measurements from critical components
- Implementing workload-based control to adapt fan speeds to the current workload, reducing fan power consumption during periods of low utilization
- Exploring predictive control techniques using machine learning algorithms to anticipate cooling demands and proactively adjust fan speeds
- Balancing cooling performance and energy efficiency through intelligent fan speed control strategies

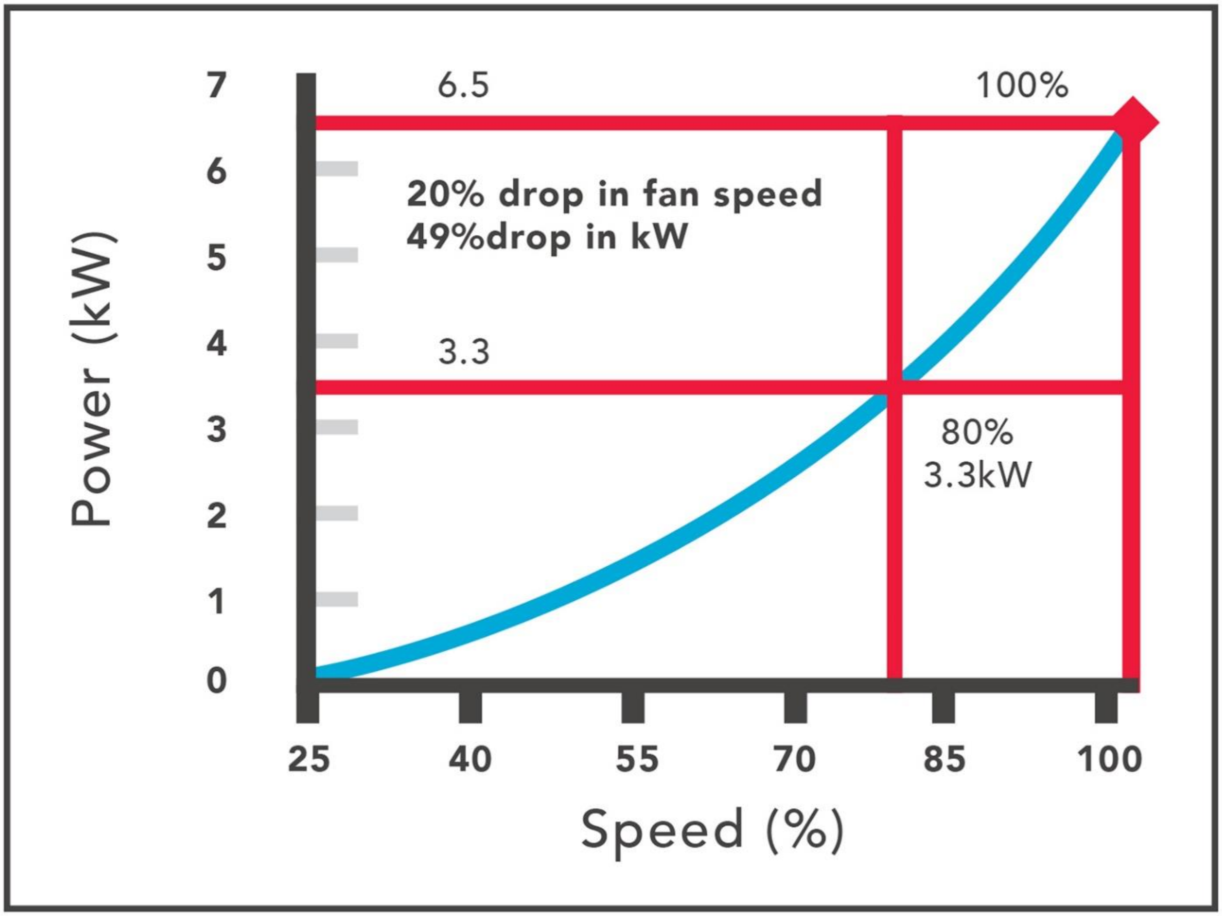


Figure 5. *The power consumption of a fan is a function of the cube of the fan speed. [26]*

3.3. *Airflow Management*

- Implementing air baffles and blanking panels to prevent air recirculation and mixing of cold and hot air streams
- Properly sealing gaps and openings to minimize air leakage and maintain a controlled airflow path
- Managing cables and other obstructions to reduce airflow resistance and improve cooling efficiency

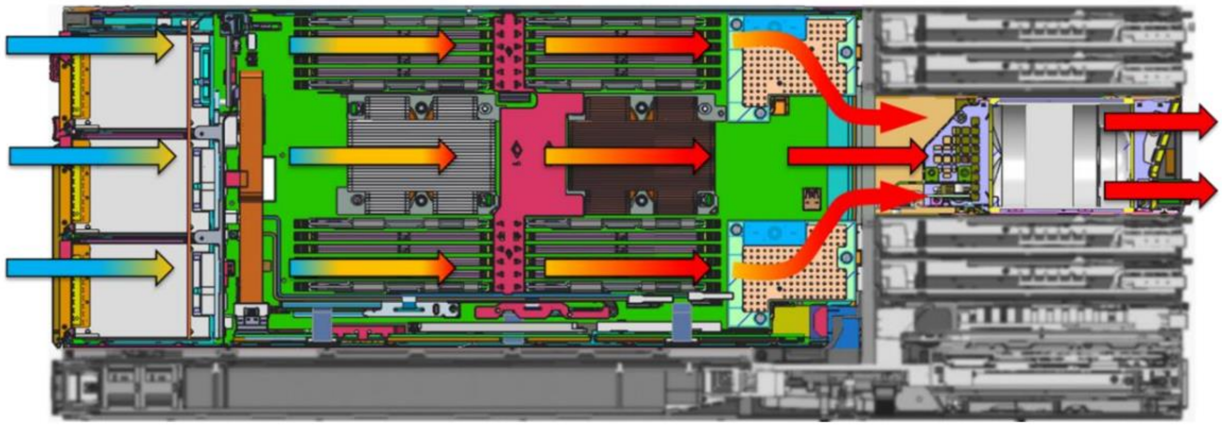


Figure 6. *Dell MX7000 Airflow [27]*

3.4. *Thermal Interface Materials*

- Selecting materials with high thermal conductivity to minimize thermal resistance between components and heatsinks
- Ensuring proper application and coverage of thermal interface materials to eliminate air gaps and maximize heat transfer
- Regularly inspecting and replacing thermal interface materials to maintain optimal performance over time

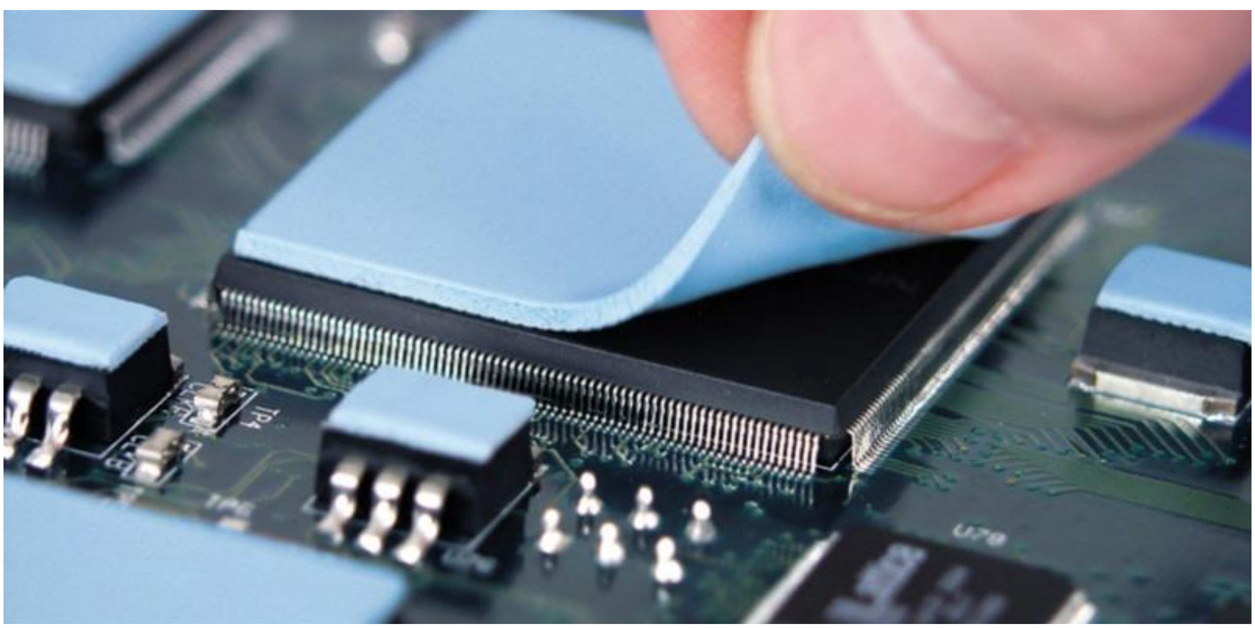
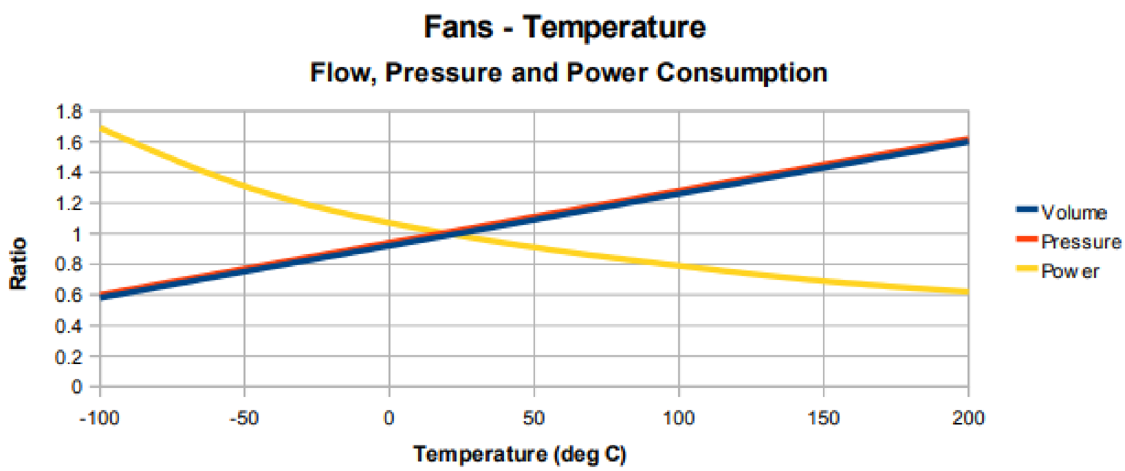


Figure7. TIM [28]

3.5. *Environmental Conditions*

- Considering the impact of ambient temperature and humidity on fan cooling effectiveness
- Recognizing that higher ambient temperatures reduce the cooling capacity of the air and may require increased fan speeds or supplemental cooling methods
- Designing fan cooling systems to accommodate the specific environmental conditions of the data center

Understanding and optimizing these factors is essential for maximizing the effectiveness of server fan cooling and achieving energy efficiency in data centers.



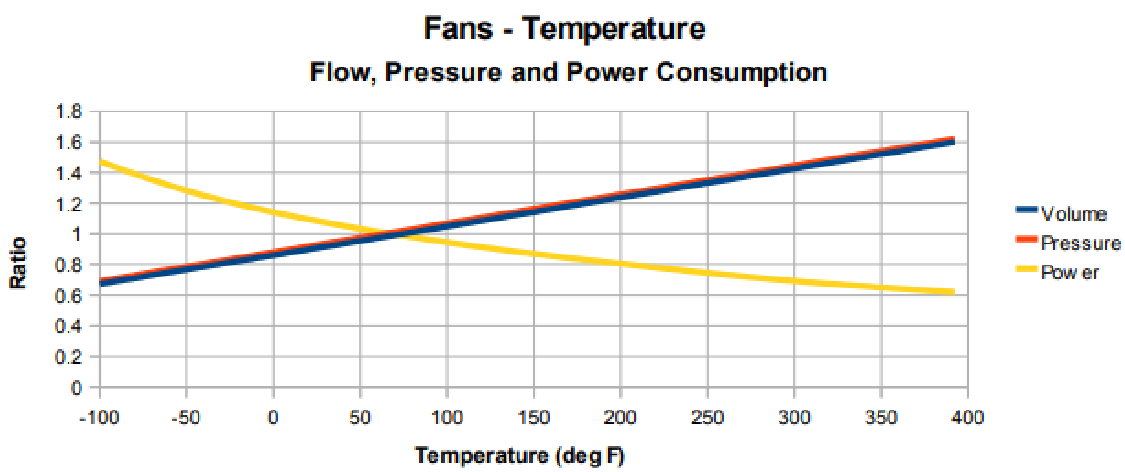


Figure 8. *The volume, pressure and power ratios. The chart is based on a NTP reference with temperature of 20 ºC . [29]*

4. Advantages and Disadvantages of Fan Cooling in Data Center Servers

Fan cooling remains the most widely used method for thermal management in data center servers due to its simplicity, cost-effectiveness, and compatibility with existing server designs. However, it also has certain limitations that should be considered when evaluating cooling strategies. This section discusses the key advantages and disadvantages of fan cooling in data center servers.

4.1. *Advantages of Fan Cooling:*

1. Simplicity and ease of implementation: Fan cooling is relatively simple to design, install, and maintain compared to other cooling methods. It does not require complex piping, pumps, or specialized coolants, making it easier to integrate into server systems.

2. Cost-effectiveness: The initial implementation and ongoing maintenance costs of fan cooling are generally lower than those of liquid cooling or hybrid systems. Fan cooling utilizes readily available components and does not require significant infrastructure changes, making it an economical choice for many data centers.

3. Compatibility with existing server designs: Fan cooling is compatible with a wide range of server form factors and can be easily adapted to different configurations. This compatibility allows for flexibility in server design and enables the use of standard server components, reducing development and procurement costs.

4. Scalability and modularity: Fan cooling systems can be easily scaled and modularized to accommodate different server densities and cooling requirements. Additional fans can be added or removed as needed, allowing for granular control over cooling capacity and energy consumption.

4.2. *Disadvantages of Fan Cooling:*

1. Limited cooling capacity at high power densities: As server power densities continue to increase, fan cooling may struggle to keep pace with the rising heat loads. In high-density deployments, fan cooling alone may not be sufficient to maintain optimal operating temperatures, leading to potential thermal issues and reduced server performance.

2. Inefficient airflow management: Poor airflow management within the server can lead to hot spots, air recirculation, and mixing of cold and hot air streams. These inefficiencies reduce the effectiveness of fan cooling and can result in uneven temperature distribution across server components.

3. Noise generation: High-speed fans can generate significant noise levels, which may be a concern in certain data center environments. The noise generated by fan cooling systems can create an unpleasant working environment for data center personnel and may require additional acoustic treatments to mitigate.

4. Energy consumption and inefficiency at low utilization: Fan cooling systems often operate at constant speeds, regardless of the actual cooling demand. This can result in excessive energy consumption during periods of low server utilization when the cooling requirements are reduced. Inefficient fan operation can lead to higher overall energy costs and reduced data center efficiency.

5. Dependency on environmental conditions: Fan cooling is dependent on the ambient temperature and humidity of the data center environment. In hot and humid climates, fan cooling may struggle to maintain the desired server inlet air temperatures, leading to reduced cooling effectiveness and potential reliability issues.

5. Comparison of Fan Cooling to Other Cooling Methods

To understand the relative strengths and weaknesses of fan cooling, it is important to compare it to other common cooling methods used in data centers, such as liquid cooling and hybrid cooling.

6.1. *Fan Cooling vs. Liquid Cooling*:

a) Cooling capacity: Liquid cooling offers higher heat transfer efficiency compared to fan cooling, making it more suitable for high-density server deployments. Liquid cooling systems can handle higher heat loads and maintain lower component temperatures, enabling improved server performance and reliability.

b) Energy efficiency: Liquid cooling systems can operate at higher temperatures than fan cooling, reducing the need for chiller plants and allowing for more efficient heat rejection. This can result in lower energy consumption and improved overall data center efficiency.

c) Complexity and cost: Liquid cooling systems are more complex to design, install, and maintain compared to fan cooling. They require specialized knowledge, skills, and infrastructure, such as piping, pumps, and coolant management systems. The initial implementation and ongoing maintenance costs of liquid cooling are generally higher than those of fan cooling.

d) Compatibility and flexibility: While fan cooling is compatible with a wide range of server designs, liquid cooling may require significant modifications to server components and layouts. This can limit the flexibility and scalability of liquid cooling systems, especially in existing data center environments.

6.2. *Fan Cooling vs. Hybrid Cooling*:

a) Targeted cooling: Hybrid cooling systems combine the benefits of both fan cooling and liquid cooling by using liquid cooling for high-heat-density components and fan cooling for general server cooling. This targeted approach allows for more efficient heat removal where it is most critical, improving overall cooling effectiveness.
b) Flexibility and customization: Hybrid cooling enables customization based on specific server requirements and cooling needs. It allows for the optimization of cooling performance and cost-effectiveness by selectively applying liquid cooling to the most demanding components while relying on fan cooling for less critical areas.
c) Complexity and integration: Hybrid cooling systems introduce additional complexity compared to pure fan cooling, as they require the integration of both air and liquid cooling subsystems. This integration necessitates careful design and coordination to ensure optimal performance and reliability.
d) Cost-effectiveness: Hybrid cooling can be more cost-effective than full liquid cooling by leveraging the benefits of fan cooling for less demanding components. However, the overall cost of hybrid cooling systems may still be higher than that of pure fan cooling due to the inclusion of liquid cooling components and infrastructure.

In summary, fan cooling remains a popular choice for data center servers due to its simplicity, cost-effectiveness, and compatibility. However, it faces challenges in high-density deployments and may struggle to keep pace with increasing power densities. Liquid cooling offers superior cooling capacity and energy efficiency but comes with higher complexity and costs. Hybrid cooling aims to balance the advantages of both fan and liquid cooling, providing targeted cooling and flexibility, but introduces additional complexity in system integration.

When selecting a cooling method for data center servers, factors such as server density, cooling requirements, energy efficiency targets, budget constraints, and existing infrastructure should be carefully considered. The choice between fan-cooling, liquid cooling, or hybrid cooling depends on the specific needs and priorities of the data center, as well as the long-term strategy for managing increasing power densities and cooling demands.

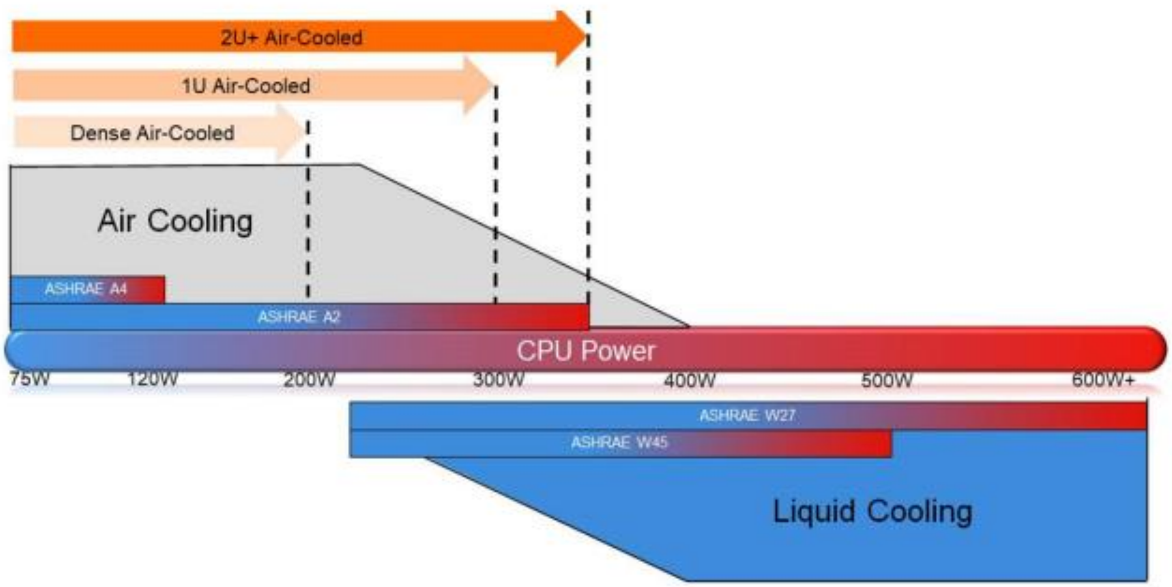


Figure 9. *Air cooling versus liquid cooling, transition, and temperatures [30]*

6. Introduction to the software Ansys Discovery 2024

The Discovery software interface provides a robust set of tools and functionalities for design, modeling, and simulation workflows. Upon launch, users are greeted by a comprehensive welcome screen that offers overviews of the application's stages, user interface components, and navigation tools, alongside interactive tutorials to guide them through various simulations. The Home interface displays recently accessed files and provides access to sample documentation for further exploration.

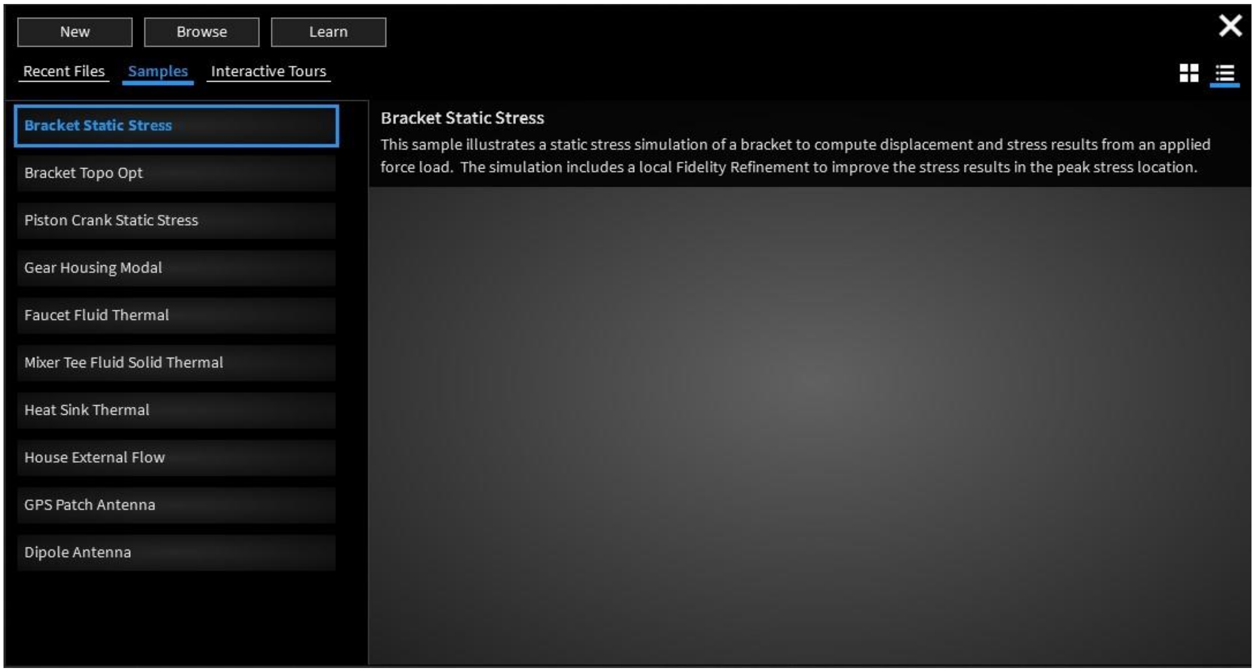


Figure 10. *Welcome Screen*

The primary workspace features an isometric sketch grid and a Stage Navigator prominently positioned at the bottom center. This critical interface element enables users to monitor and transition seamlessly between the three primary operational modes: Model, Explore, and Refine. These stages facilitate a structured workflow, from initial design conceptualization through physics-based behavioral analysis to final design validation via detailed simulation.

The hierarchical interface architecture includes a primary menu (three horizontal lines in the top-left corner) for accessing core functions such as file management and system configurations. Adjacent toolbar ribbons categorize tools into logical groups, including Design, Display, and Repair, with the Design tab housing primary geometry manipulation utilities. The Model Tree, positioned on the left, provides a structured visualization of design elements, such as:

- Sketched curves (lines, circles, rectangles),
- Surfaces (zero-thickness planar or three-dimensional faces),
- Solid bodies (enclosed three-dimensional volumes), and
- Assembly components (grouped entity collections).

Sophisticated visualization controls are offered through the View Arc, located in the bottom-left corner, which includes:

- Graphics display configuration,
- Home View orientation management,
- Predefined view selection,
- Material-based color assignment, and
- Transparency control.

Additionally, Advanced Selection capabilities in the bottom-right toolset include grouping, filtering, and selection history management. The Heads-up Display (HUD) further enhances the interface by providing a central halo element for expedited access to frequently utilized tools and simulation parameters. Comprehensive documentation and interactive help (accessible via **F1**) ensure users can fully leverage Discovery's capabilities.

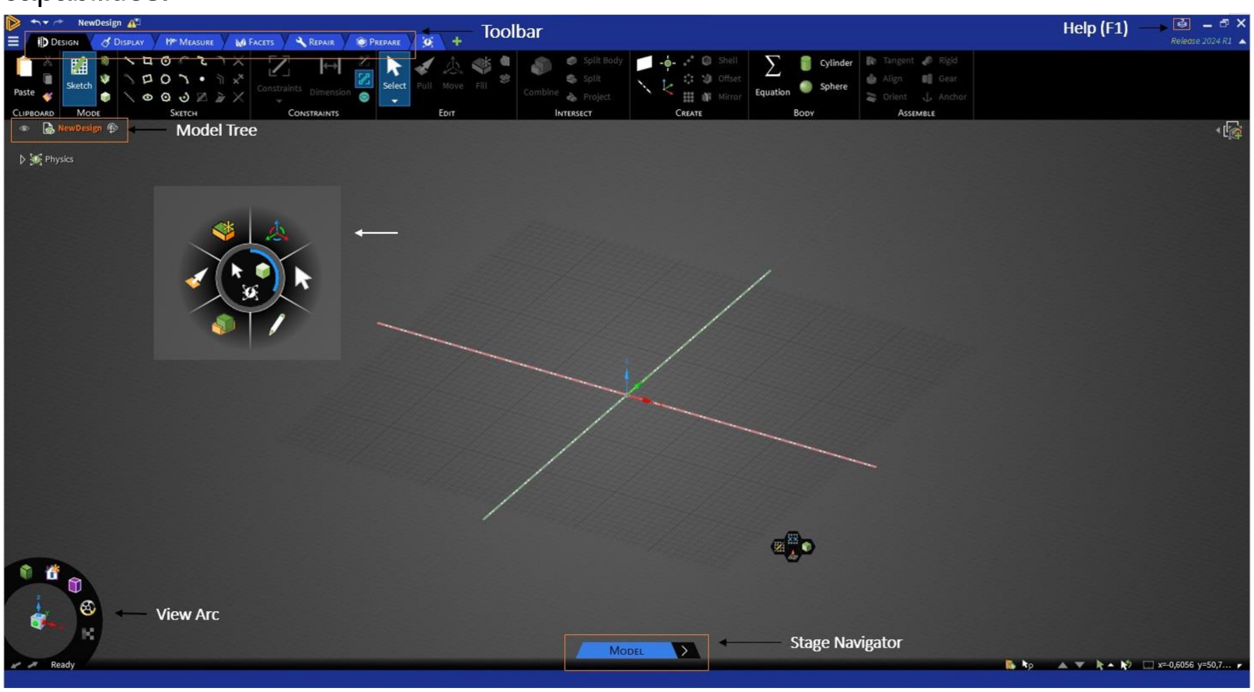


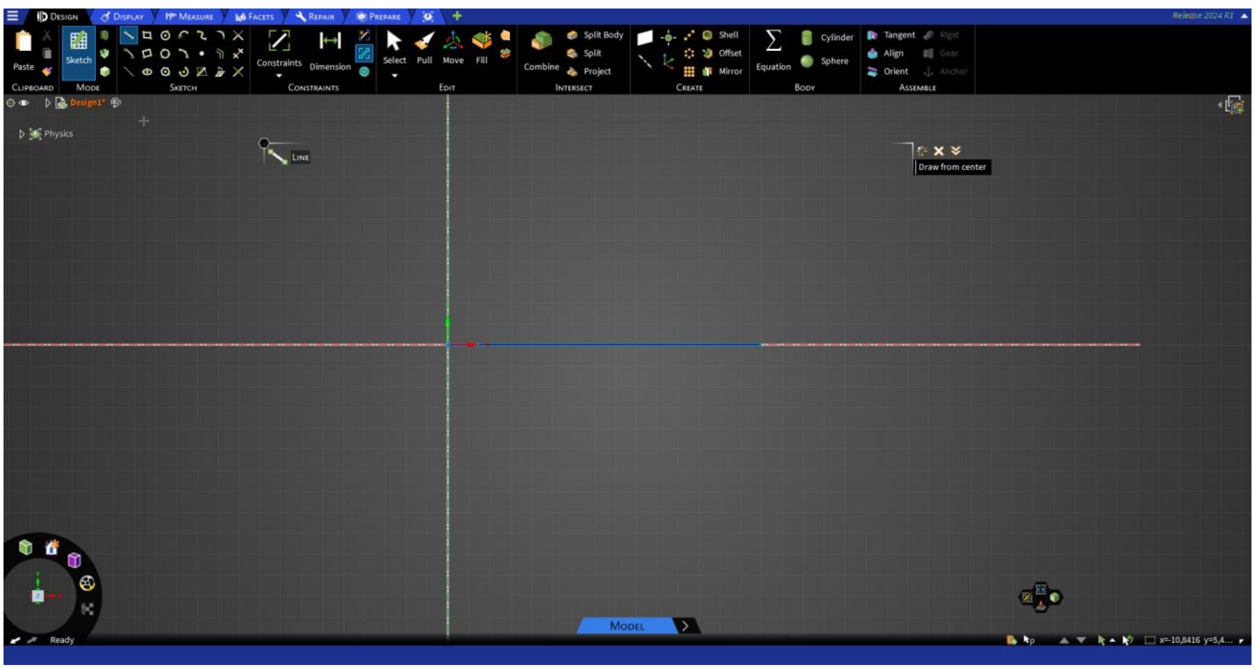
Figure 11. *Primary Workspace*

6.1. *Overview of Key Design Commands in Ansys Discovery*

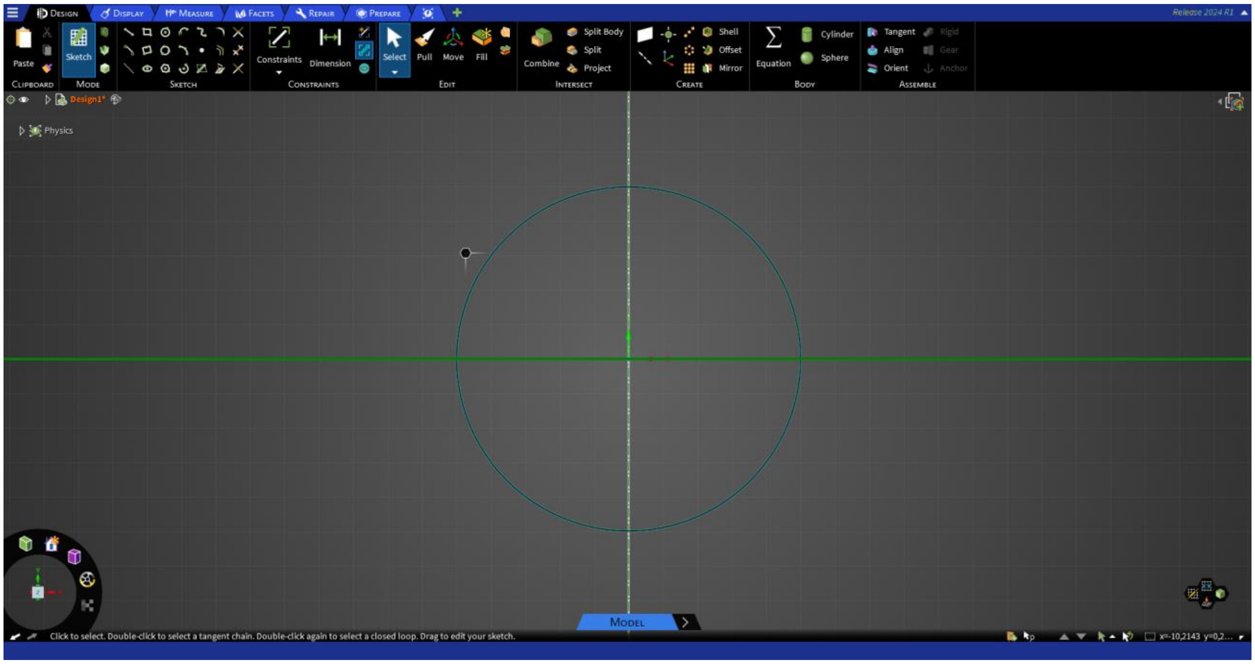
This section provides an overview of the essential design commands available in Ansys Discovery, focusing on those most relevant to the 3D modeling process covered in the subsequent chapters. While Ansys Discovery offers a wide array of powerful tools and capabilities, the following key commands form the foundation for efficient and effective modeling workflows:

1. Sketching Tools:

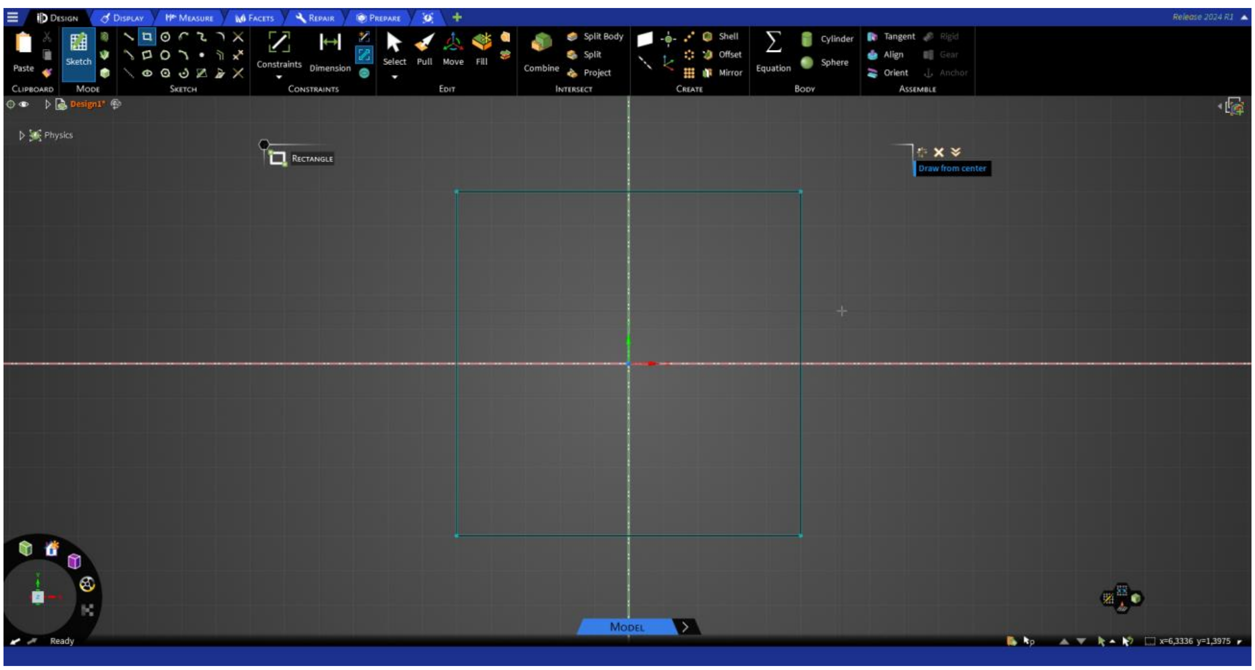
- Line: Allows you to draw straight lines between two points.



- Circle: Lets you draw circular geometry.

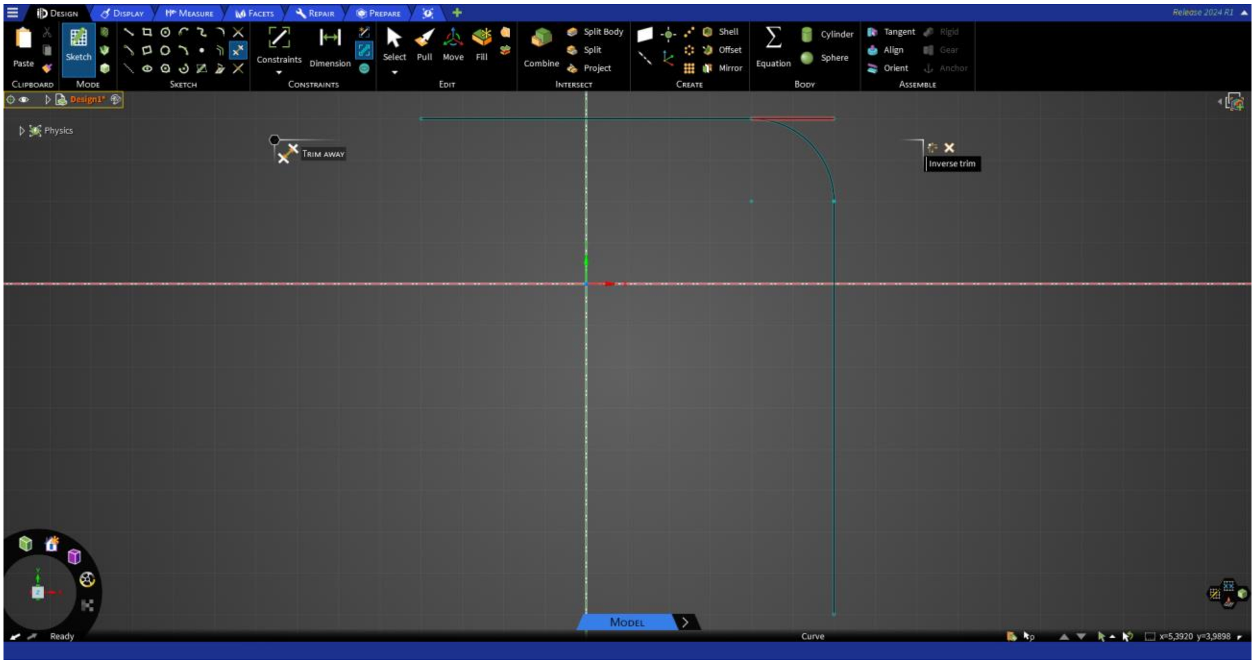


- Rectangle: Provides a tool for creating rectangular shapes.



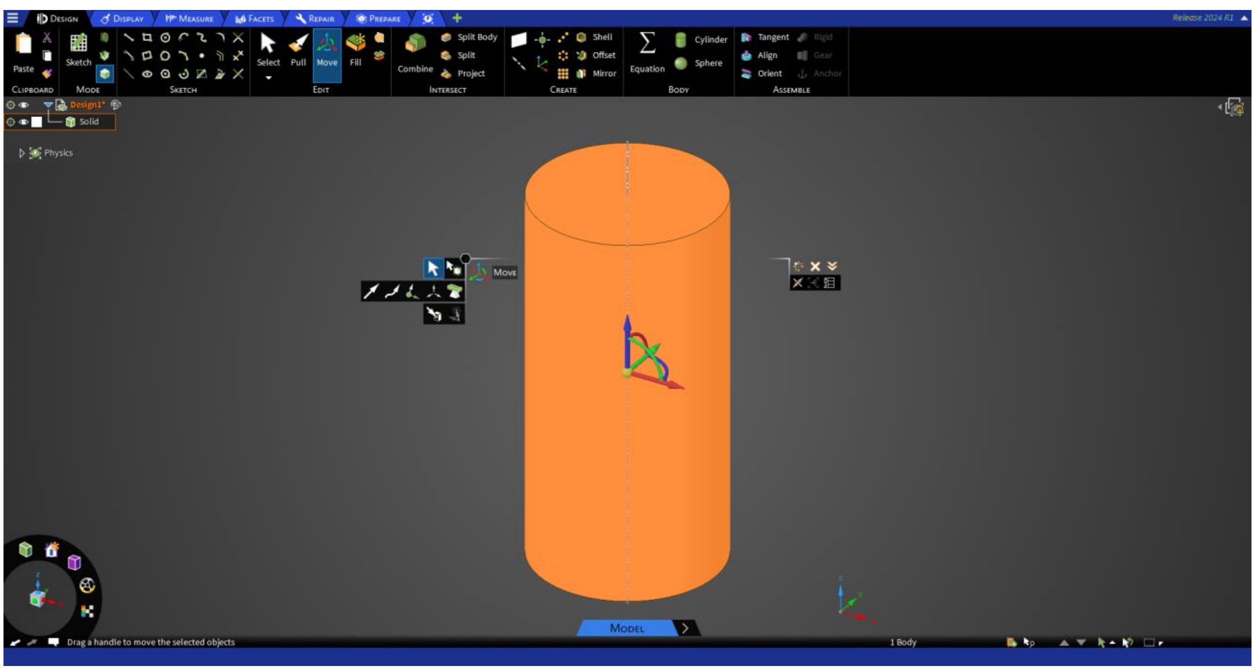
You can efficiently input both dimensions by pressing the Tab key.

- Trim: Allows you to remove the portion of an entity that extends beyond an intersection with another entity.

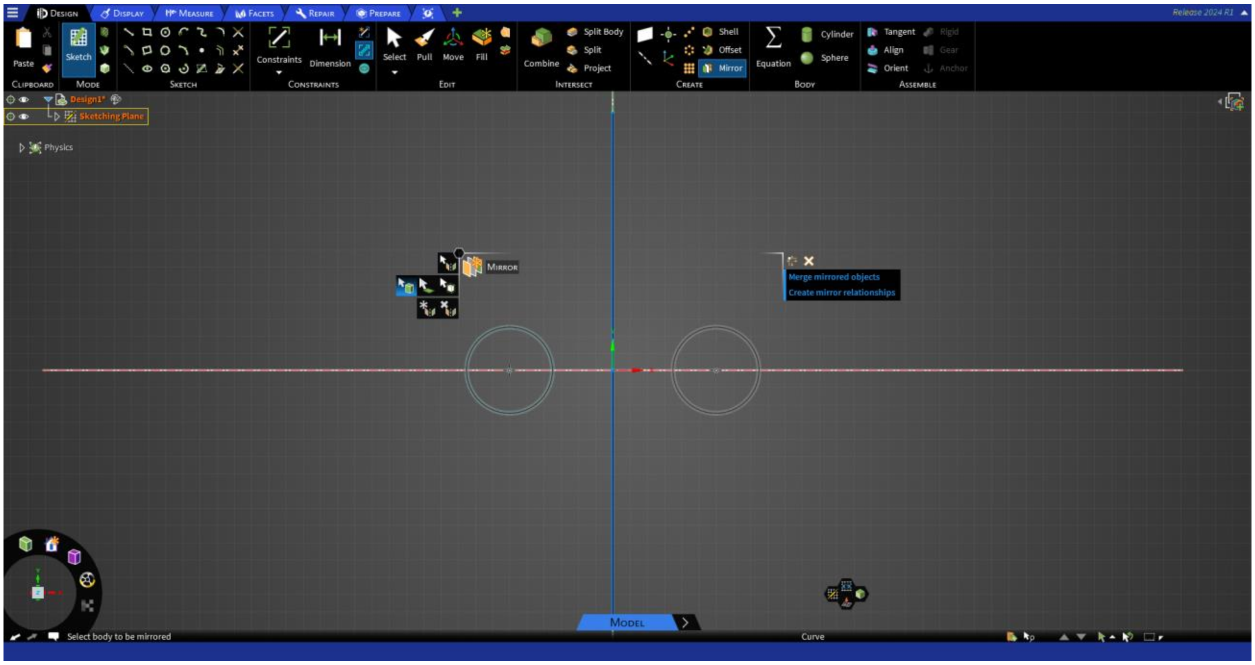


2. Editing Tools:

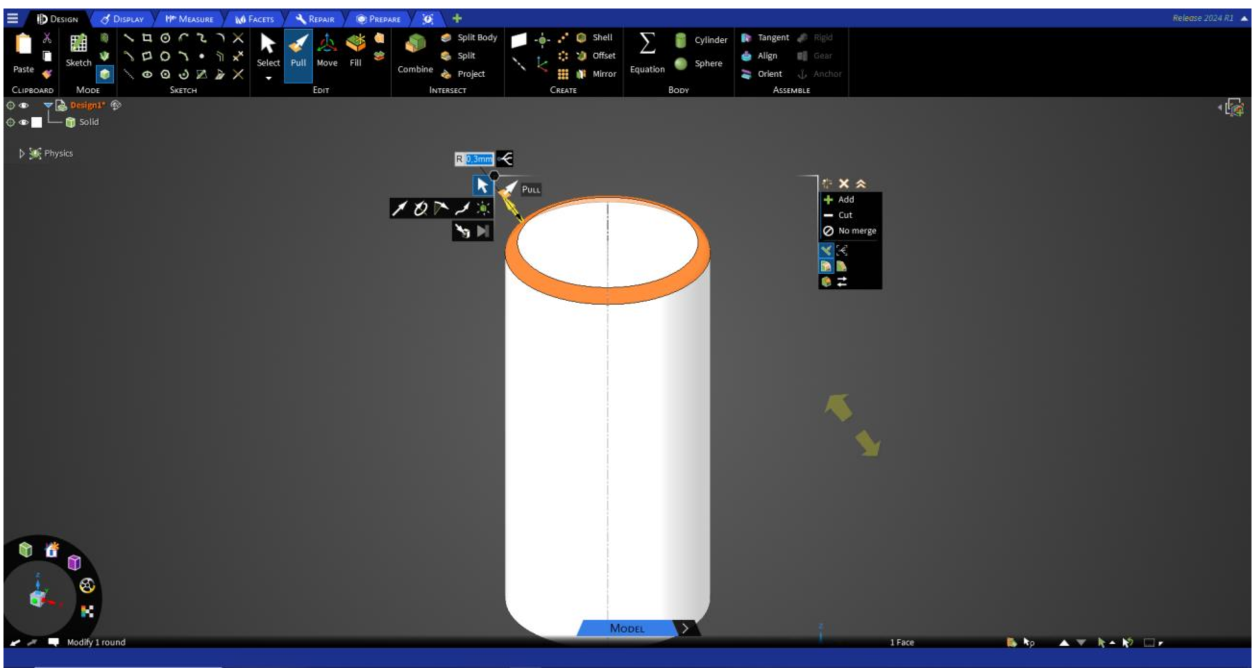
- Move: Enables the movement of selected entities to a new location.
- Rotate: Allows you to rotate selected entities around a specified axis.



- Mirror: Lets you create a mirrored copy of selected entities.

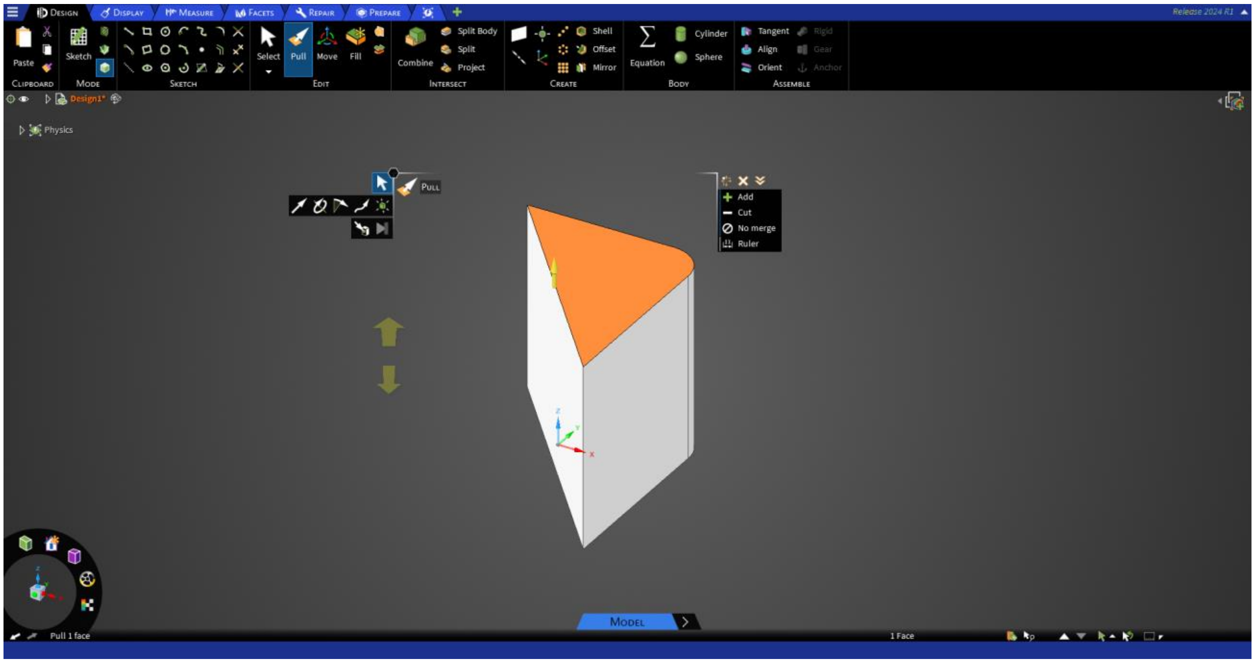


- Round: Enables the creation of rounded corners between two intersecting entities.

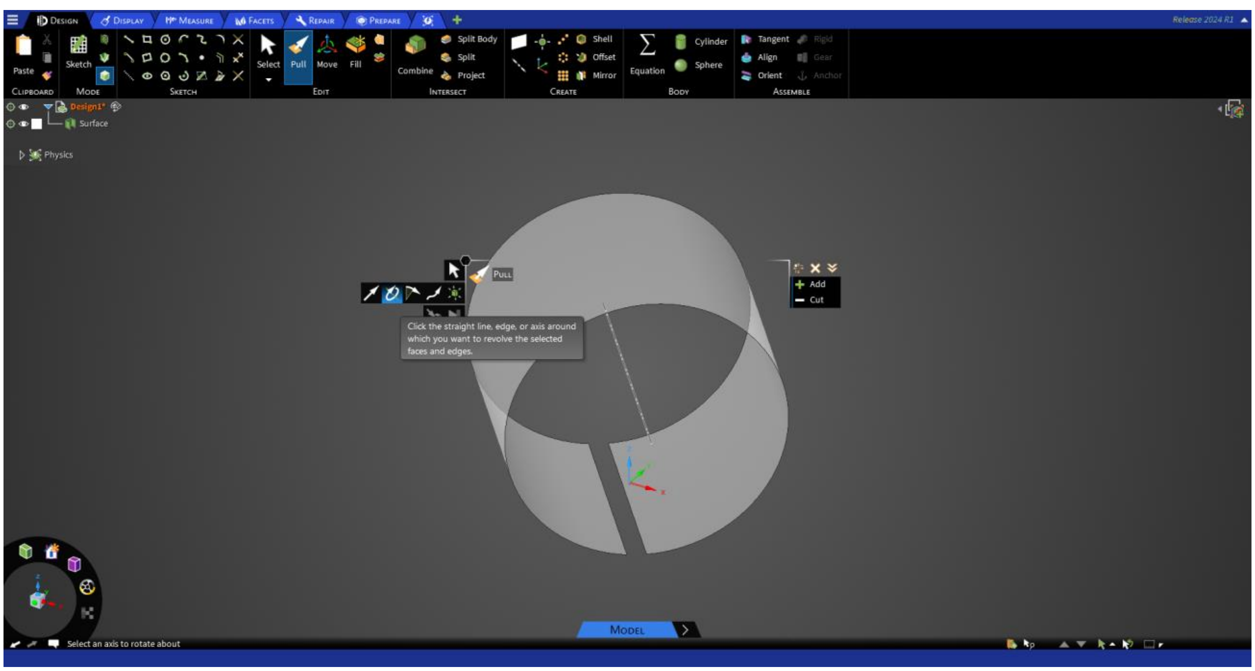


3. Modeling Tools:

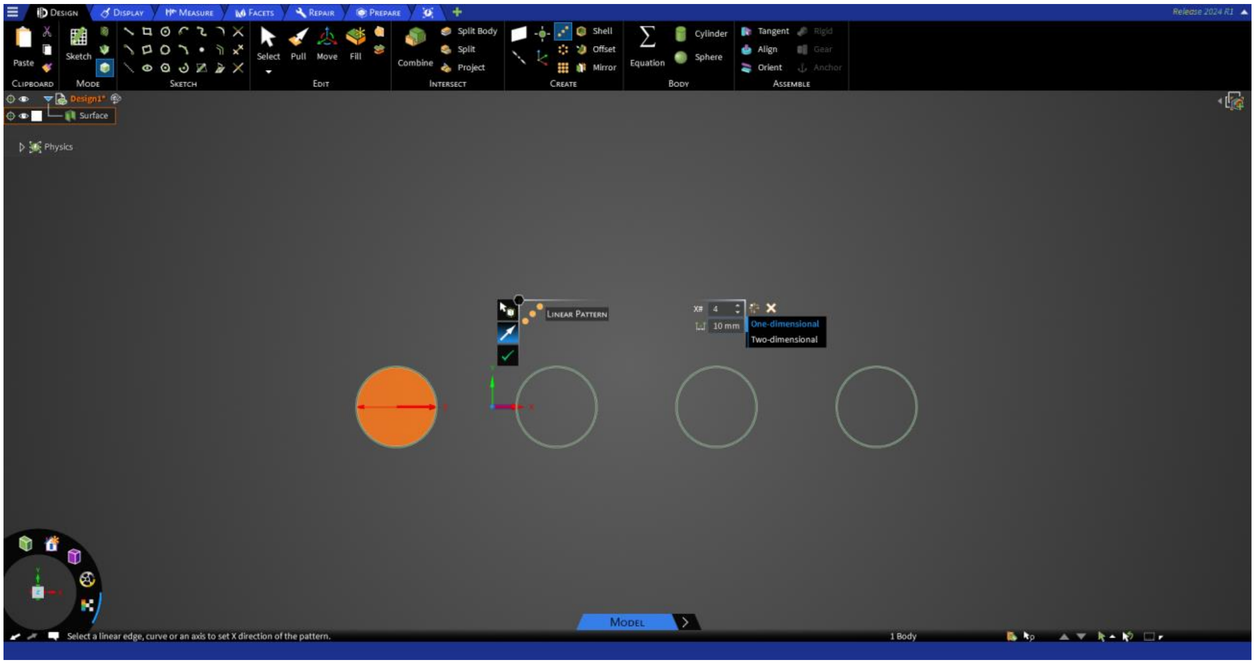
- Extrude lets you create 3D models by extruding 2D sketches along a specified distance.



- Revolve: Allows you to create 3D models by revolving a 2D sketch around an axis.



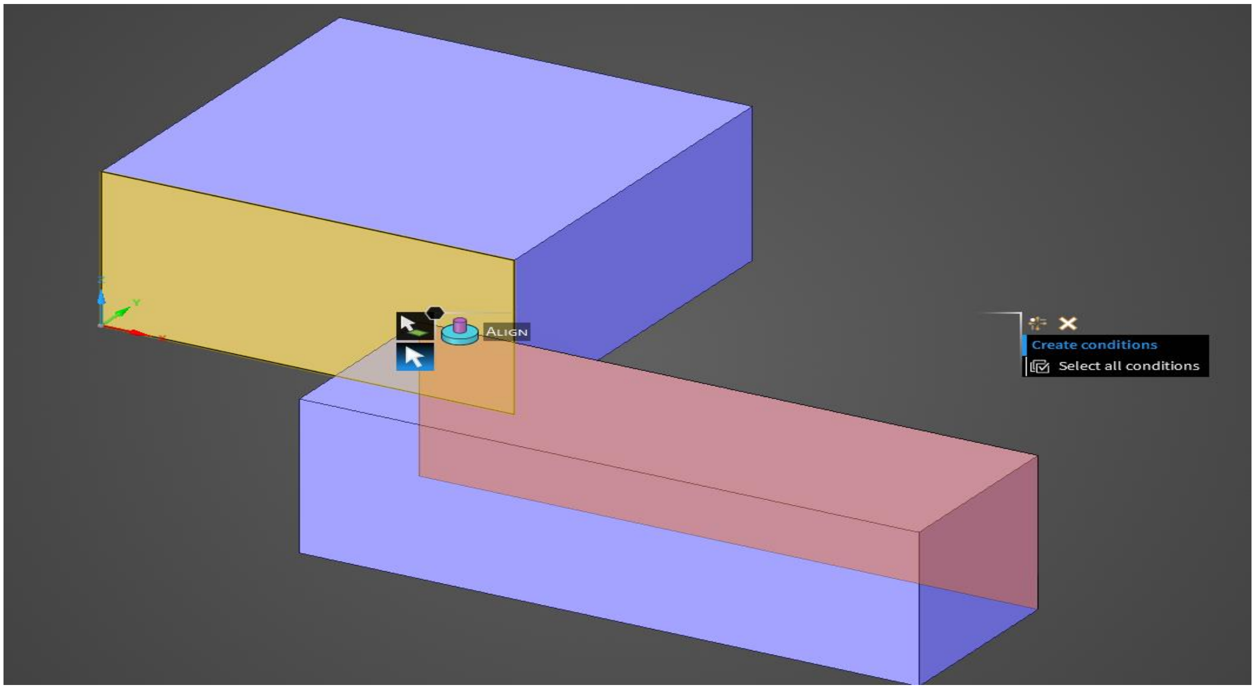
- Linear Pattern - A tool used to create multiple copies of a feature arranged in a linear array.



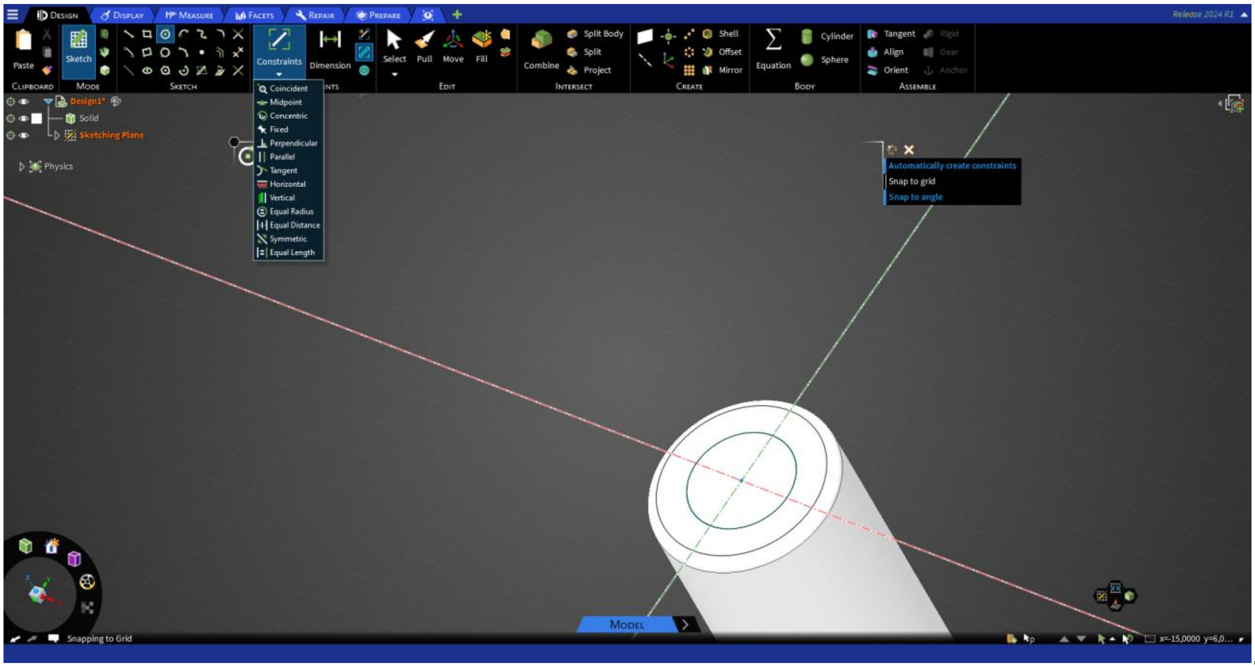
- Circular Pattern - A tool used to create multiple copies of a feature arranged in a circular array.

4. Assembly Tools:

- Align: Allows you to align the orientation of components in an assembly.



- Constrain provides the ability to apply various constraints (such as fixed, roller, or slider) to components in an assembly



5. Simulation Tools:

- Structural: Enables the analysis of structures under static loads and boundary conditions.
- Thermal: Allows you to analyze the thermal behavior of a model, including heat transfer and temperature distribution.
- Fluid Flow (CFX): Enables the simulation of fluid flow and related phenomena, such as pressure, velocity, and turbulence.

7. Server Component Architecture and Design

7.1. System Overview

This section lists the main components of a 1U rack-mounted HPE ProLiant DL325 Gen10 Plus server. The server consists of the following components:

1. Central Processing Unit (CPU)

The CPU assembly incorporates multiple elements working together to provide processing capabilities while maintaining thermal stability. This includes the CPU socket, the processor itself, heatsink, substrate board, and thermal interface material. The design ensures optimal heat dissipation while maintaining structural integrity.

2. Motherboard

The motherboard serves as the primary foundation for all server components. It provides the interconnection between various components and hosts essential system features including power distribution, signal routing, and mounting points for other components.

3. Power Supply Unit (PSU)

The power supply unit is strategically positioned along the server's edge to optimize space utilization and thermal management. Its design incorporates efficient power delivery while maintaining the thermal requirements of the system.

4. Random Access Memory (RAM)

The memory system consists of two main components: the memory board and the socket. The retention mechanism features a sophisticated design that ensures secure module placement while facilitating heat dissipation. The system supports multiple memory configurations for scalable performance.

5. Solid State Drive (SSD)

The storage system incorporates both the SSD socket and drive units. The design features a dual-bank configuration with mirrored placement, optimizing space utilization while maintaining access for maintenance.

6. External Server Casing

The server enclosure provides structural support and protection while facilitating proper airflow. It features strategic ventilation patterns and mounting points for cooling components.

7. Cooling System

The cooling solution consists of multiple fans with precisely engineered housing units. The design incorporates advanced airflow management features to maintain optimal operating temperatures across all components.

All design specifications are based on commercially available products used in enterprise data centers. The server components are sourced from the following manufacturers:

- The server platform is based on the HPE ProLiant DL325 Gen10 Plus specifications
- The processor utilizes AMD EPYC™ 7002/7003 Series Processors
- The motherboard is an HPE-designed server board optimized for EPYC processors
- Storage options include HPE NVMe and SATA SSDs
- Memory modules are compatible with industry-standard DDR4 specifications
- The power supply units are HPE Flexible Slot Power Supplies

- The cooling solution incorporates HPE's thermal engineering expertise for optimal performance

The integration of these components creates a robust server platform designed for enterprise-level reliability and performance while maintaining effective cooling capabilities across various operational scenarios.

7.2. Core Processing Components

7.2.1. Motherboard Design

The drawing starts by selecting the Top plane as the drawing plane and selecting the sketch command. Then, using the sketch from the center command, a dotted line passing through the origin of the axes is created, defining the plane of symmetry.

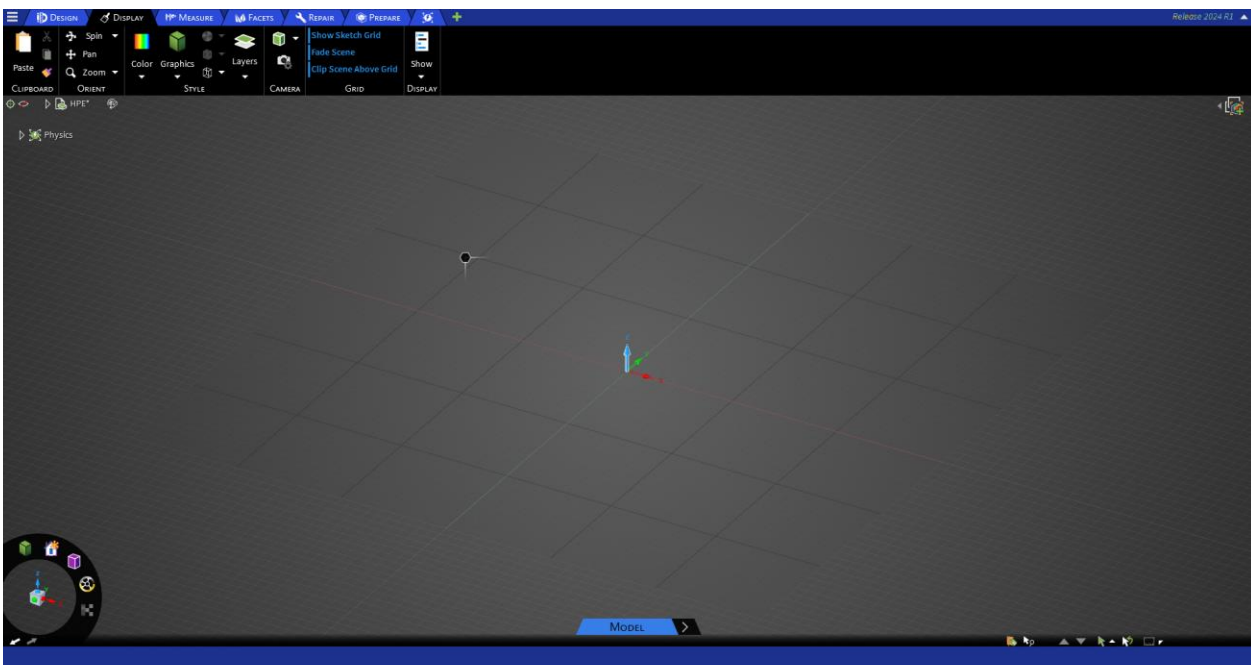


Figure 7. *Initial sketch setup with center plane and axis definition*

As shown in Figure 9, by pressing R in the keyboard, we enable the sketch of a rectangle that is aligned with the sketch grid, measuring 330mm in length and 303mm, establishing the foundation for the motherboard layout. To provide structural integrity and support for the various components, a thickness of 1.6mm is added to the sketched rectangle using the Pull tool.

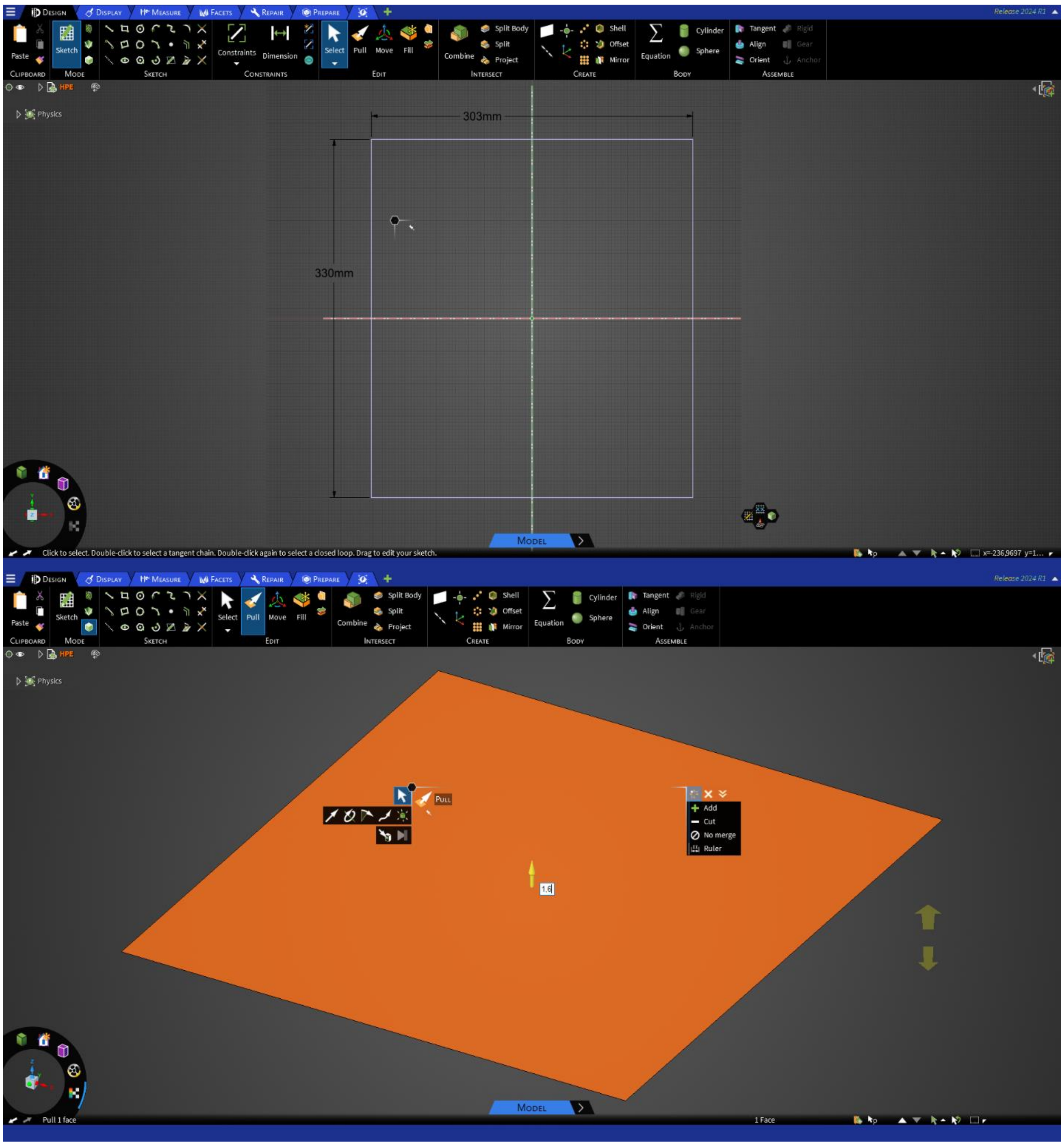


Figure 8. *Motherboard base dimensions and extrusion parameters*

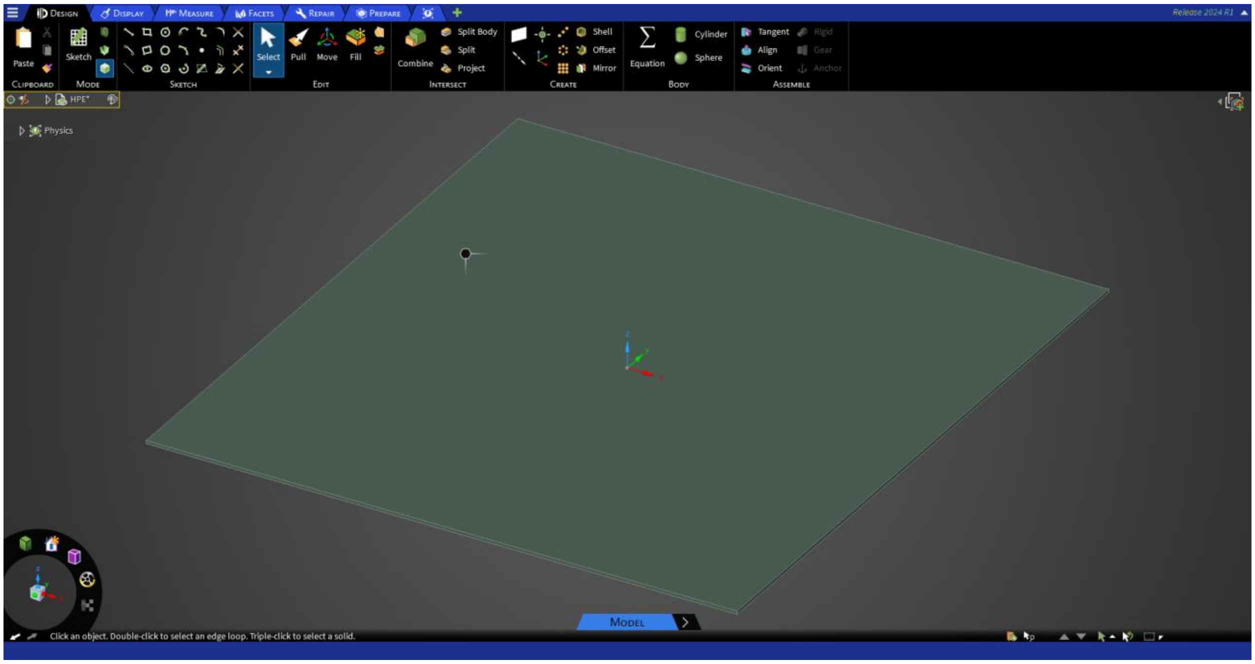


Figure 10. *Final motherboard model*

<u>Note</u>

When preparing the model for the fluid flow and thermal simulation, the volume extraction process will create a fluid domain that represents the air volume within the server casing. This fluid domain will be based on the internal dimensions of the casing itself, rather than the specific dimensions of the motherboard. As a result, the exact measurements of the motherboard become less critical for the simulation, as the motherboard geometry will be extended or simplified to fit within the boundaries of the extracted fluid volume. This approach allows for a more focused analysis of the airflow and heat transfer within the server, while reducing the complexity of the model and computational requirements. However, it is important to ensure that the essential features of the motherboard, such as component placement and heat source locations, are still accurately represented within the context of the casing-defined fluid domain.

7.2.2. CPU Support Structure

7.2.2.1. Stiffener Frame Design

The SP3 Socket Stiffener Frame represents a precisely engineered component designed to provide structural support and stability for CPU socket assemblies. The frame features a symmetrical design with overall dimensions of 92.32mm in height and 59.4mm in width at its central section, incorporating a rectangular opening of 20.18mm width at its core. Four mounting tabs extend from the corners, each measuring 30.26mm in width, creating a stable mounting platform. The design incorporates carefully calculated transitions, including corner radii of 1.51mm at specified junction points, and varying tab thicknesses of 12.24mm at the upper section and 11.91mm at the lower section. Critical dimensions are maintained throughout, with the upper section height at 30.64mm and lower section at 30.52mm, ensuring precise alignment and load distribution. The frame's single-piece construction demands strict manufacturing tolerances of ±0.05mm, with particular attention paid to mounting hole perpendicularity and surface finish uniformity.

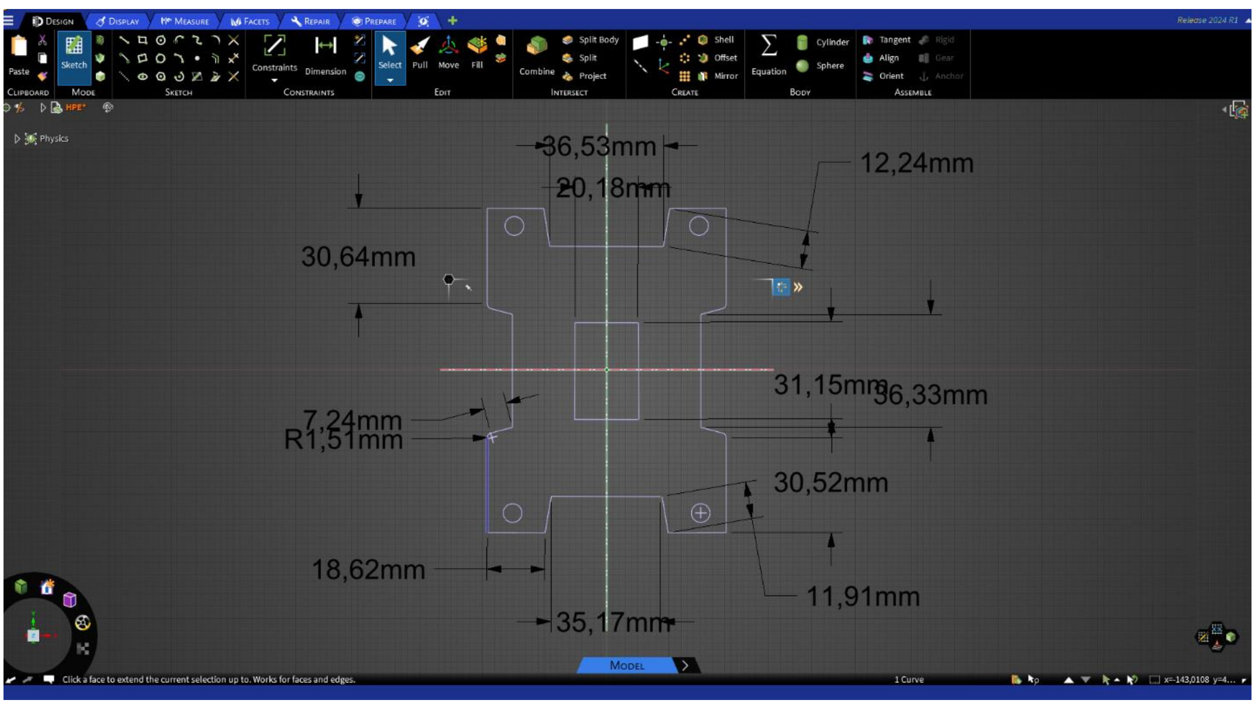


Figure 11. *SP3 Socket stiffener frame detailed dimensional specifications*

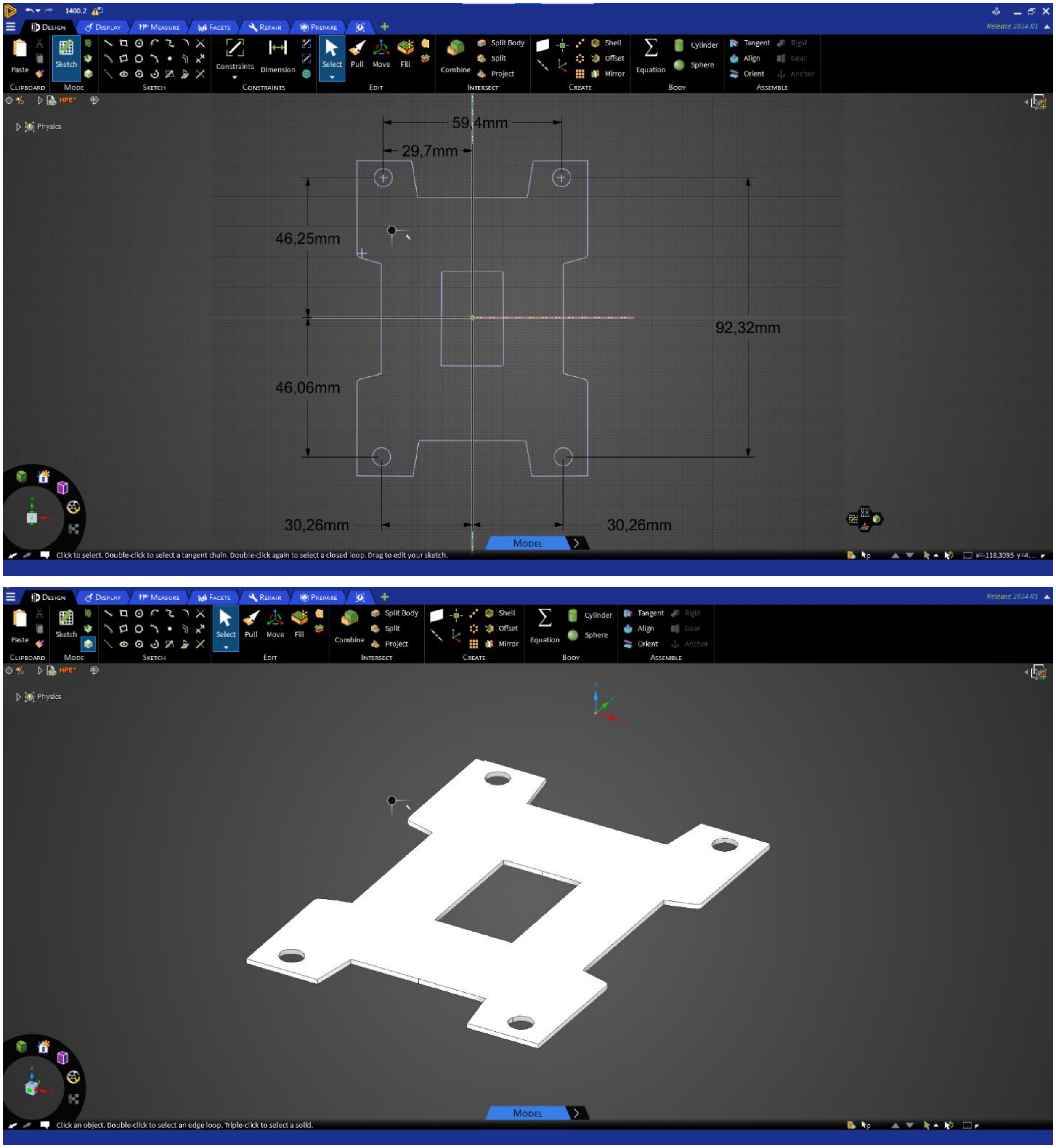


Figure 12. *SP3 Socket Stiffener Frame - Dimensional Overview and Tolerance Specifications*

7.2.2.2. Heat Sink Attachment Design

The SP3 socket heatsink attachment mechanism employs a sophisticated design that ensures optimal thermal contact and structural integrity. The frame incorporates four M3.5x0.6 PEM nut standoffs positioned at a height of 5.0mm from the PCB surface. These standoffs are strategically placed at coordinates defined by a 46.0mm x 40.28mm rectangular pattern, with an overall frame dimension of 75.54mm x 85.13mm. The design includes precise edge distances, with the frame's mounting points positioned 12.58mm from the top edge and 8.75mm from the bottom edge, ensuring balanced pressure distribution. A critical design element is the central mounting region, which features a carefully engineered thickness profile that maintains proper contact force between the heatsink and CPU lid. The frame's structural elements include reinforced corners with a radius of R3.69mm, providing additional rigidity while accommodating the specified spring screw force of 75±15 lbf. This design supports thermal solutions for processors with TDP ratings ranging from 120W to 225W, all while maintaining the heatsink mass requirement of less than 450g. The frame's geometry is optimized to work within the motherboard keep out zone of 79.90mm x 120.30mm, ensuring compatibility with standard system configurations and maintaining proper clearance for adjacent components.

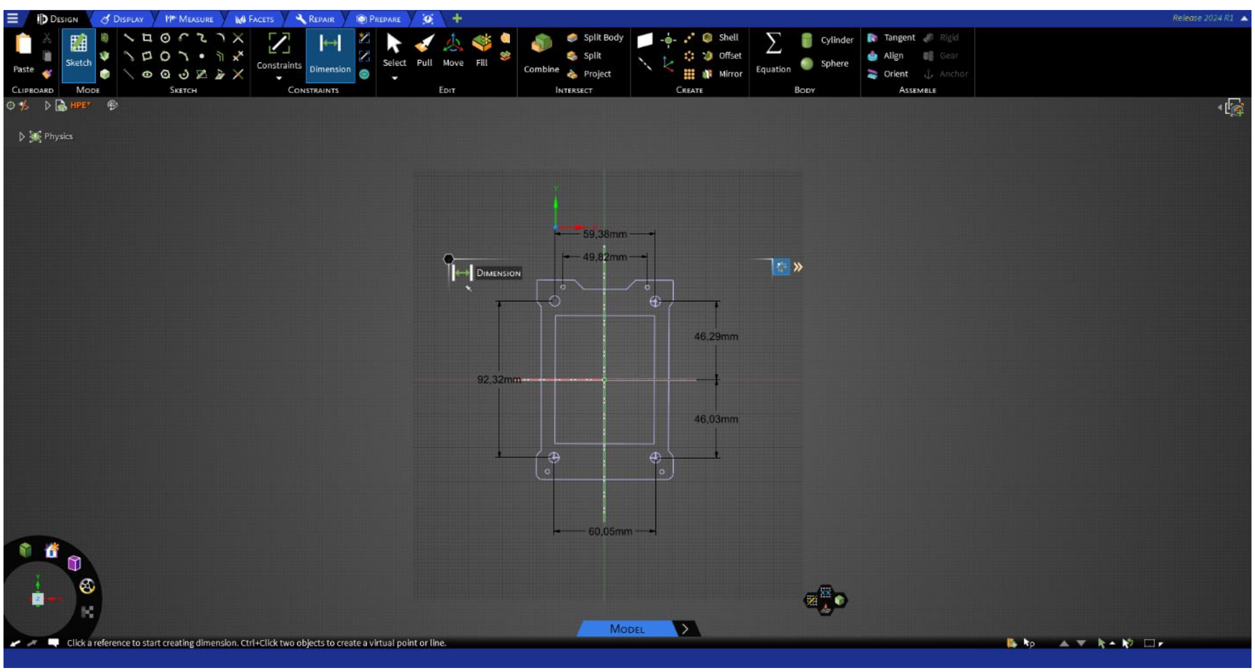


Figure 13. *Heatsink attachment mechanism cross-sectional view and mounting details*

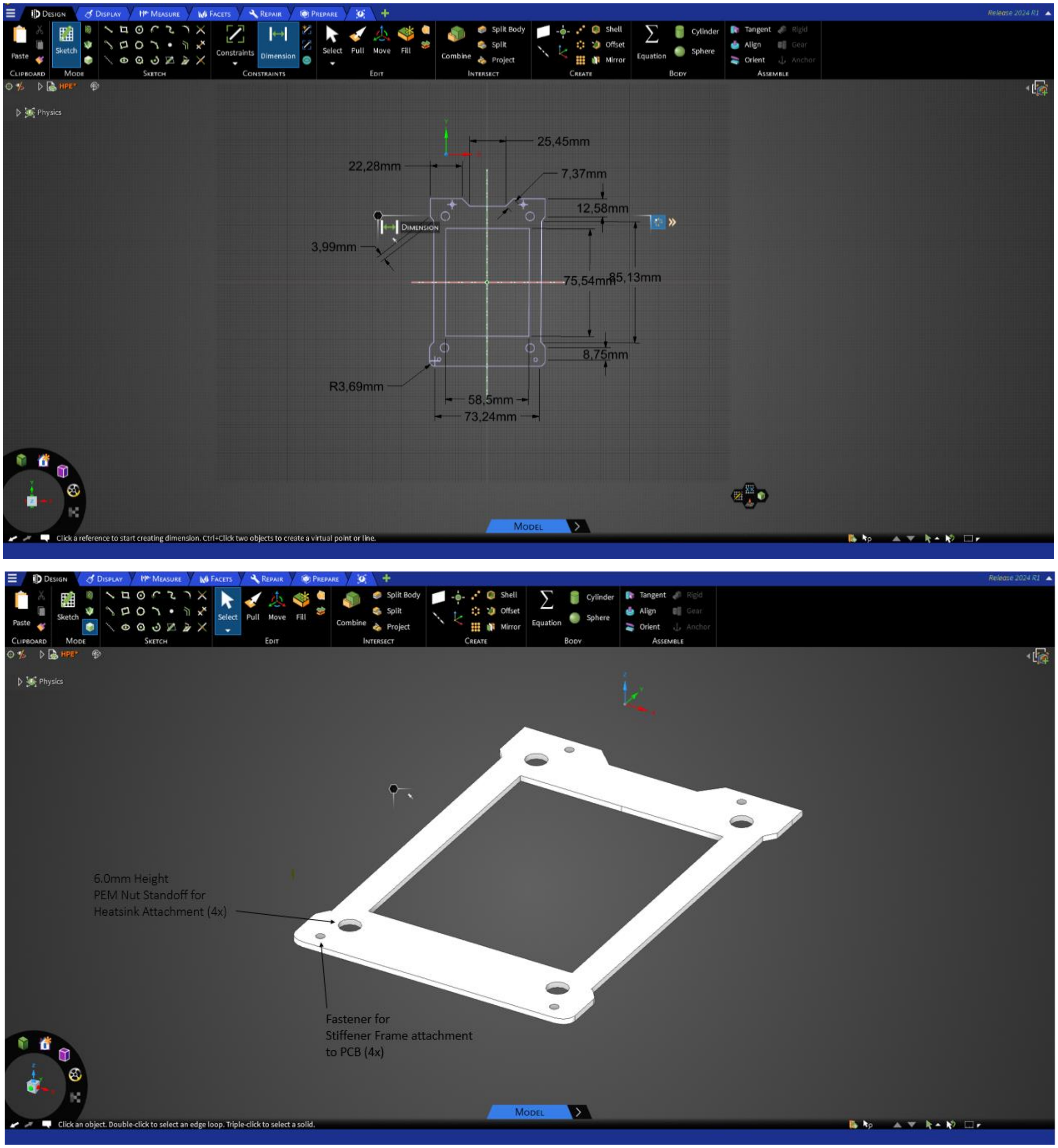


Figure 14. *SP3 Socket Heatsink Attachment Mechanism – Design and Specifications*

7.1.2.3. Force Frame Design

The SP3 Socket Force Frame is designed with precise geometric features to ensure optimal CPU retention and pressure distribution. The top section is crafted using a pull-sweep operation, creating a smooth profile with a height of approximately 12.58mm and spanning a width of 59.20mm. The bottom portion is manufactured using a pull-round tool to achieve an 11.91mm height while maintaining structural integrity. The left and right sides employ pull-draft operations to create the frame's vertical walls, with draft angles ensuring proper mold release during manufacturing. To maintain perfect symmetry and dimensional accuracy, mirror operations are utilized along the central axis. This creates identical features on both sides, including mounting holes positioned at 73.24mm apart (outer edges) and 58.5mm apart (inner edges). The design incorporates raised sections at each corner for secure mounting, with radii of R3.69mm at critical junctions to prevent stress concentration.

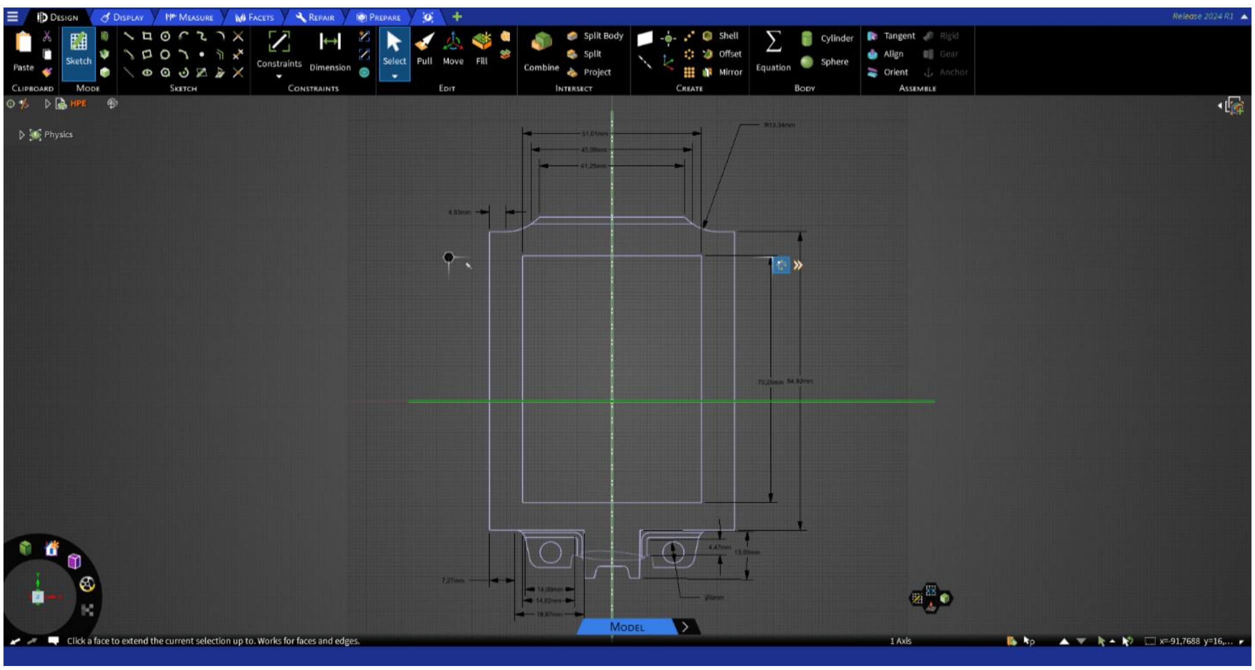


Figure 15. *Heatsink attachment mechanism cross-sectional view and mounting details*

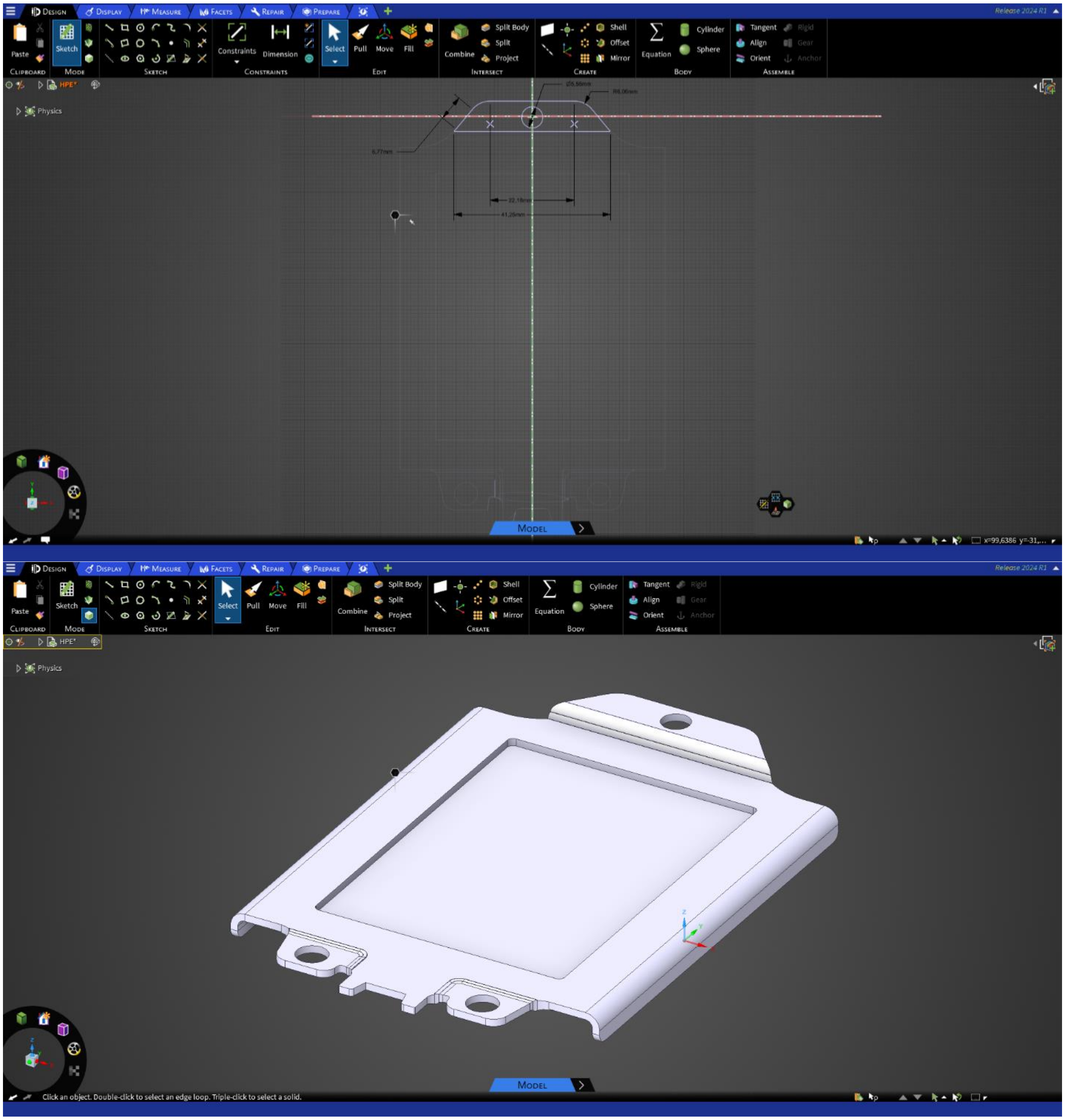


Figure 16. *SP3 Socket Force Frame - Geometric Design and Manufacturing Considerations*

This force frame is engineered to work in conjunction with the stiffener frame to provide the specified 75±15 lbf of spring screw force, ensuring optimal thermal transfer between the processor and heatsink while maintaining structural stability across operating temperatures ranging from those required for 120W TDP processors up to 225W TDP configurations.

7.2.2.4. CPU Design

The SP3 socket CPU design process begins with creating the base outline, which serves as the CPU substrate. The dimensions are 43.4mm x 63.9mm with R1.3mm corner radii. After sketching this profile, we use the pull tool to extrude it to a height of 2mm to create the substrate. On the top surface, a second sketch is created to define the CPU cavity with dimensions of 44mm x 64mm, incorporating 1mm thick borders and reaching a total height of 1.2mm from the substrate level.

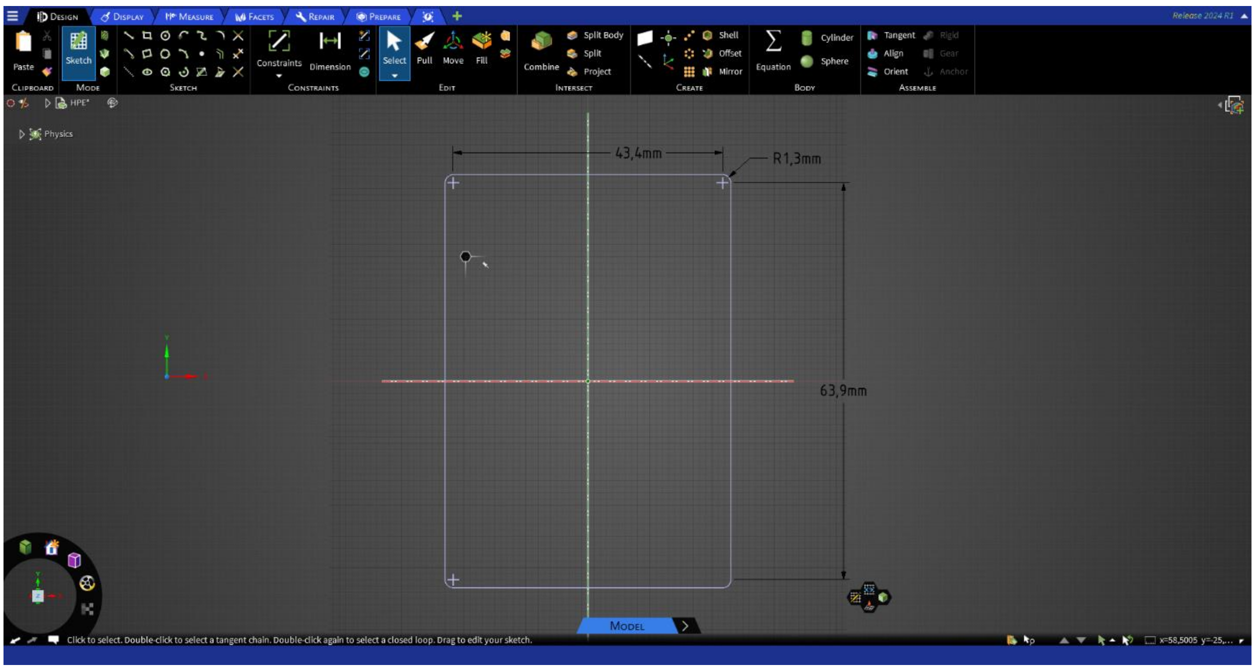


Figure 17. *SP3 Socket CPU Base Design - Substrate and Cavity Creation*

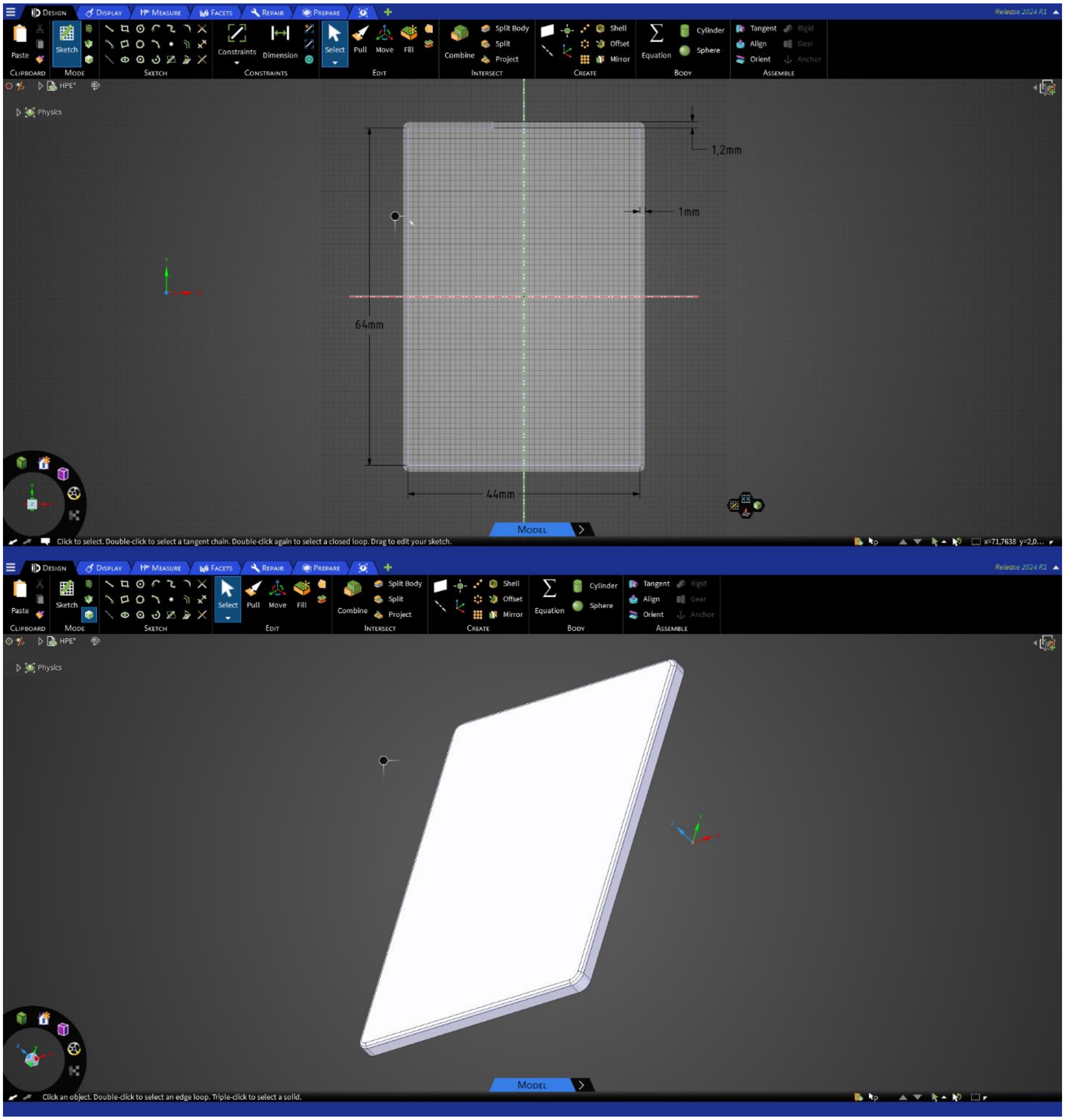


Figure 18. *SP3 Socket CPU - Dimensional Overview*

The assembly is completed by aligning the CPU socket centrally on the motherboard, with the mounting holes corresponding to the server's mounting pattern. The complete stack-up includes the stiffener frame with its PEM standoffs for heatsink attachment, providing the specified 75±15 lbf spring force required for optimal thermal interface material compression and heat transfer capability across TDP ranges from 120W to 225W.

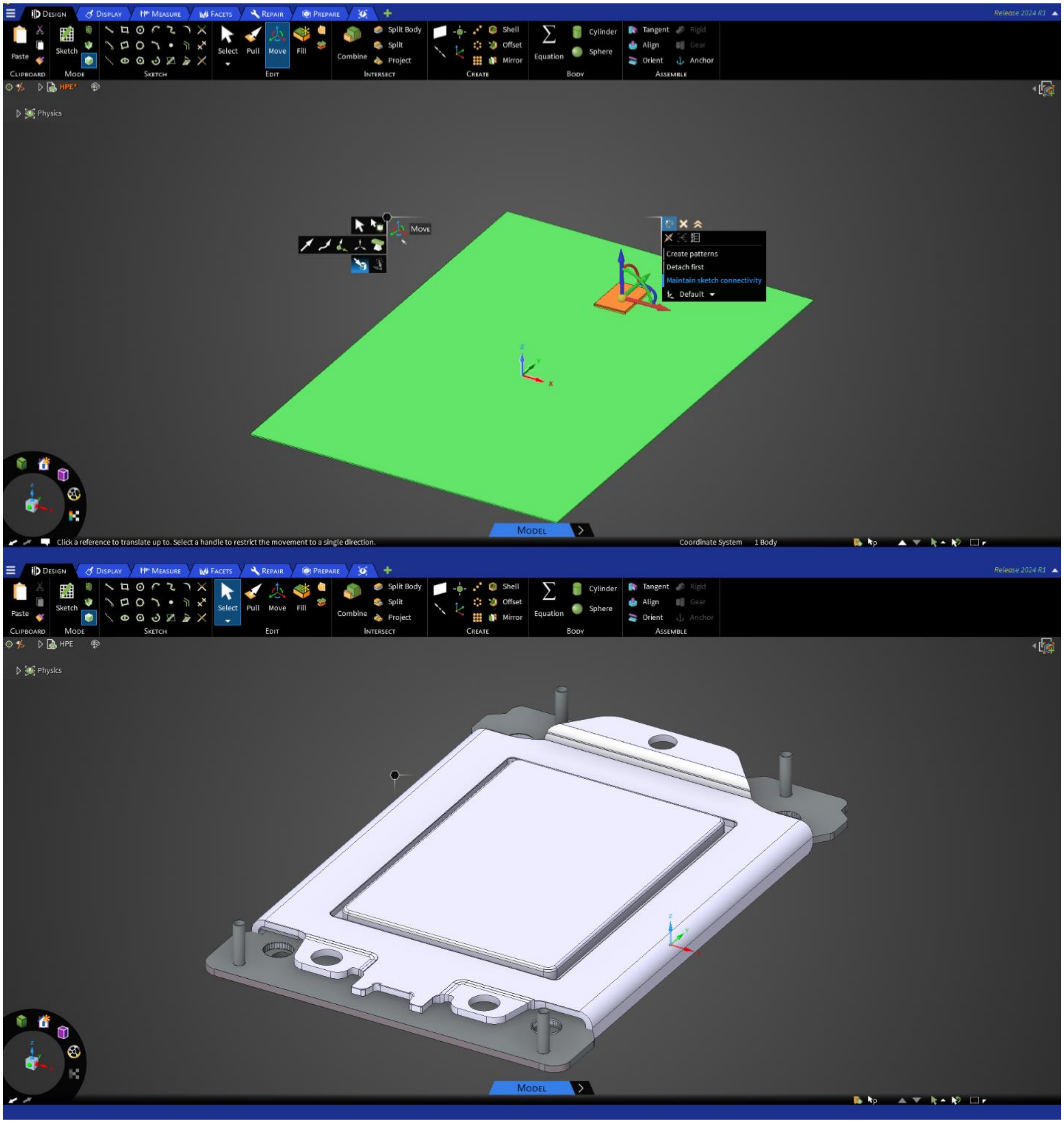


Figure 19. *SP3 Socket Assembly - Component Integration and Motherboard Alignment*

7.2.2.5. Thermal Interface Material Design (TIM)

The thermal interface design incorporates precise dimensional specifications to ensure optimal heat transfer between the CPU and cooling solution. The thermal paste application area is defined by a rectangular configuration measuring 63.9 mm in length, 43.4 mm in width, and 0.5 mm in thickness, with rounded corners featuring a radius of 1.3 mm. This geometric design is strategically positioned to provide complete coverage of the CPU's heat-generating surface. The rounded corner specification has been implemented to prevent thermal compound overflow while maintaining consistent surface tension characteristics during the application process. The carefully calculated thickness of 0.5 mm ensures optimal thermal conductivity by providing sufficient material for heat transfer while avoiding excessive application that could impede thermal efficiency.

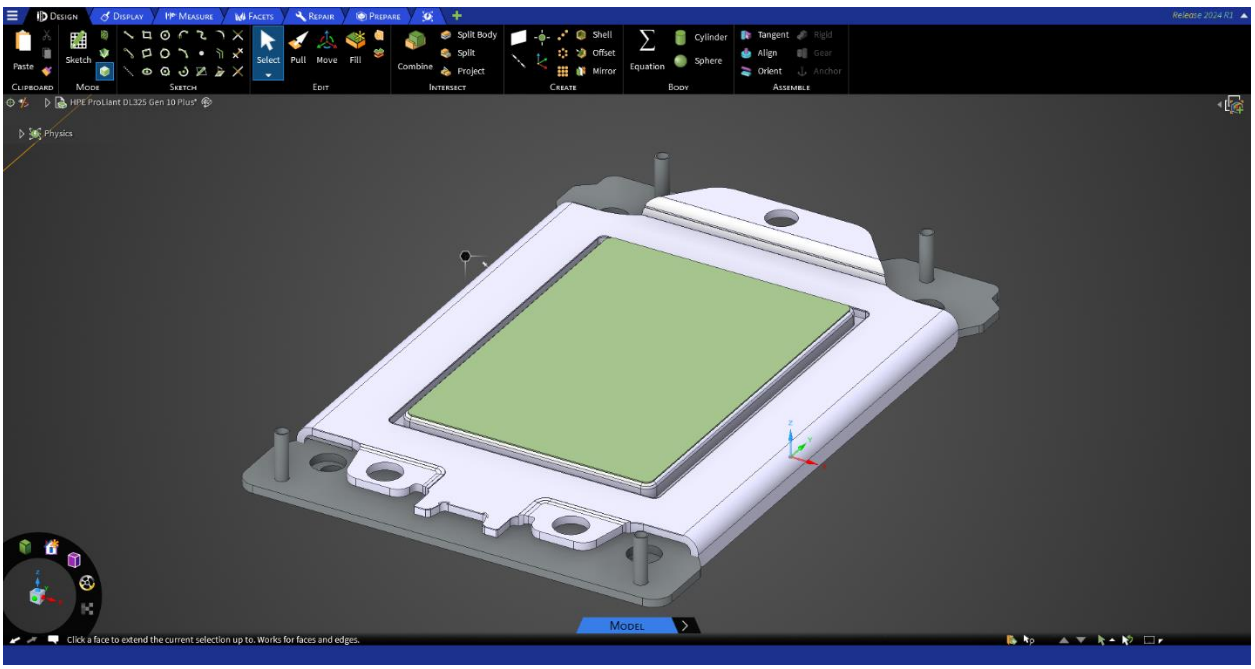


Figure 20. *CPU Thermal Interface - Dimensional Specifications*

7.3. RAM Design

The 3D modeling process for the RAM retention mechanism begins with establishing the precise geometry for the component housing. Using specialized CAD tools, the initial profile is drafted with carefully defined dimensions: the main vertical wall height measures 9.46mm, with stepped sections of 2.86mm and 1.44mm creating the characteristic retention geometry. The central mounting area extends 10.36mm vertically, incorporating cutouts and ledges essential for secure RAM module placement.

The design features a symmetrical layout, achieved by utilizing the mirror function to replicate the detailed profile across the central axis, resulting in matching retention clips on both sides. The total span across the component measures 140mm, accommodating standard RAM module dimensions. To ensure proper component interaction and longevity, all edges are finished with a precise 0.1mm radius round, providing both functional reliability and manufacturing feasibility.

This mechanical design specifically addresses the requirements for secure RAM module retention while allowing for practical installation and removal operations in computer motherboard applications. The dimensions and geometry are optimized to provide robust mechanical retention while maintaining compatibility with industry-standard RAM module specifications.

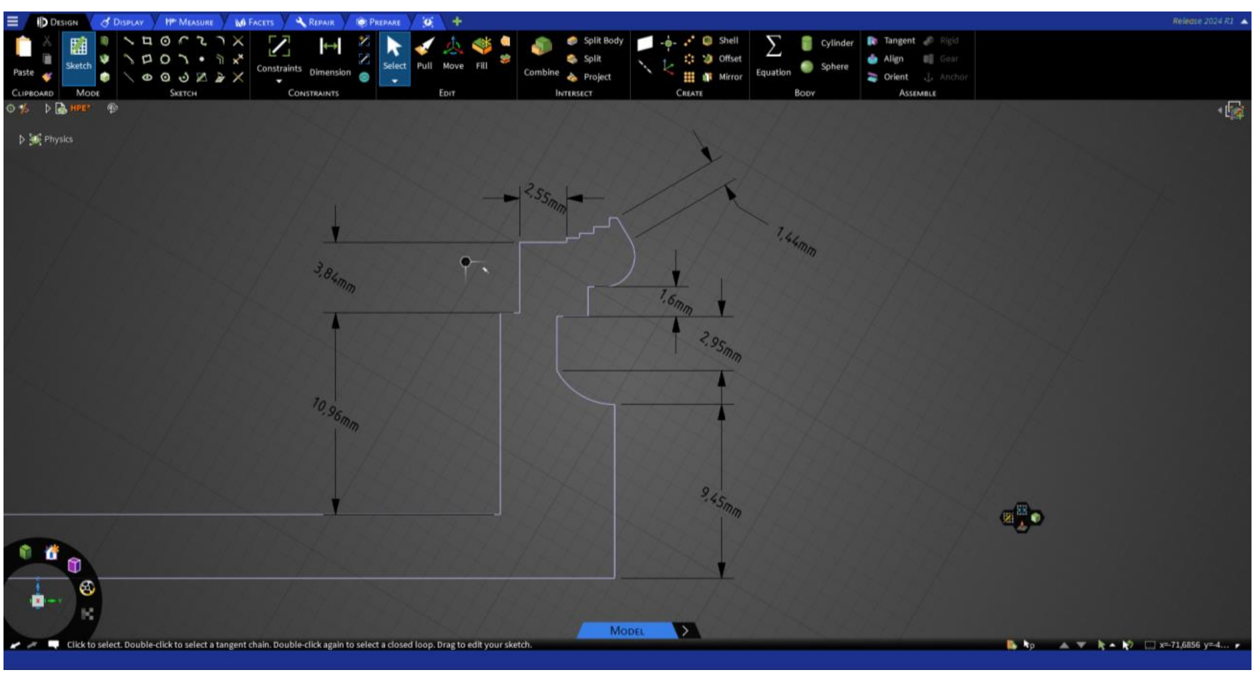


Figure 21. *Retention Mechanism Base – Initial 2D Sketch with Key Dimensions*

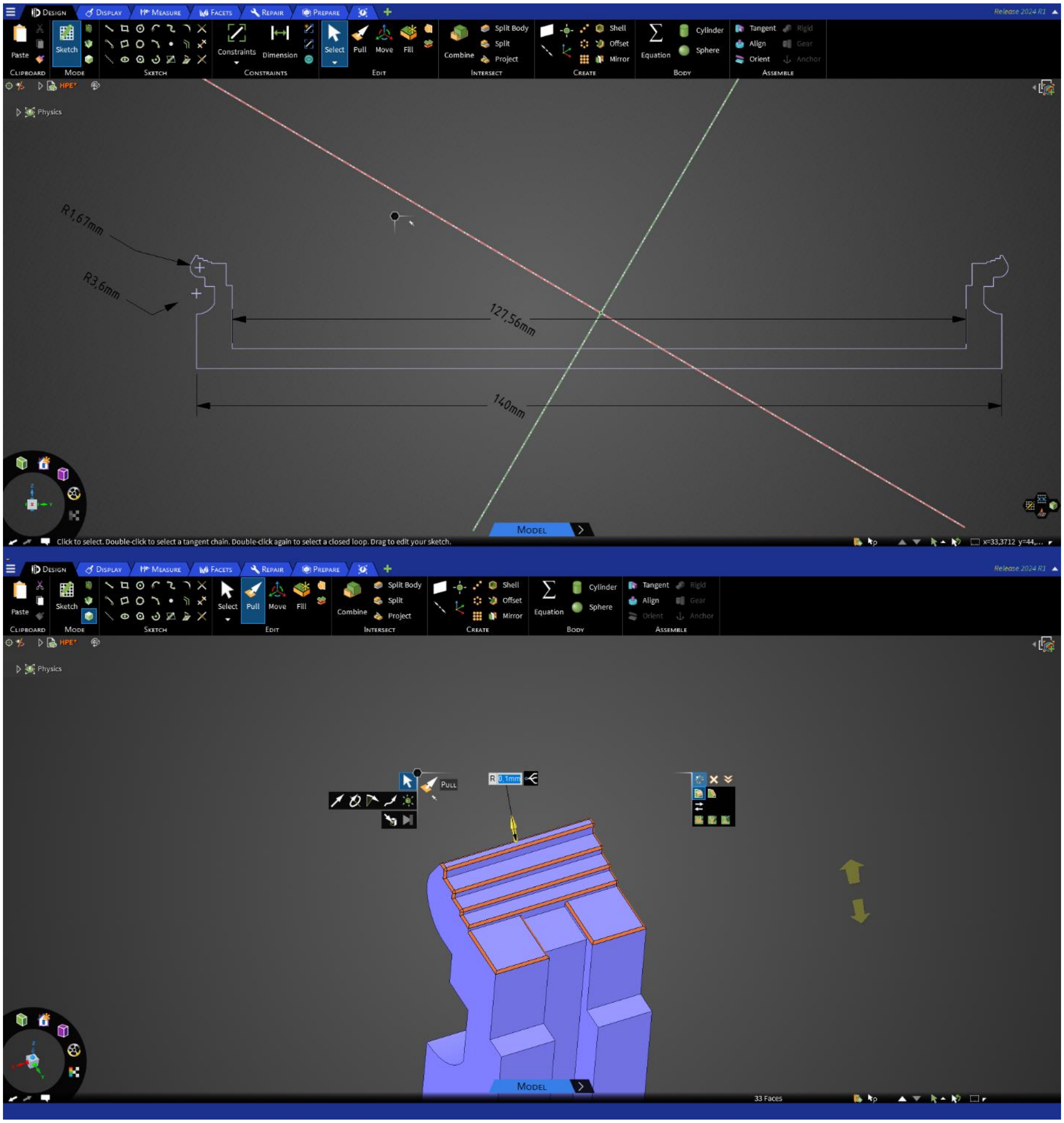


Figure 22. *Retention Mechanism Base - Edge Refinements*

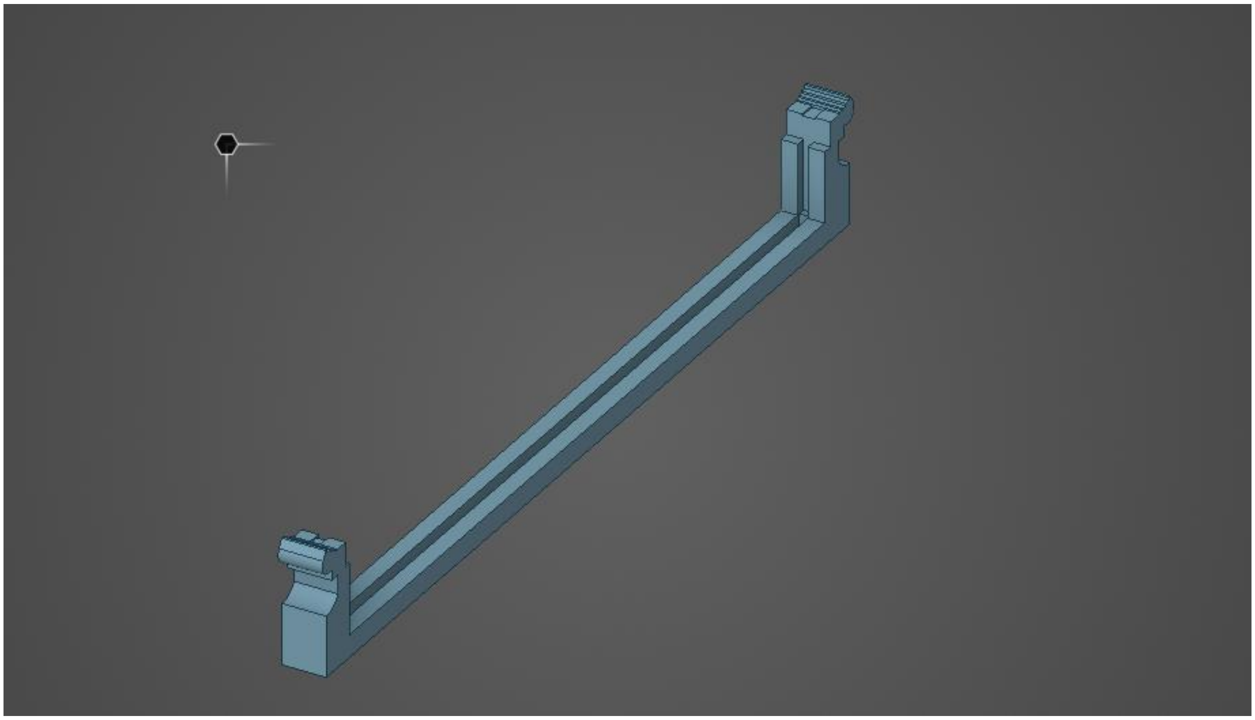


Figure 23. *Retention Mechanism Base - Final 3D Model*

Finally, a dedicated plane is established on the reception base to accommodate the design of the RAM modules themselves. Figure 24 displays the dimensions and geometry of the RAM module, which is engineered to fit seamlessly into the retention mechanism. The RAM module measures 130.06 mm in length and 2.18 mm in width, with a thickness of 1 mm. The precise dimensions and form factor of the RAM module are carefully considered to ensure compatibility with the reception base and optimal performance within the system.

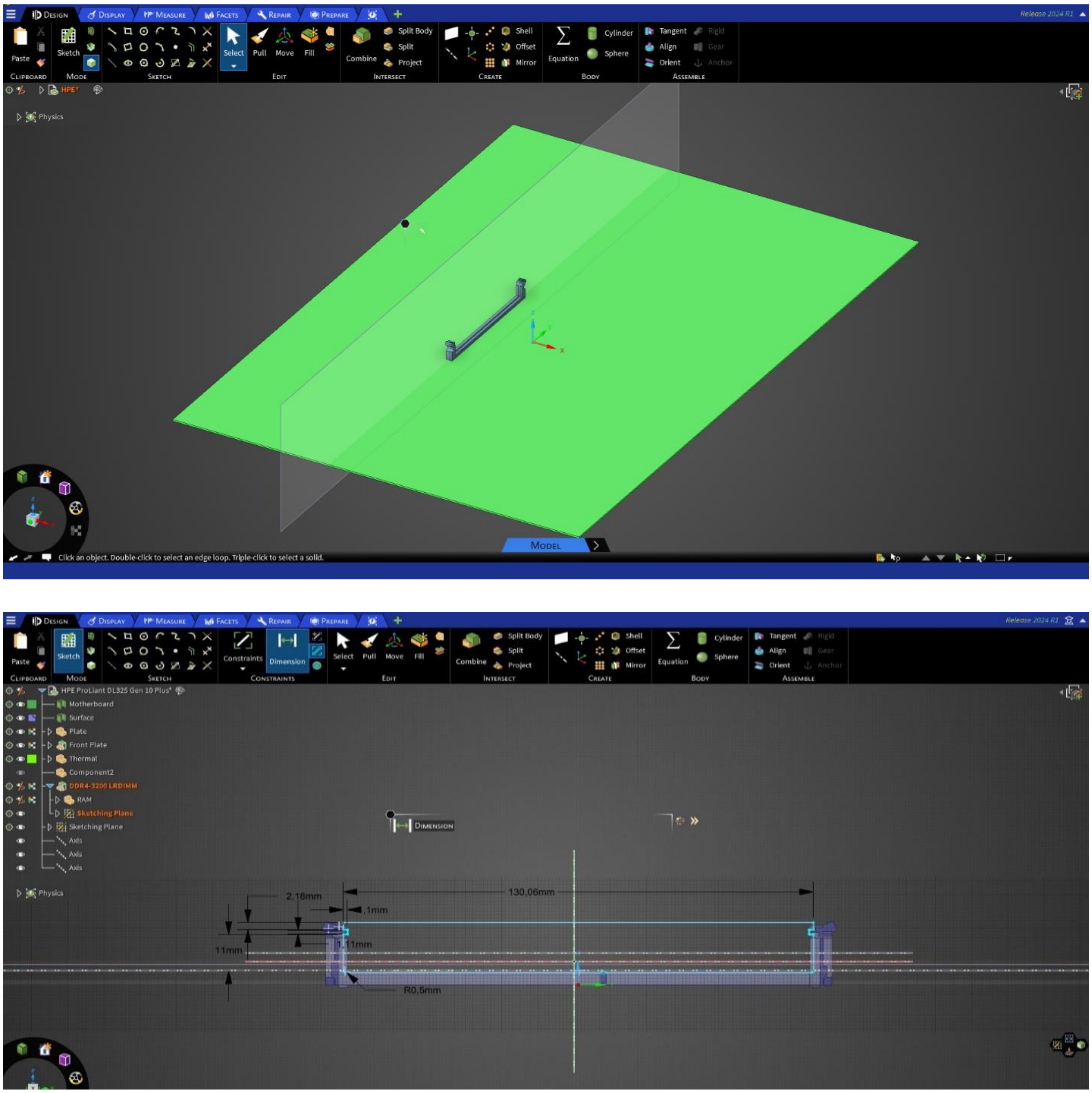


Figure 24. *Random Access Memory - Geometric Design*

The initial pattern sequence for the RAM module was executed using the Linear Pattern tool to generate eight precisely spaced duplicates of the base fin geometry, maintaining a uniform distribution along the primary axis with a consistent 10 mm gap between each fin. This standardized spacing ensures optimal thermal performance and structural integrity.

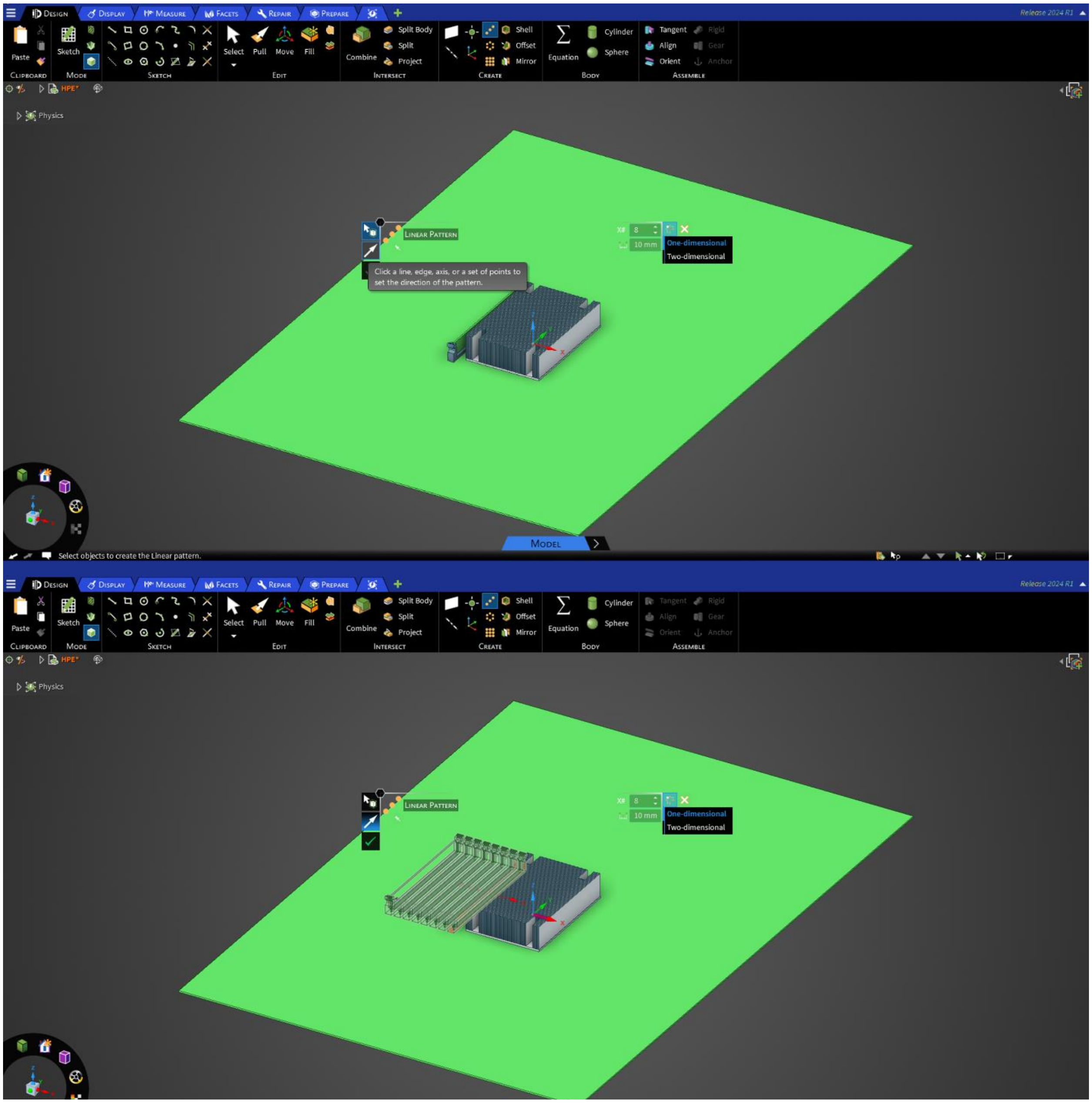


Figure 25. *Random Access Memory (RAM) – Linear Pattern*

Subsequently, to achieve the complete dual-bank memory configuration, the Create Pattern tool was employed to mirror the entire eight-fin array across the module's central axis, resulting in a symmetrical sixteen-fin arrangement. The mirrored set of fins is positioned at a distance of 174 mm from the initial octet, allowing for adequate clearance and airflow between the two banks. This mirrored layout guarantees balanced heat dissipation across both memory banks while upholding manufacturing consistency and structural equilibrium. The final assembly exhibits perfect bilateral symmetry, with each bank of eight fins maintaining the 10 mm inter-fin spacing established in the initial linear pattern.

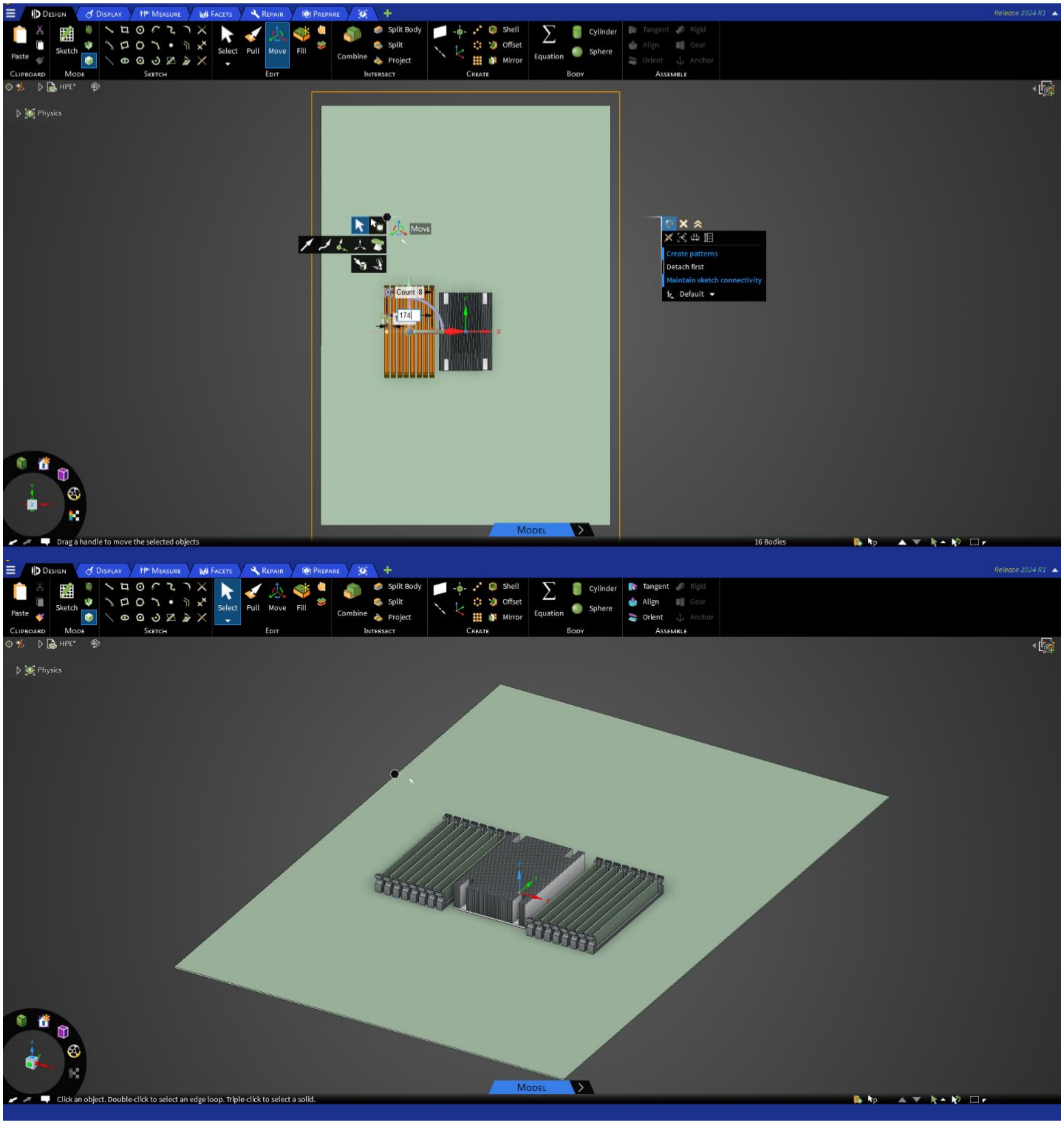


Figure 26. *Random Access Memory (RAM) – Create Pattern*

7.4. Heatsink Design

The heatsink is a critical component in computer systems, responsible for dissipating the heat generated by the CPU. The design process for the heatsink in Ansys Discovery begins by creating the base using the dimensions shown in the first picture. A rectangle is sketched with a length of 82mm and a width of 120mm. The Pull tool is then used to extrude the base to a height of 3.5mm, providing a solid foundation for the fins.

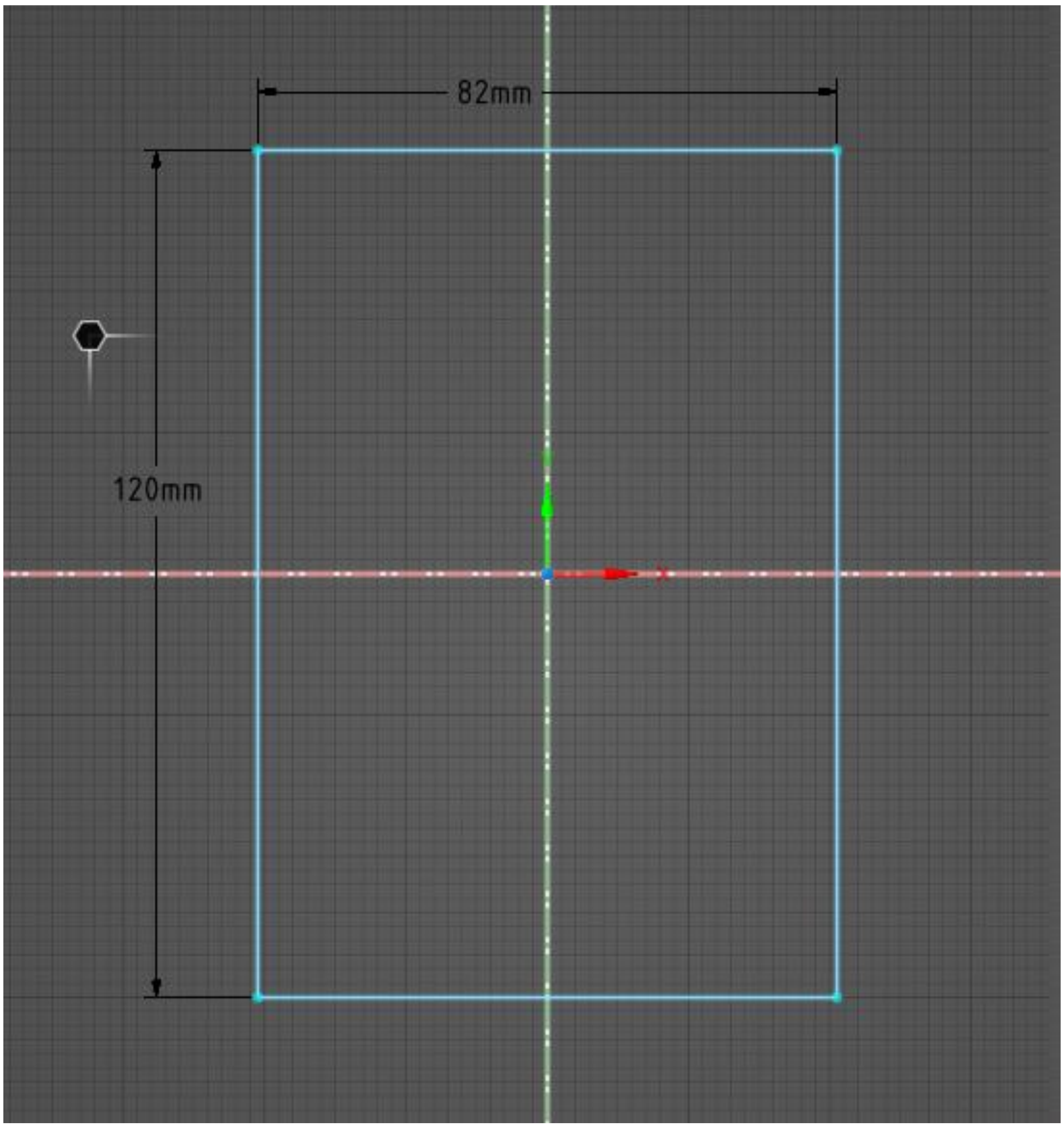


Figure 27. *Heatsink Base - Design*

Next, a single fin is created by sketching a rectangle on the top face of the heatsink base. To create the array of fins, the Move tool is employed, generating a pattern of 74 evenly spaced fins in total. The Advanced Selection tool is then used to select all the fins simultaneously, and the Pull tool is utilized to extrude the fins to a height of 25.5mm, significantly increasing the surface area for heat dissipation.

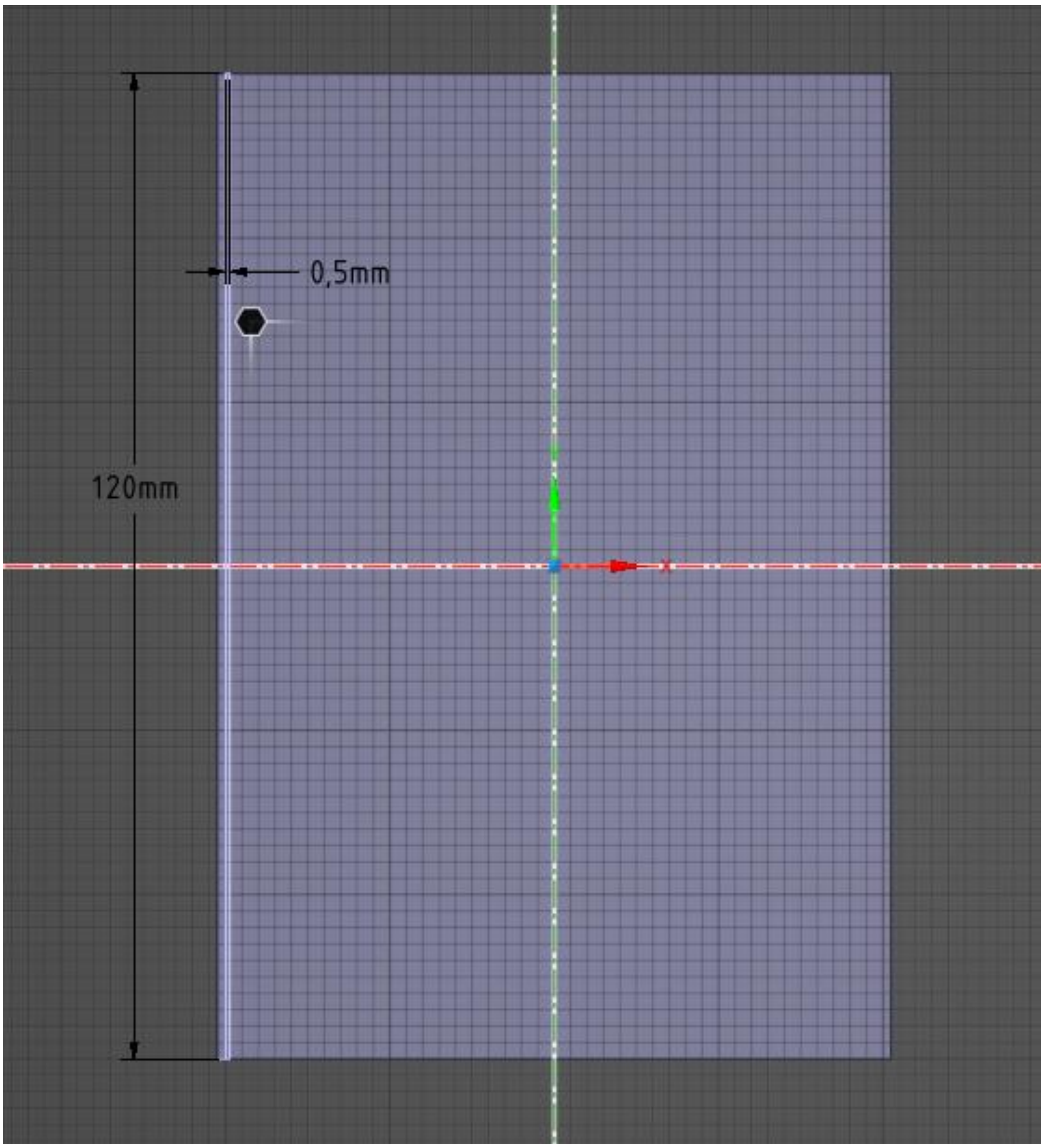


Figure 28. *Heatsink' Fin - Design*

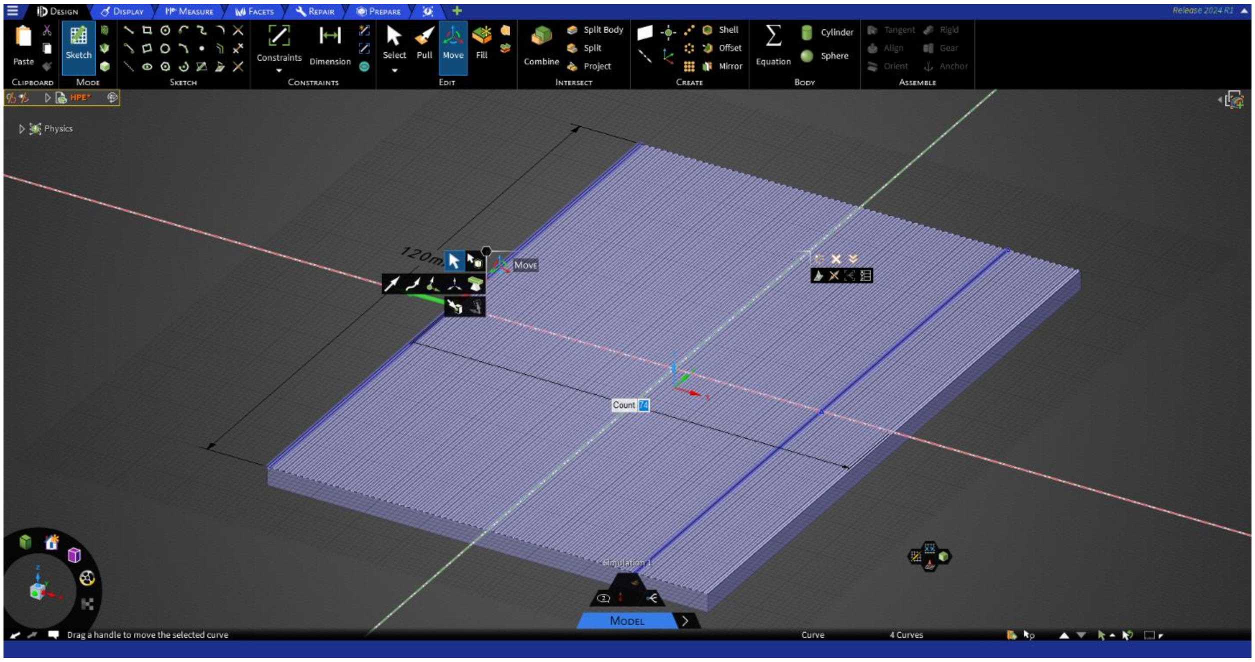


Figure 29. *Heatsink' Fins – Create Pattern*

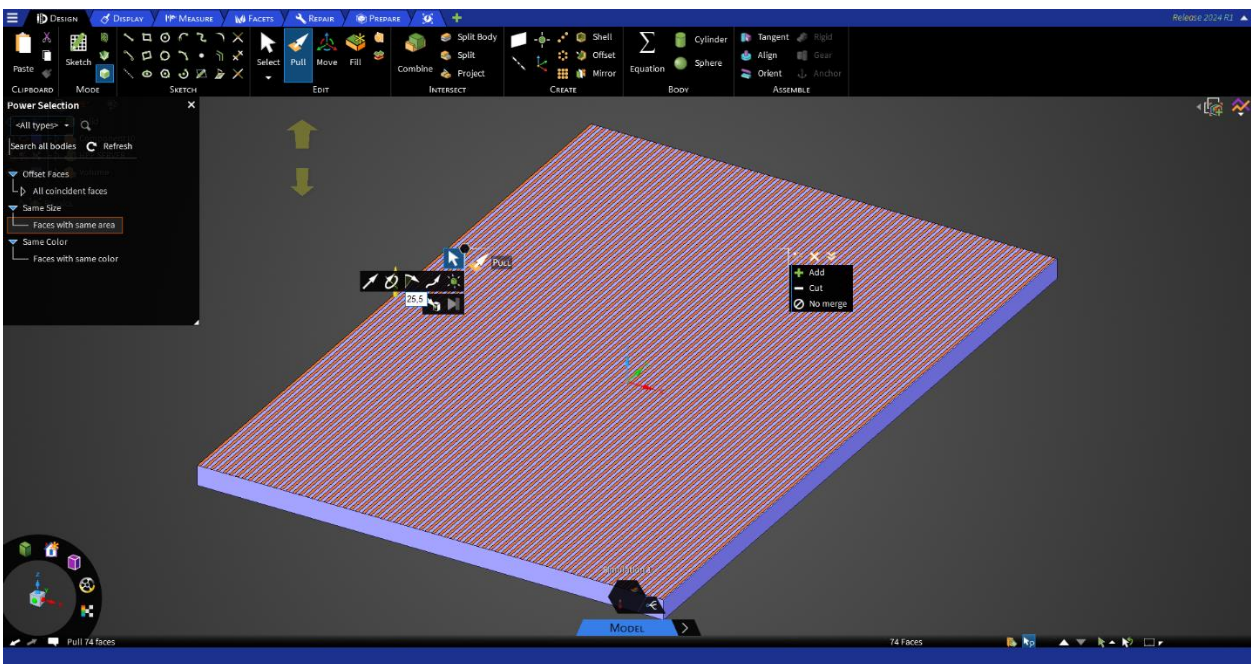


Figure 30. *Heatsink' Fins Array*

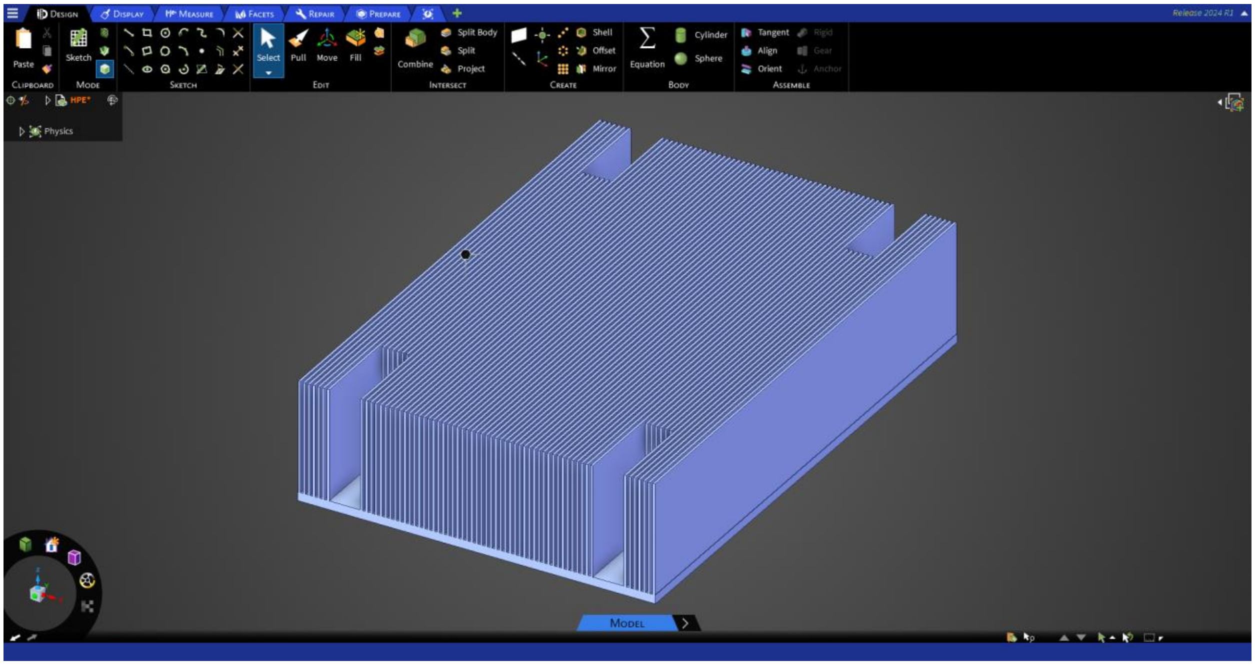


Figure 31. *Complete Heatsink Assembly*

7.5. Power Supply Unit Design (PSU)

The power supply design for the SP3 server platform begins by creating two surface sketches at the edge of the motherboard, which serve as the foundation for the power supply unit (PSU) housing. Using precise measurements, a rectangular profile is drawn extending from these surfaces, spanning 81.3mm in width and 279.4mm in length as shown in the dimension guidelines. The pull tool is then employed to extrude this rectangular profile to a height of 40mm, creating the three-dimensional PSU enclosure. To maintain proper server layout conventions and ensure optimal space utilization, the power supply unit is aligned with the left edge of the motherboard. This alignment not only follows standard server design practices but also facilitates efficient airflow and thermal management within the chassis, while providing easy access for power connections. The placement considers the spatial requirements of other components like the CPU socket assembly and its associated thermal solution, ensuring all components work together in the confined server environment.

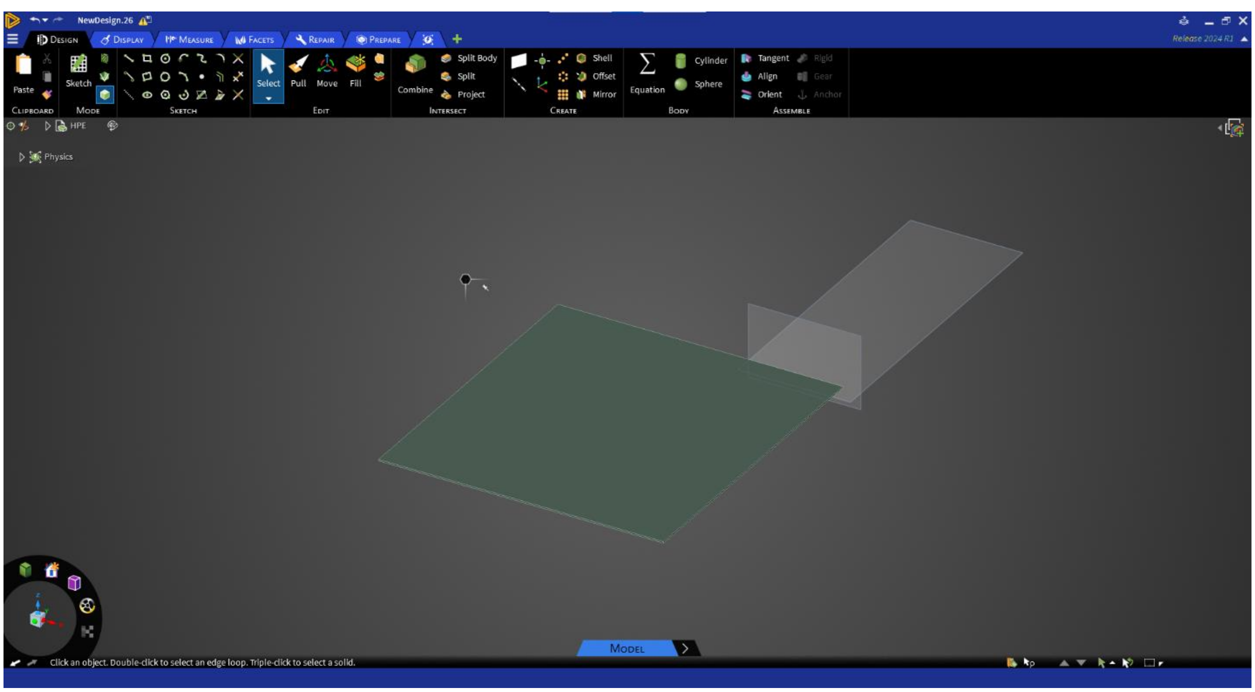


Figure 32. *Power Supply Unit Layout*

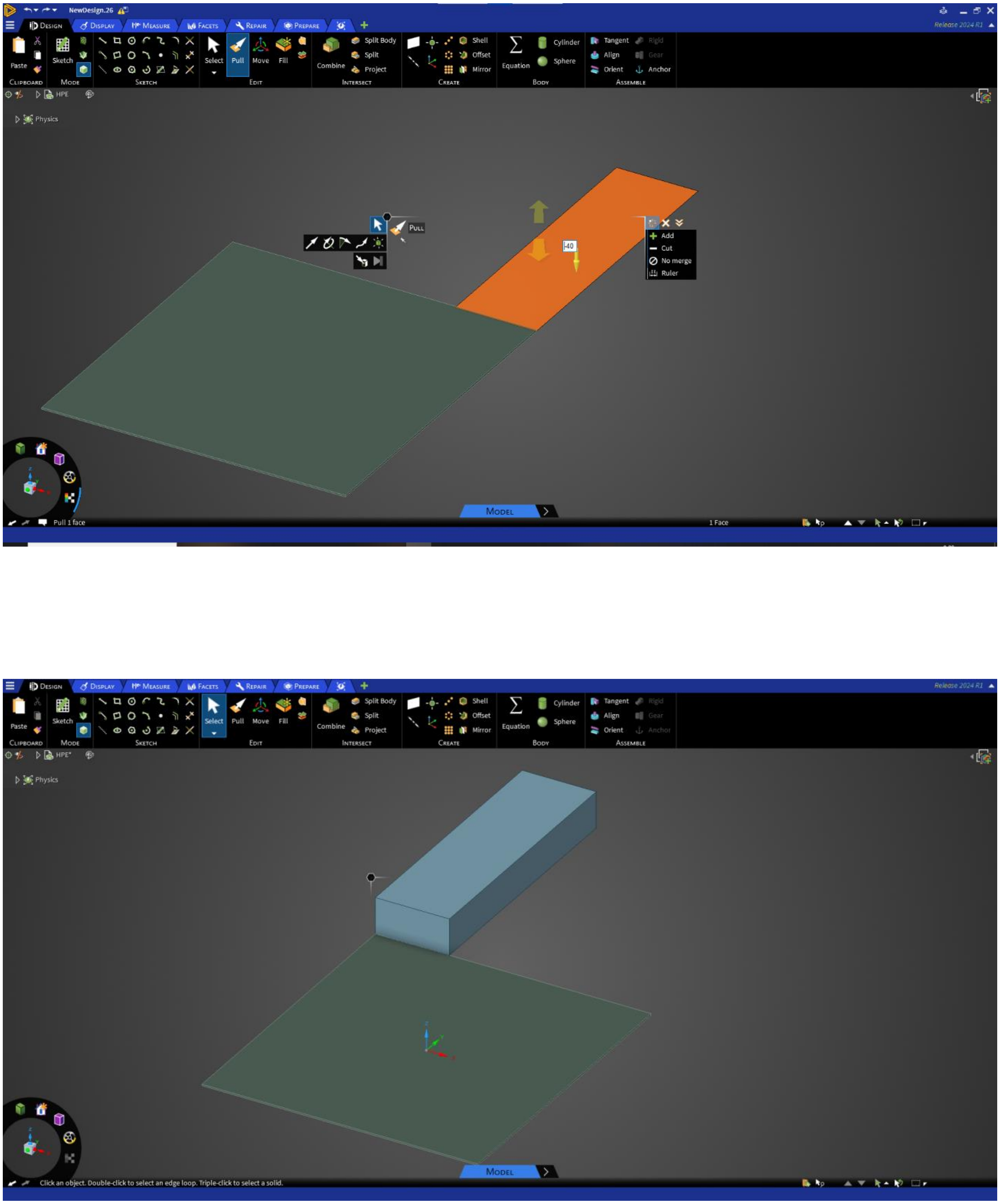
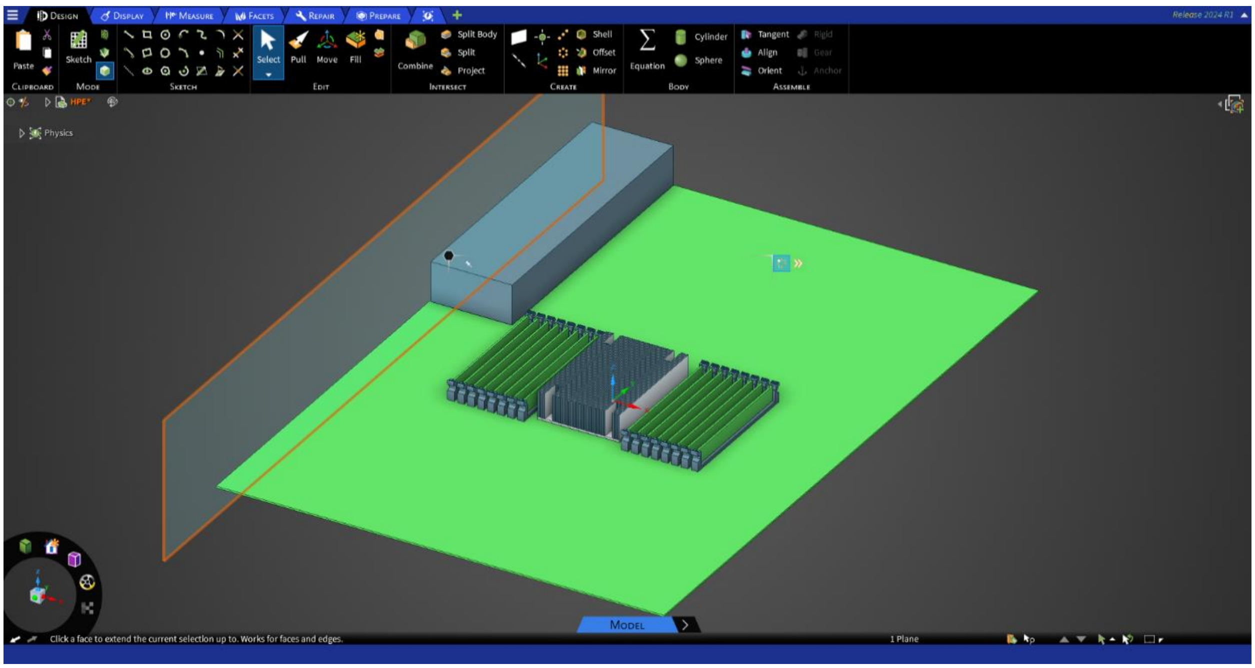


Figure 33. *Final PSU Assembly*

7.6. SSD Design

The SSD design process begins by creating a new plane on the left side of the motherboard when viewed from the front. On this plane, two rectangles are sketched, each measuring 82.45 mm in length and 17 mm in height. Using the pull tool, one of the faces created by the rectangles is selected, and a thickness of 72 mm is added to achieve the desired width. This process is repeated for the second rectangle, resulting in two solid shells. To create a hollow shell with a 1 mm wall thickness on each side, the front face of each solid is removed using the shell tool.



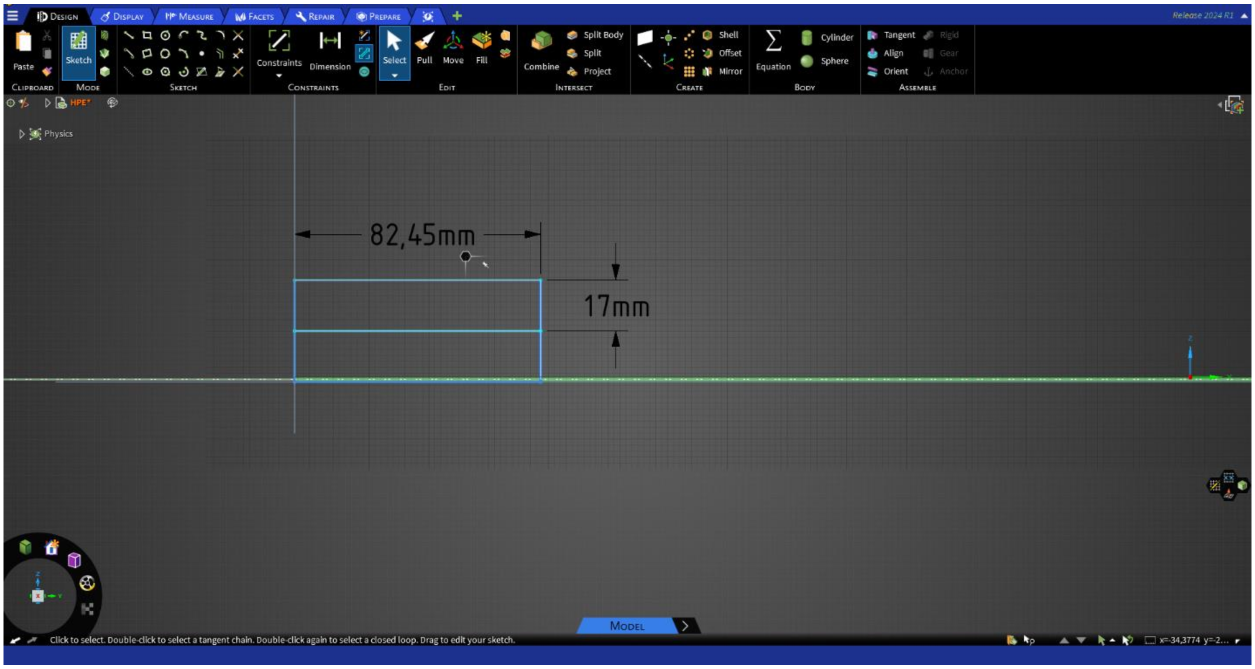
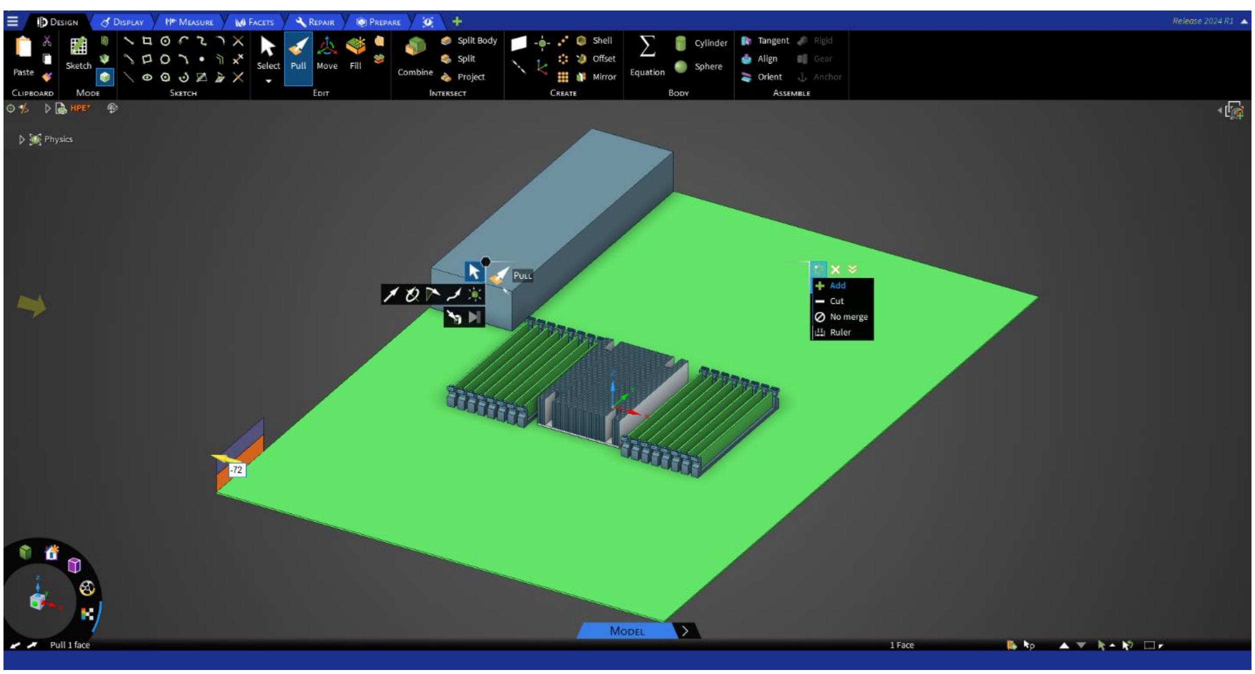


Figure 34. *SSD Drive Bay Dimensional Specifications*



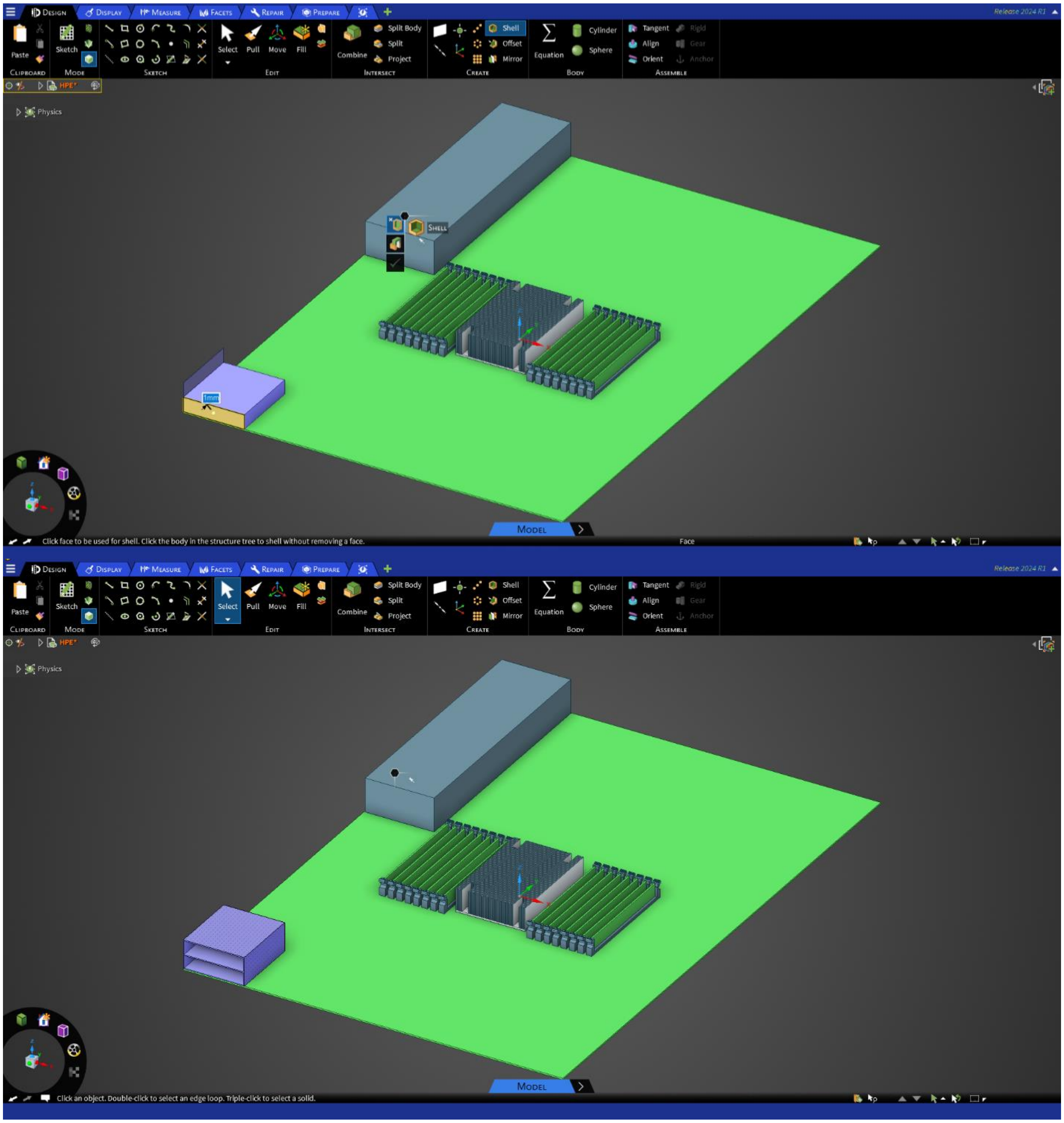


Figure 35. *Complete SSD Drive Bay Installation*

With the two SSD shells created, they are selected using the move tool and rotated 90 degrees to the left. The shells are then carefully aligned to the left corner of the motherboard, ensuring proper positioning within the overall assembly. This precise placement is crucial for maintaining the correct orientation and fitment of the SSD components.

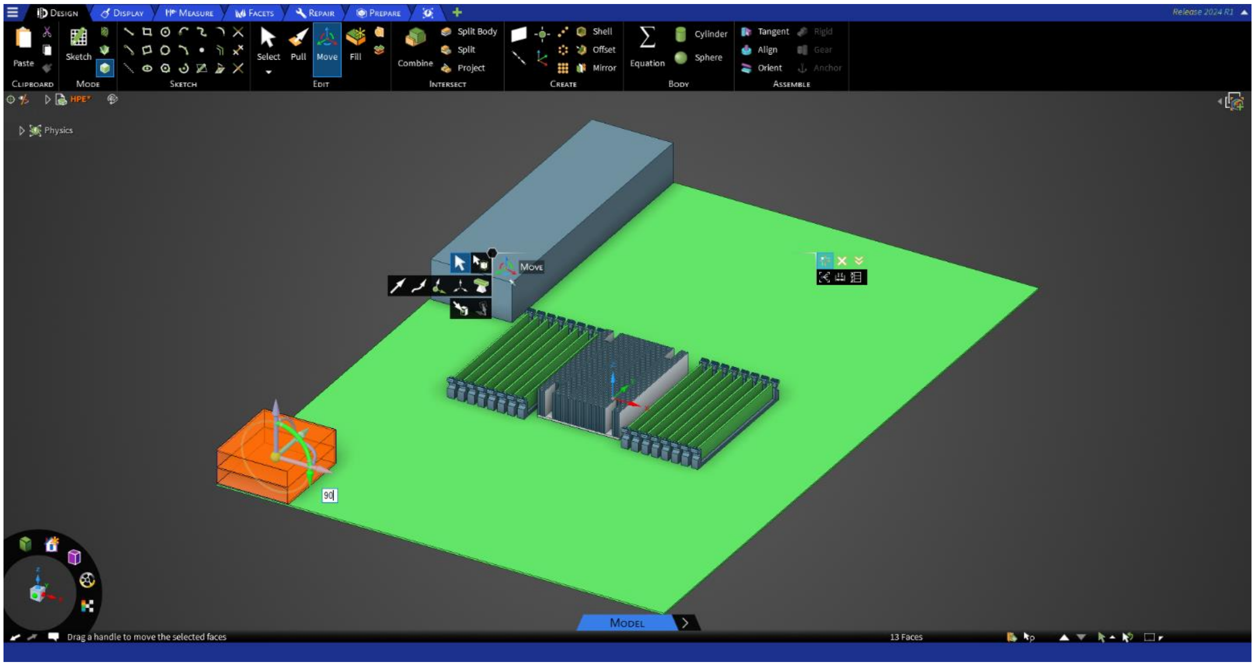


Figure 36. *SSD Drive Bay Final Layout*

To create the SSD components, the "New Component" option is selected by right clicking on the model tree located on the left side of the Ansys Discovery interface. A new sketch is created on the inner surface of one of the SSD shells using the sketch tool. Within this sketch, two rectangles are drawn, each measuring 15 mm in width and 81.45 mm in length. The pull tool, with the "Pull up to" option selected, is then used to extrude the sketched rectangles, creating two solids that represent the SSDs. This process is repeated for the second SSD shell, ensuring both shells contain the necessary SSD components.

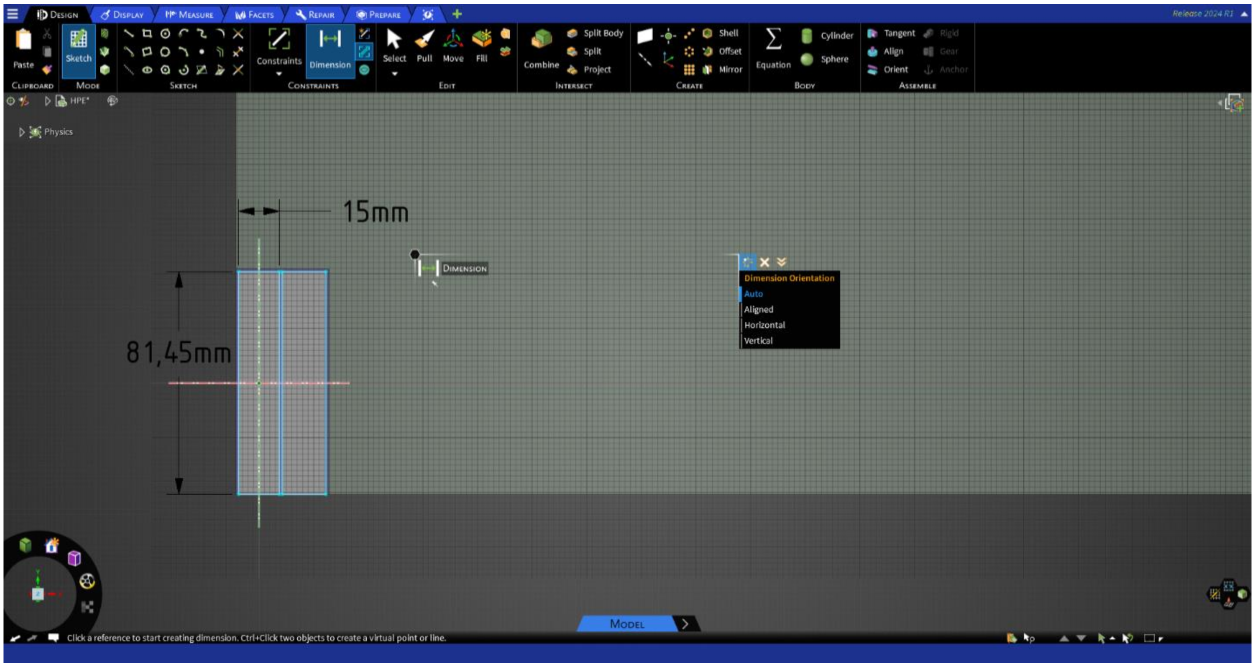


Figure 37. *SSD Component Dimensional Sketch*

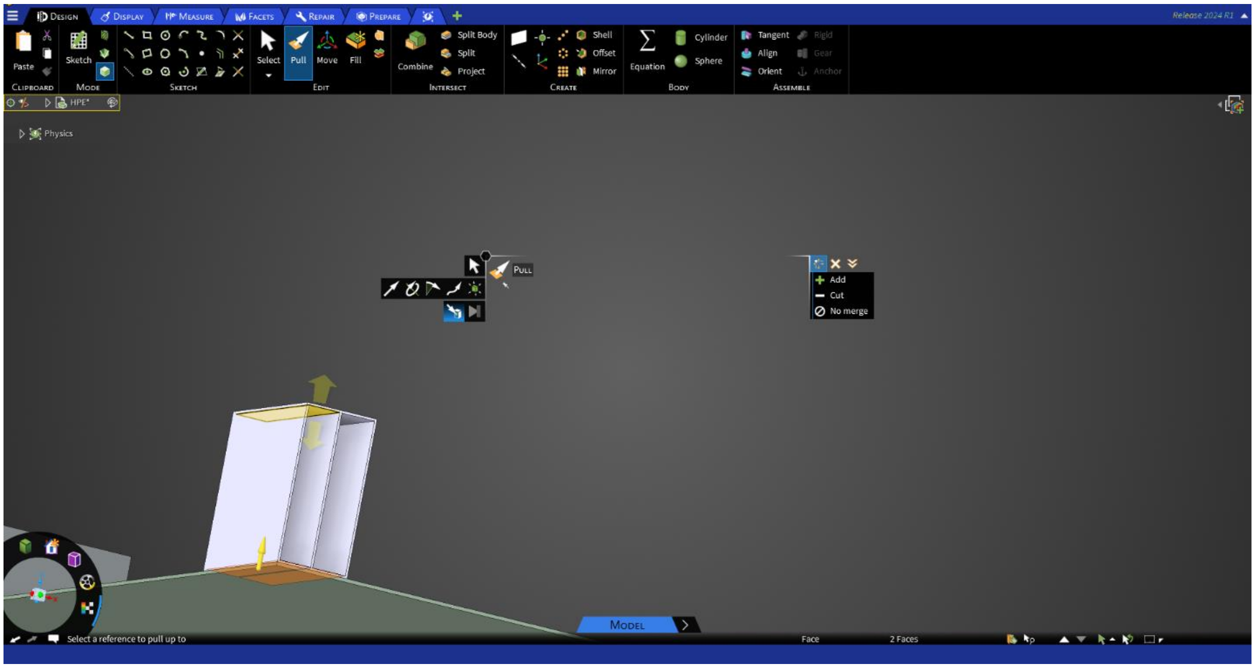


Figure 38. *SSD Extrusion Process*

With the SSD components successfully created within the shells, the "New Component" option is selected once again. The move tool is used, and the "Create Pattern" option is chosen. By selecting the arrow indicating the left direction, a mirrored duplicate of the SSD components is created on the opposite side of the motherboard. This mirroring operation ensures symmetry and balance within the overall design.

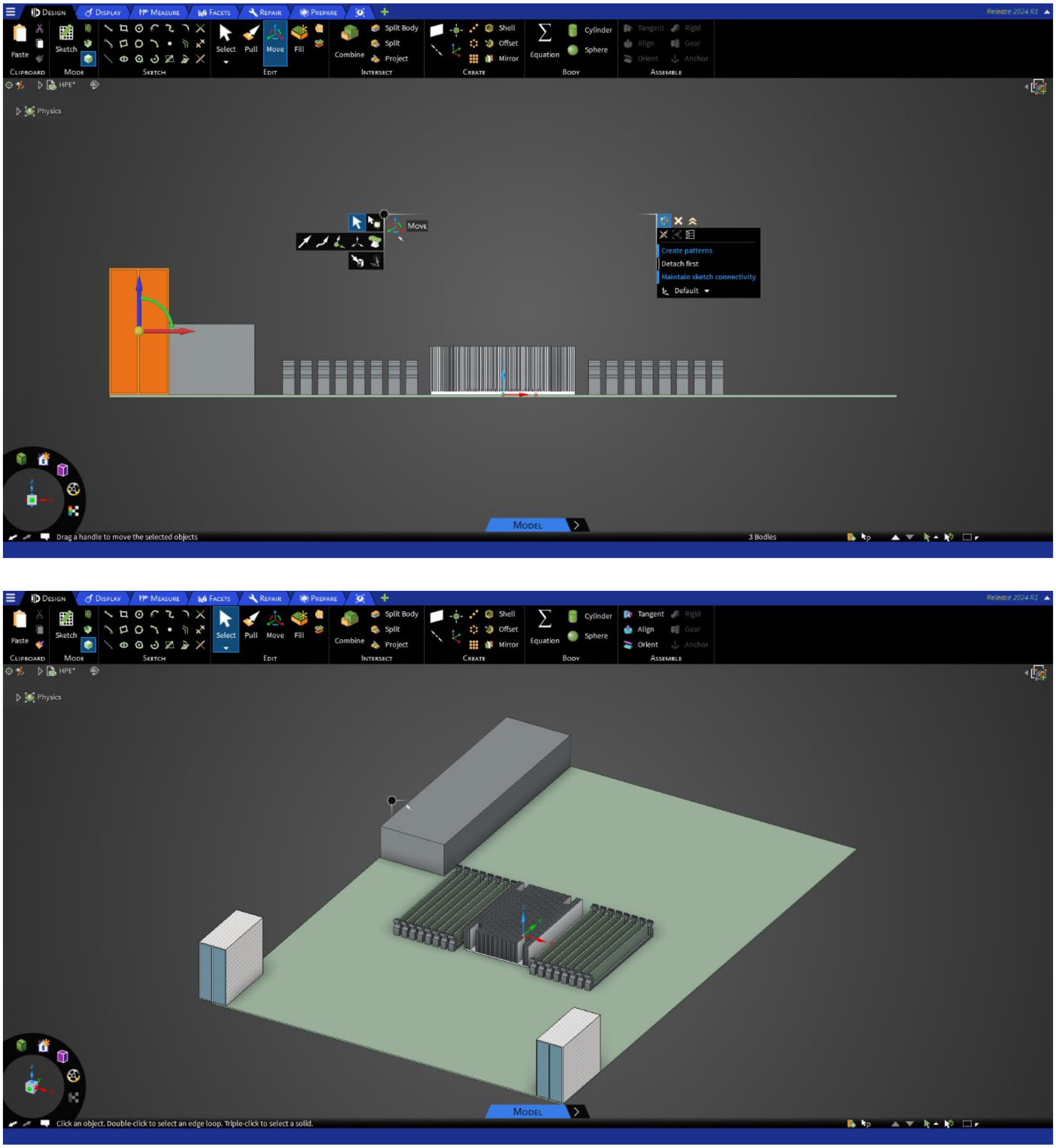


Figure 39. *Final SSD Component Integration*

7.7. Fan Housing Design

The 80mm fan housing design process begins with sketching an 80mm x 80mm square on the XY plane, extruded to a height of 20mm. On the top face, two concentric circles (70mm and 30mm diameters) are sketched, along with lines from the center to each corner. The lines are offset by 2.5mm on both sides, and the excess segments are trimmed. The resulting profiles are pulled through the block to cut the material. A 70mm circle is sketched on a plane offset -2.5mm from the front face and pulled to a depth of -15mm to create a recess. Mounting holes are added by sketching a 5mm circle 6mm from the top-left corner and using a circular pattern to replicate it at each corner. Fillets of 2.5mm are applied to the housing corners using advanced selection. The shell tool removes material from within the housing, leaving a uniform 2.5mm wall thickness. Finally, the edges of the 70mm opening are rounded by 2.5mm to complete the fan housing design.

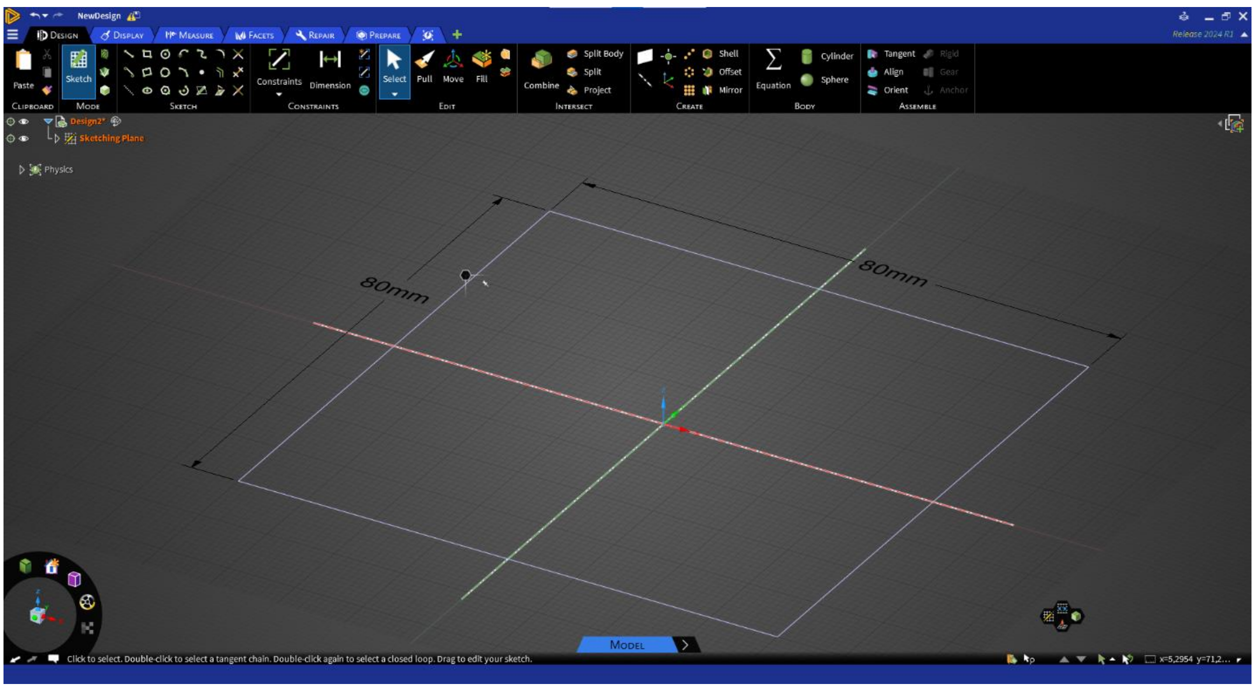


Figure 40. *Fan Housing Base Dimensional Layout*

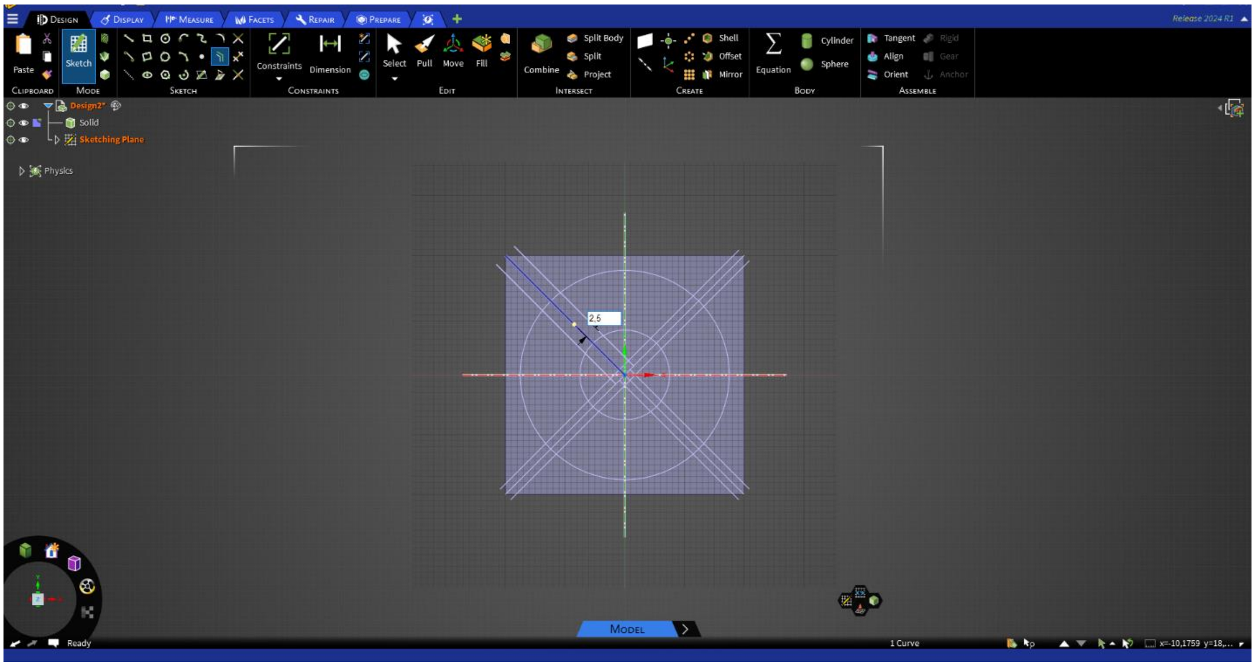


Figure 41. *Fan Housing Concentric Circle Pattern*

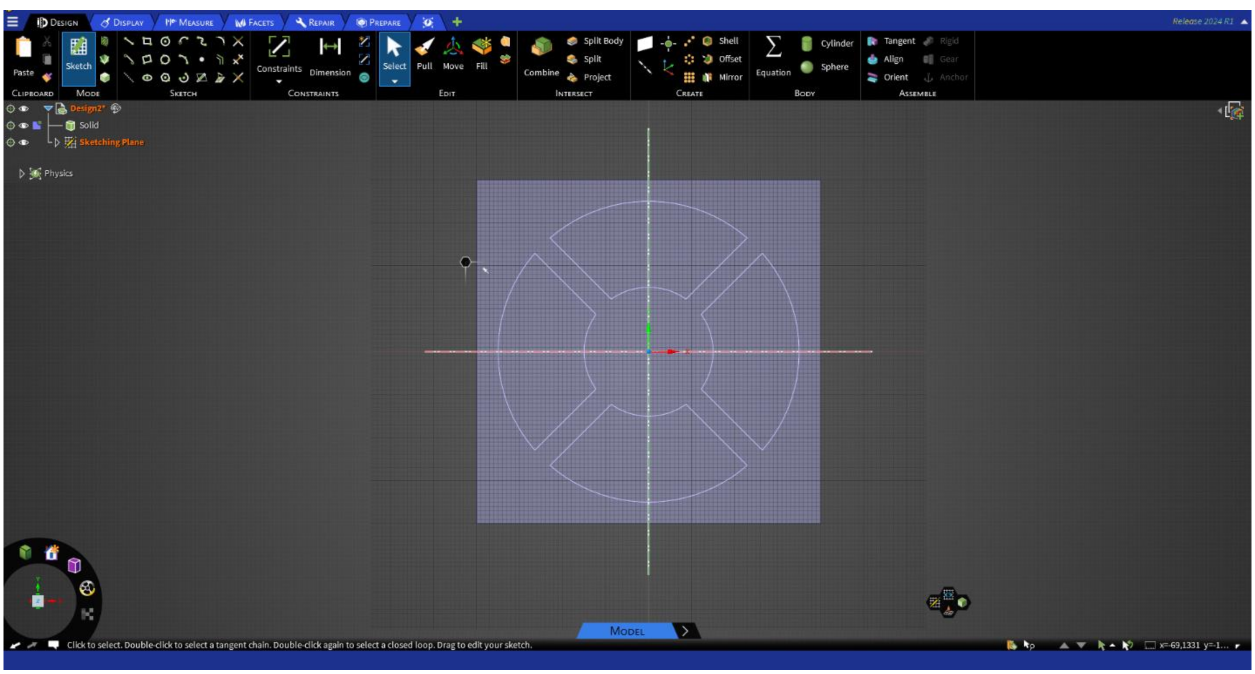


Figure 42. *Fan Blade Opening Design*

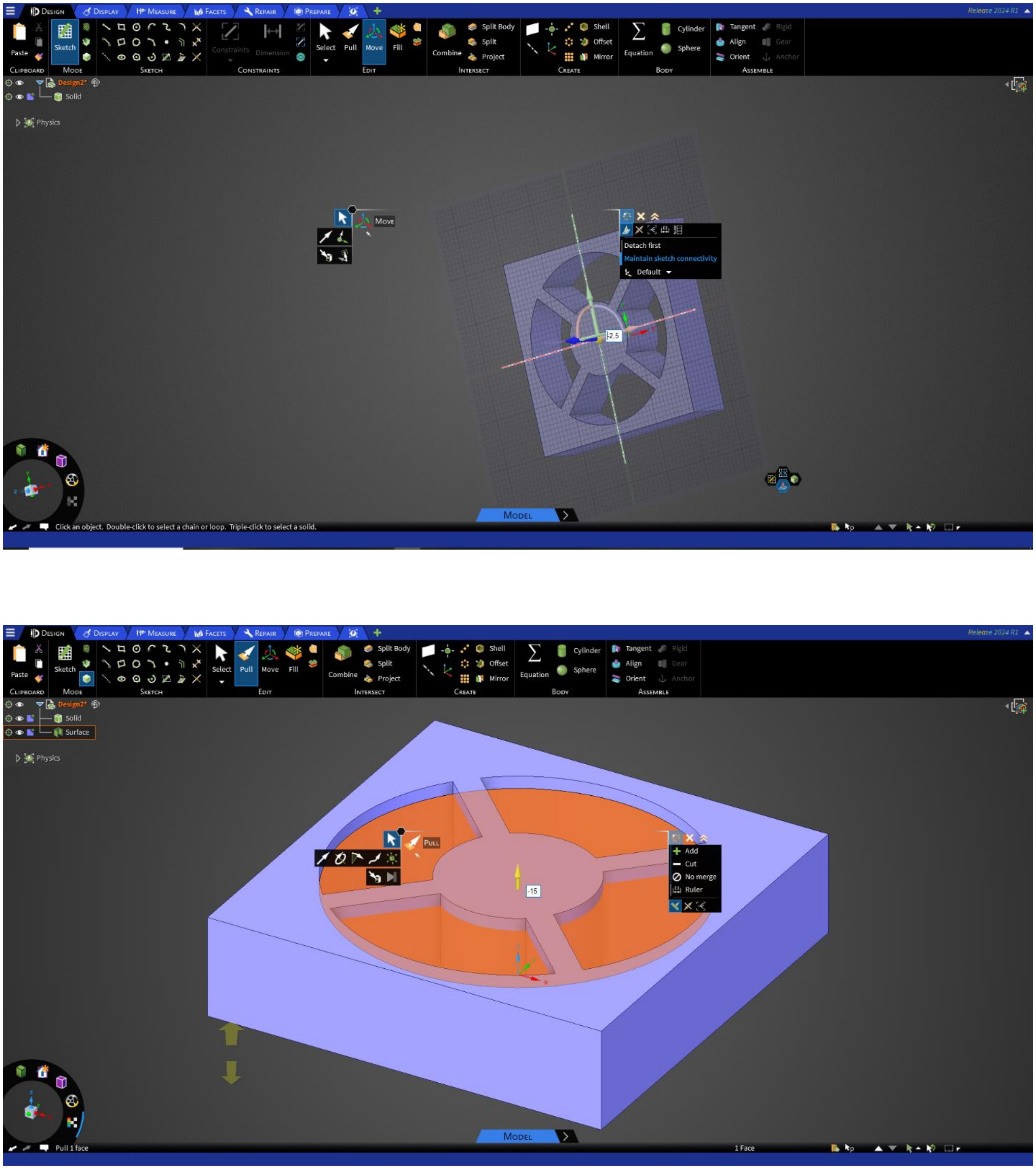


***Figure 43**. Fan Housing Initial Extrusion*

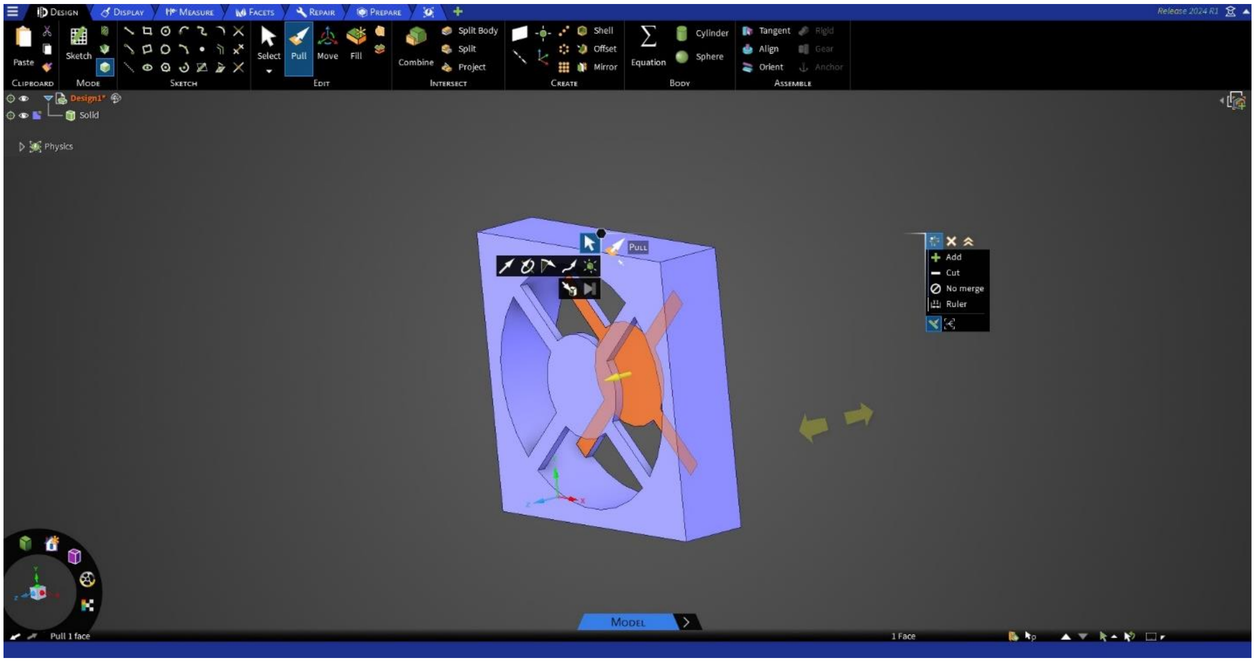
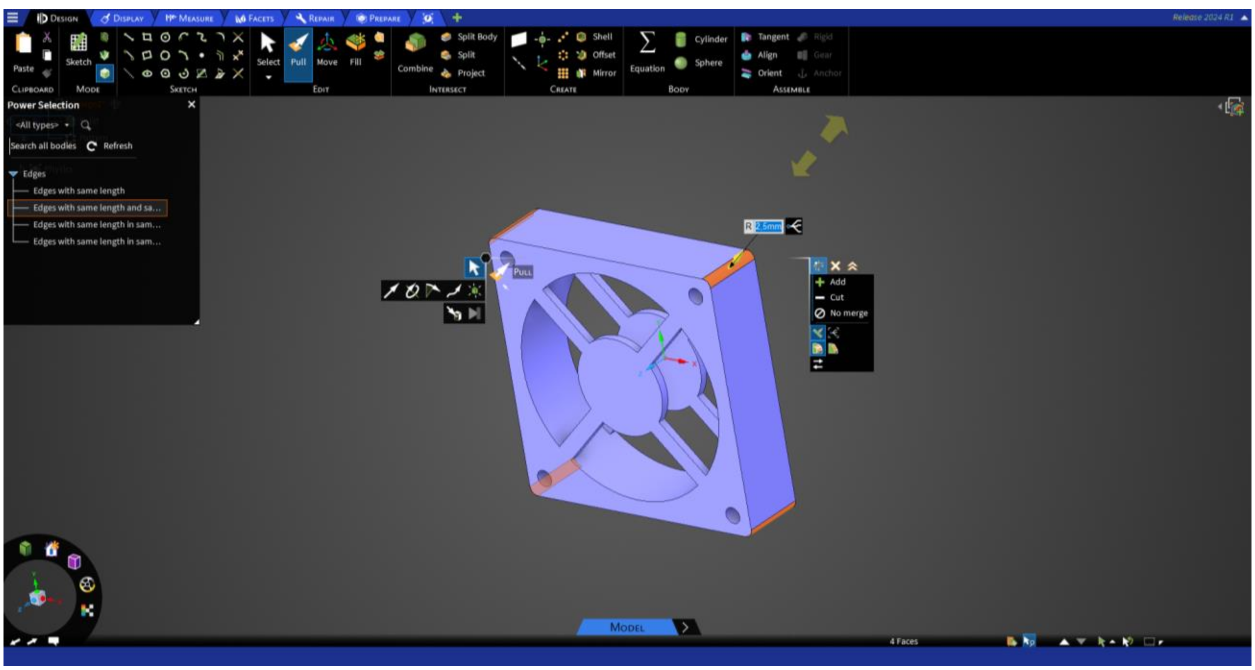


Figure 44. *Fan Housing Cross-Section Development*



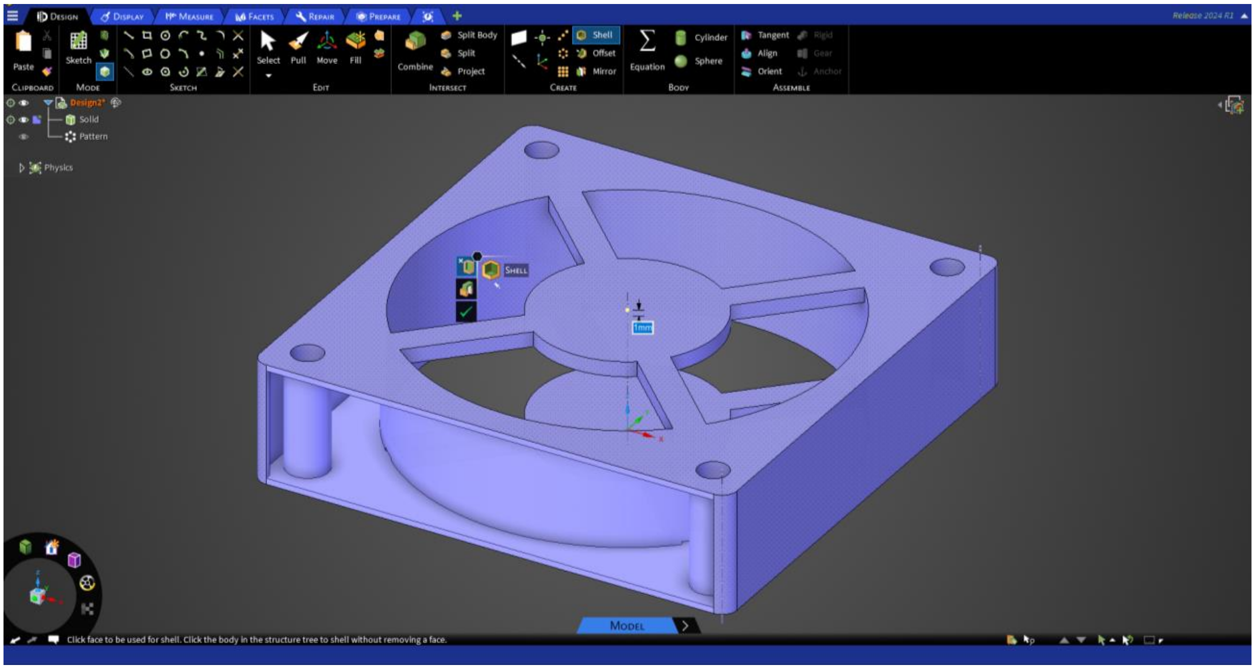


Figure 45. *Fan Housing-Shell Tool*

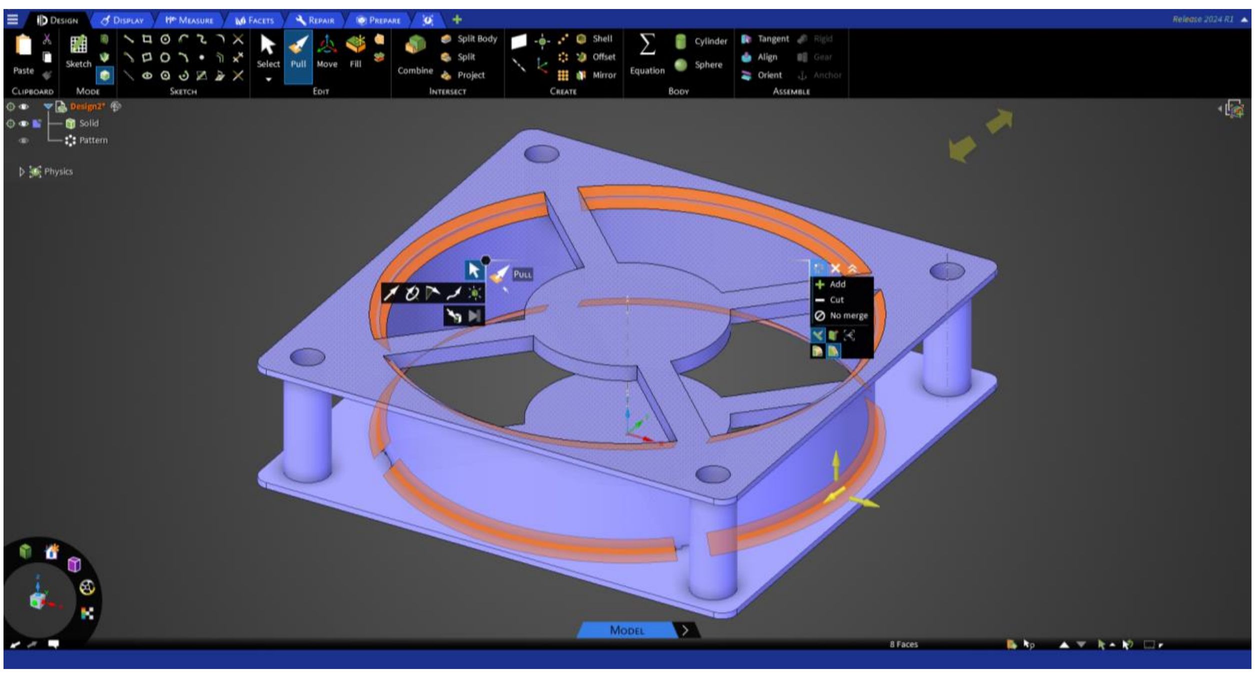


Figure 46. *Fan Housing Assembly Features*

7.8. Casing Design

The server casing design begins with establishing precise dimensional parameters to ensure optimal component housing and structural integrity. The casing features differential wall thicknesses, with the front panel constructed at 23mm for enhanced rigidity and mounting support, while the remaining sides and back panel maintain a uniform 3mm thickness for efficient material usage while ensuring adequate structural strength. The overall dimensions are set at 452mm width and 726mm length, with a 700mm internal clearance specifically calculated to accommodate all server components.

This asymmetrical thickness design serves multiple purposes: the reinforced front panel provides robust support for fan mounting and serviceability access, while the thinner side and rear walls optimize weight and material usage without compromising structural integrity. The construction method incorporates elevated edges and precise corner joints to create a unified containment structure that ensures proper component alignment and protection.

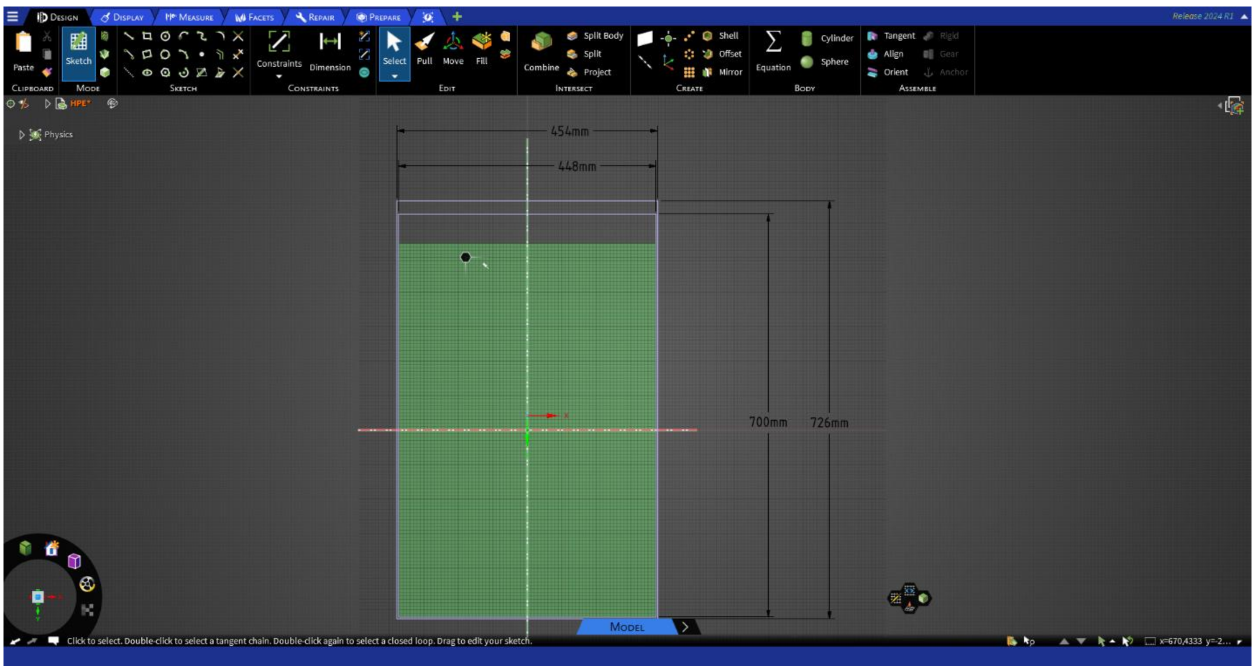


Figure 47. *Figure 49. Server Casing Dimensional Specifications*

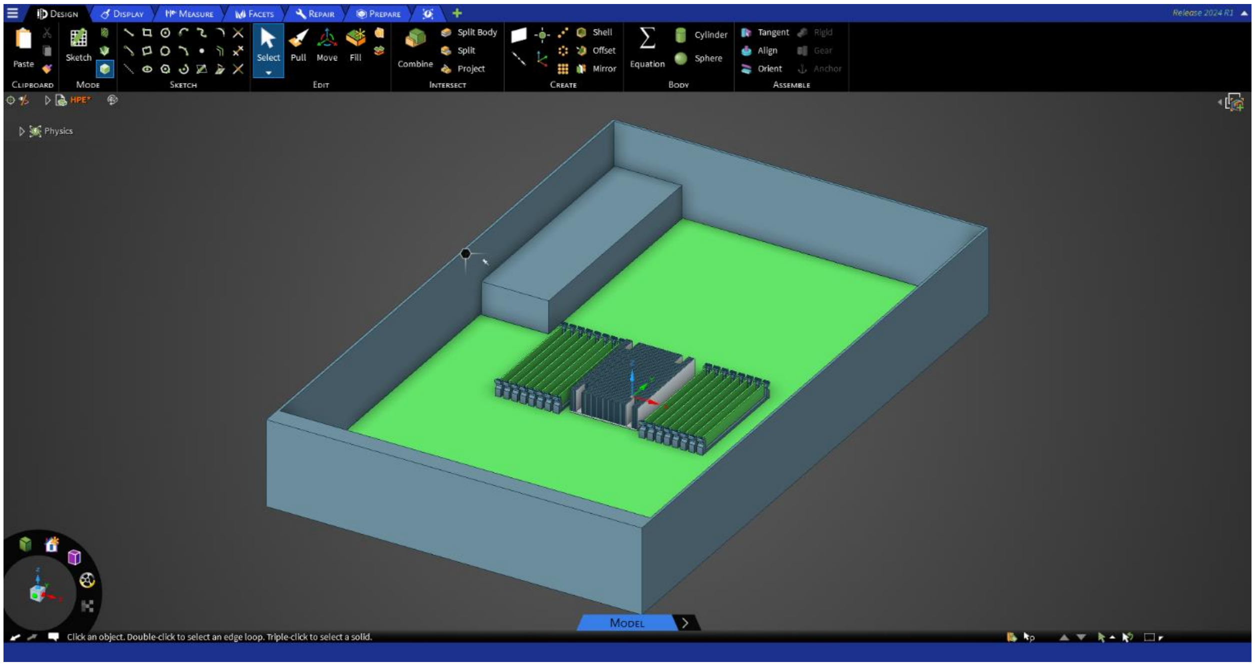


Figure 48. *Server Casing Initial Construction*

7.8.1. Ventilation Systems

To ensure adequate airflow within the server enclosure, a series of ventilation holes will be added to one face of the model using the pattern tool, which allows for the rapid duplication of a single hole across the surface. Begin by orienting the model to the back face of the enclosure using the "Views" button in the bottom left corner of the 3D modeling software. Create a new sketch on this face and use the circle tool to draw a 10 mm

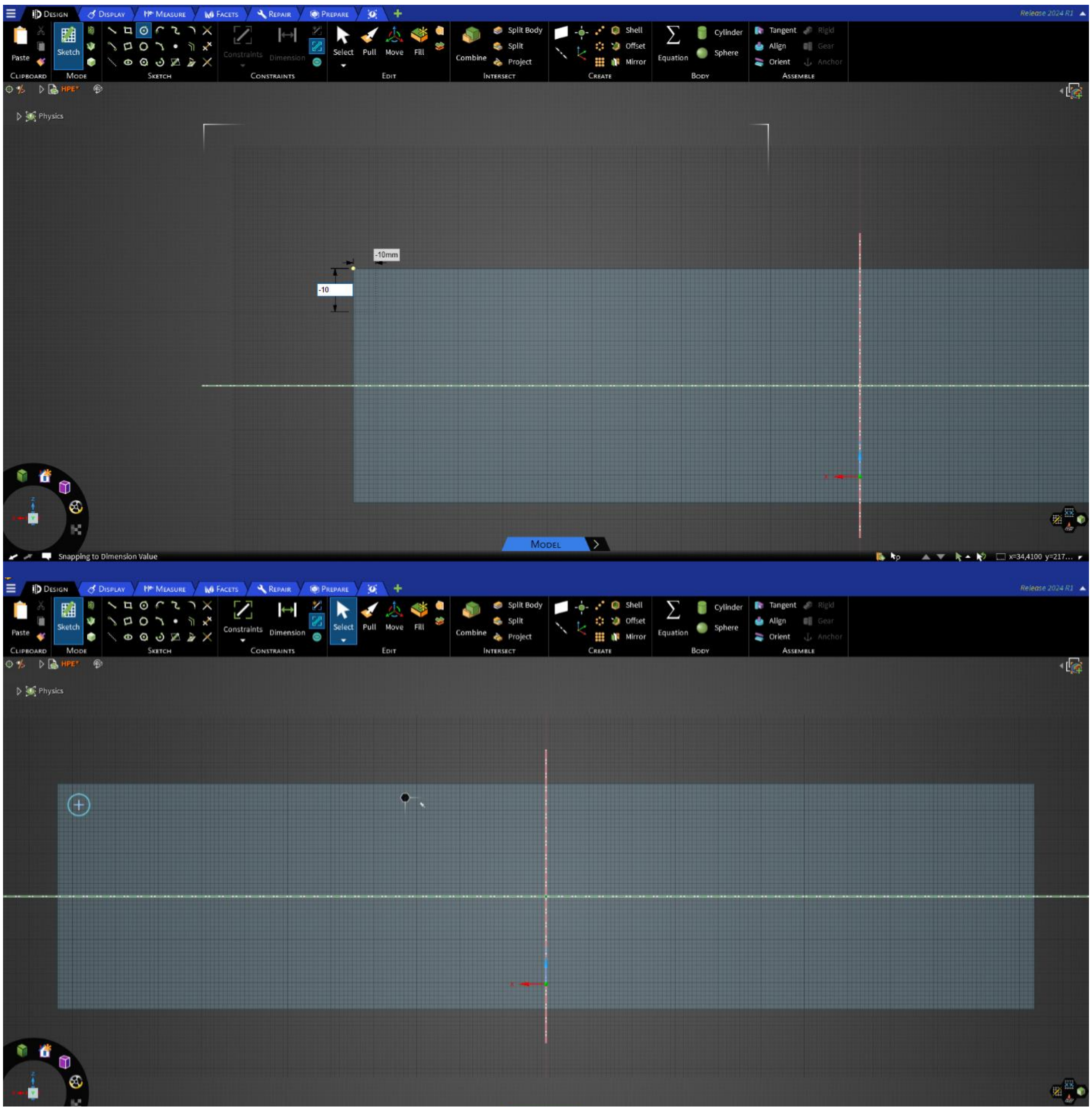


Figure 49. *Ventilation Pattern Implementation 1*

diameter hole, positioning its center point 10 mm from either the left or right edge and 10 mm down from the top.

Activate the pull tool and extrude the circular profile to cut through the enclosure, then press "S" to exit the tool. Select the inside surface of the hole and initiate the fill pattern tool, setting the pattern type to "Offset" in the option panel on the right side of the HUD. Ensure the hole is selected as the object to be patterned and set the X spacing to 4.5 mm, Y spacing to 5 mm, and margin to 5 mm. Click the top edge of the housing to define the direction reference and complete the pattern by clicking the green check mark.

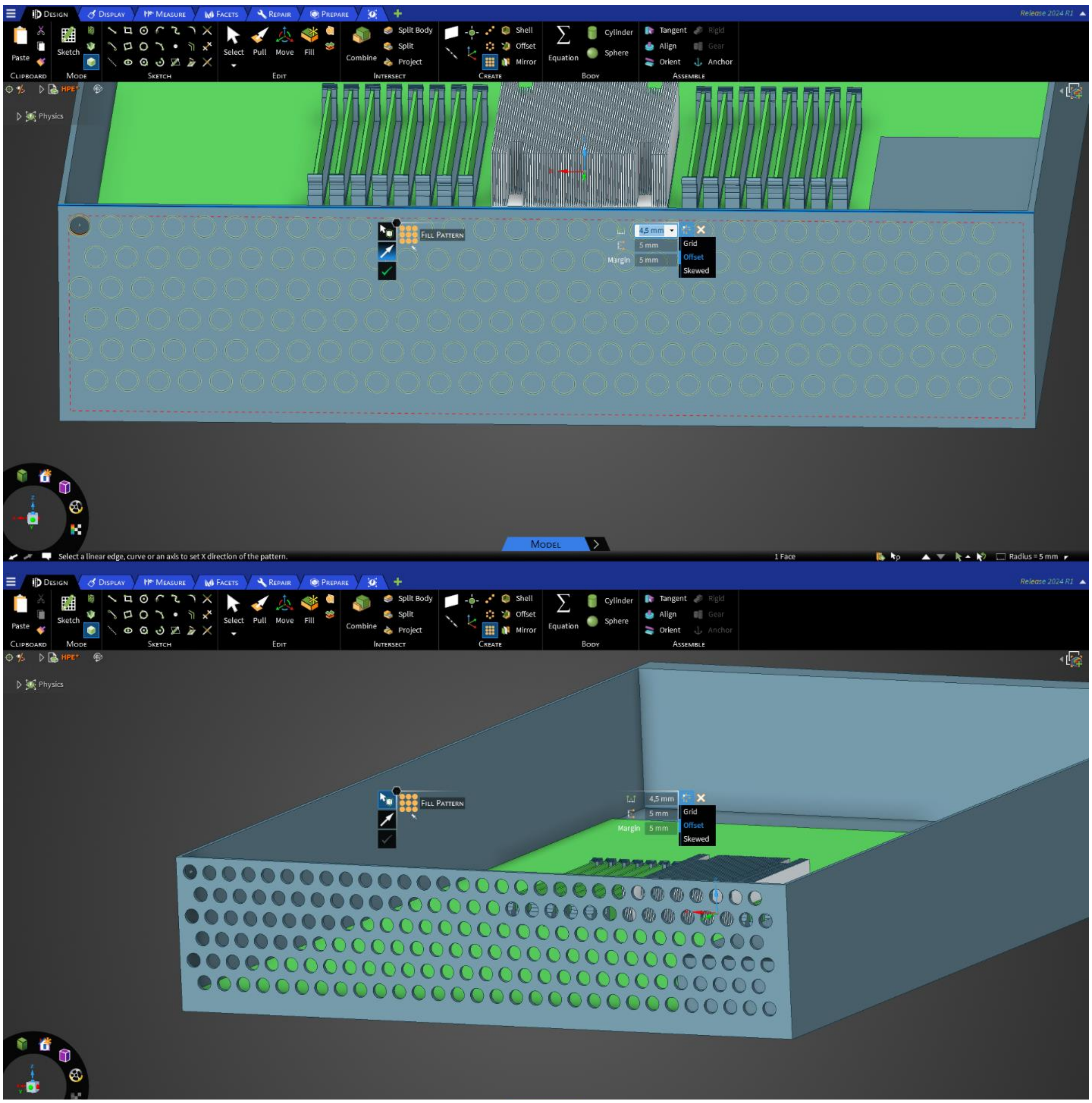


Figure 50. *Ventilation Pattern Implementation 2*

This modification will promote proper ventilation and heat dissipation within the server, contributing to the overall performance and longevity of the electronic components.

To accommodate fans in the server enclosure, dedicated mounting locations must be created on the front face of the housing. Begin by rotating the model to the front view using the green Y-axis in the view arc. Select the front planar face and press "K" to create a new sketch. Place a 70 mm diameter circle with its center 45 mm from the left edge and 47.5 mm from the top, then sketch a 5 mm diameter circle 13.5 mm from the top and 11 mm from the left. Create a second set of circles with the same dimensions, offset from the right edge. Use the pull tool to cut all four holes out of the housing wall, holding "Ctrl" to select multiple circles.

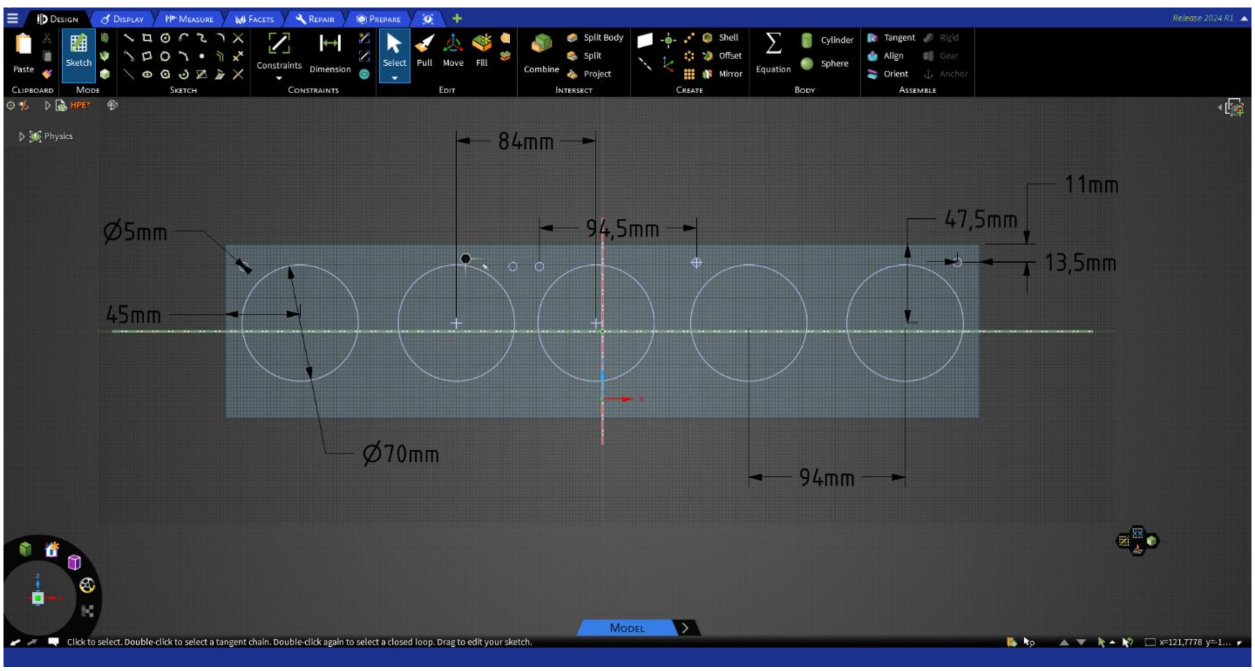


Figure 51. *Fan Mount Dimensional Layout*

Apply the circular pattern tool to one of the 5 mm holes, using the edge of the corresponding 70 mm hole as the center axis. Set the count to 4 and angle to 360 degrees for even spacing, then click the green check mark. Repeat for the other set of fan holes. This process results in two 70 mm fan holes and eight evenly spaced 5 mm mounting holes, ensuring proper airflow and cooling while maintaining the enclosure's structural integrity.

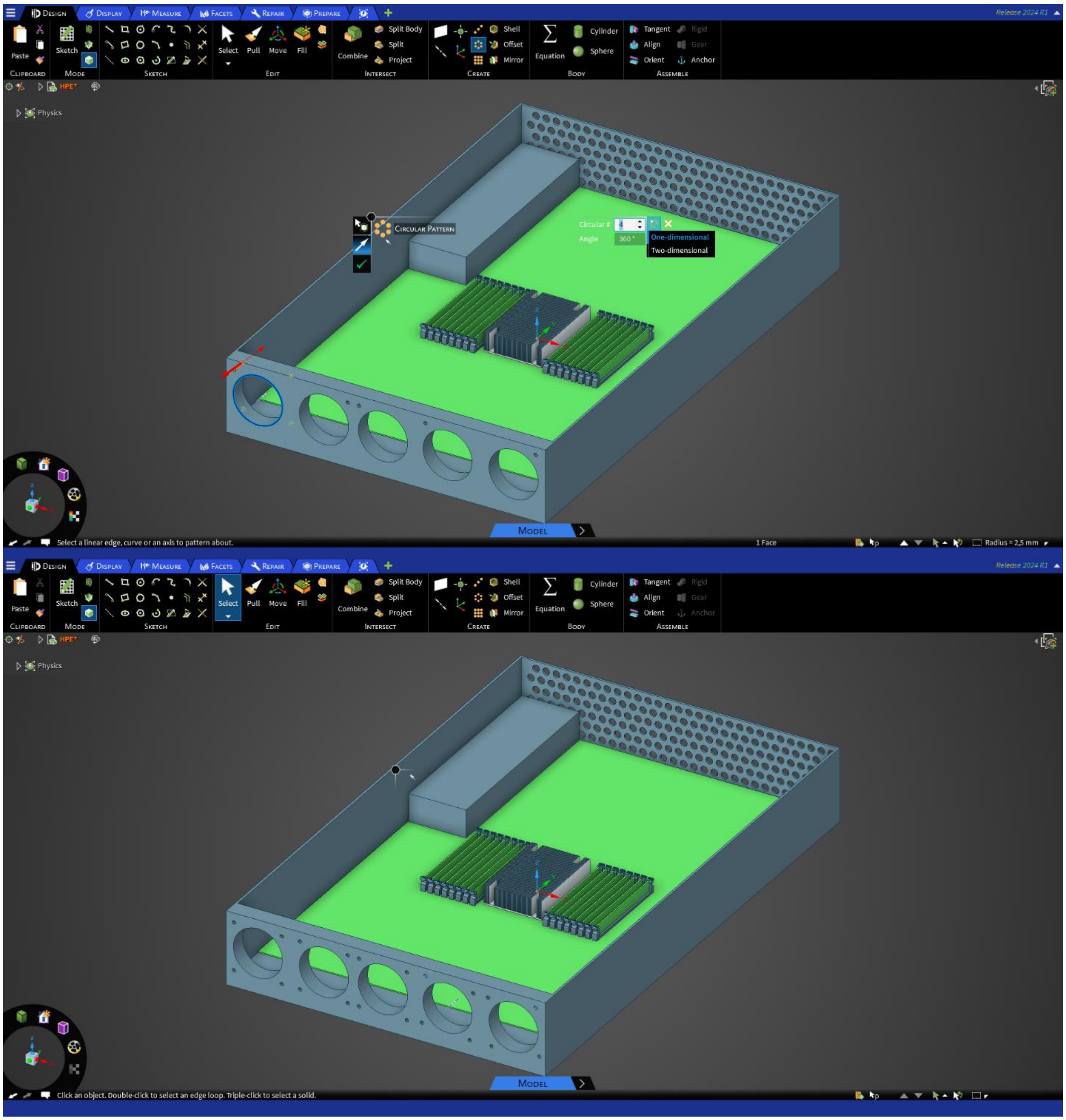


Figure 52. *Fan Mount Pattern Development*

First, select the fan component in the 3D modeling software's model tree and use the "Copy" and "Paste" options from the toolbar to create a duplicate. Move the duplicated fan away from the original using the "Move" tool, and repeat this process three more times to create a total of five fans.

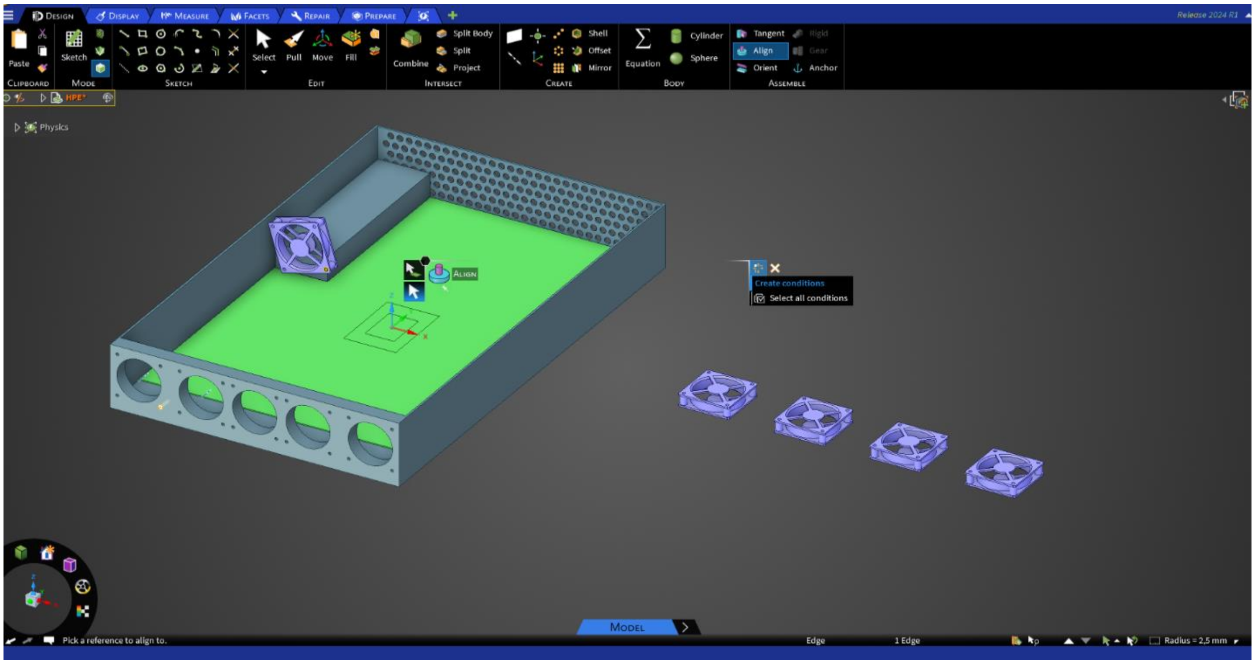


Figure 53. *Fan Positioning Setup*

Next, use the "Align" constraint in the "Assemble" menu to position the fans within the enclosure housing. To fully constrain each fan, apply three assembly constraints: align the large center hole with the corresponding cutout in the housing, align one of the small 5 mm holes with its counterpart on the housing, and make the front face of the fan coincident with the inside face of the enclosure wall.

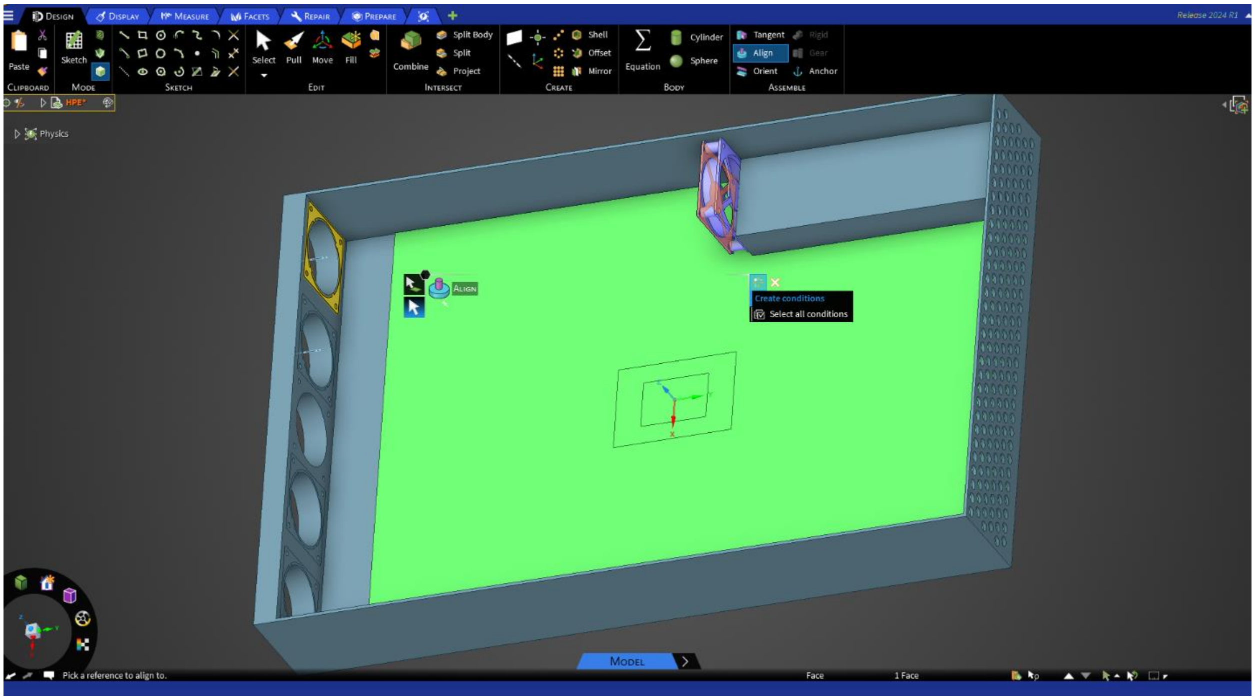


Figure 54. *Fan Assembly Alignment*

Repeat this alignment process for the remaining four fans, ensuring proper constraint within the enclosure. Accurate component placement and alignment are essential for the 3D enclosure model's representation and analysis, so verify that all constraints are applied correctly and double-check the final fan positions before proceeding with further modeling or simulation tasks.

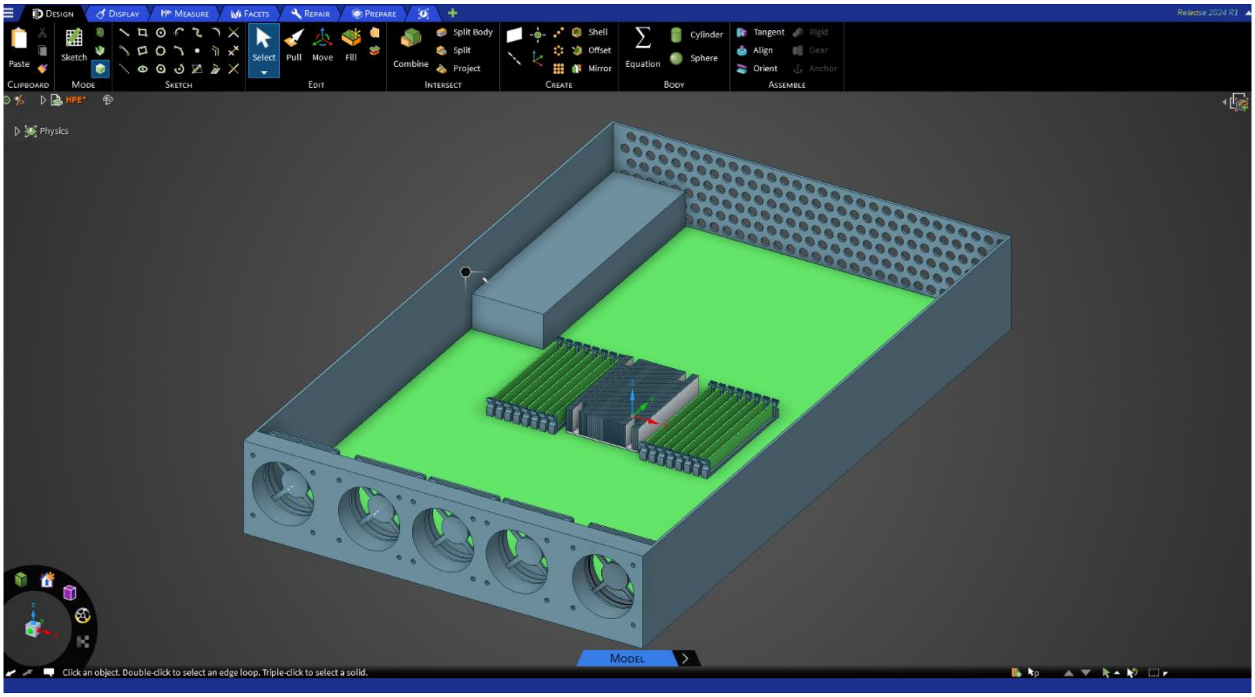


Figure 55. *Complete Server Assembly*

To prepare the fan geometry for the next step of defining the air volume inside the server enclosure, select both grille faces of one fan while holding the Ctrl key, then use the Plane tool to create a plane bisecting the fan body. Apply the Split tool with the Cutter Face option to split the inner cylindrical face of the fan, and repeat this process for the remaining four fans using the same plane.

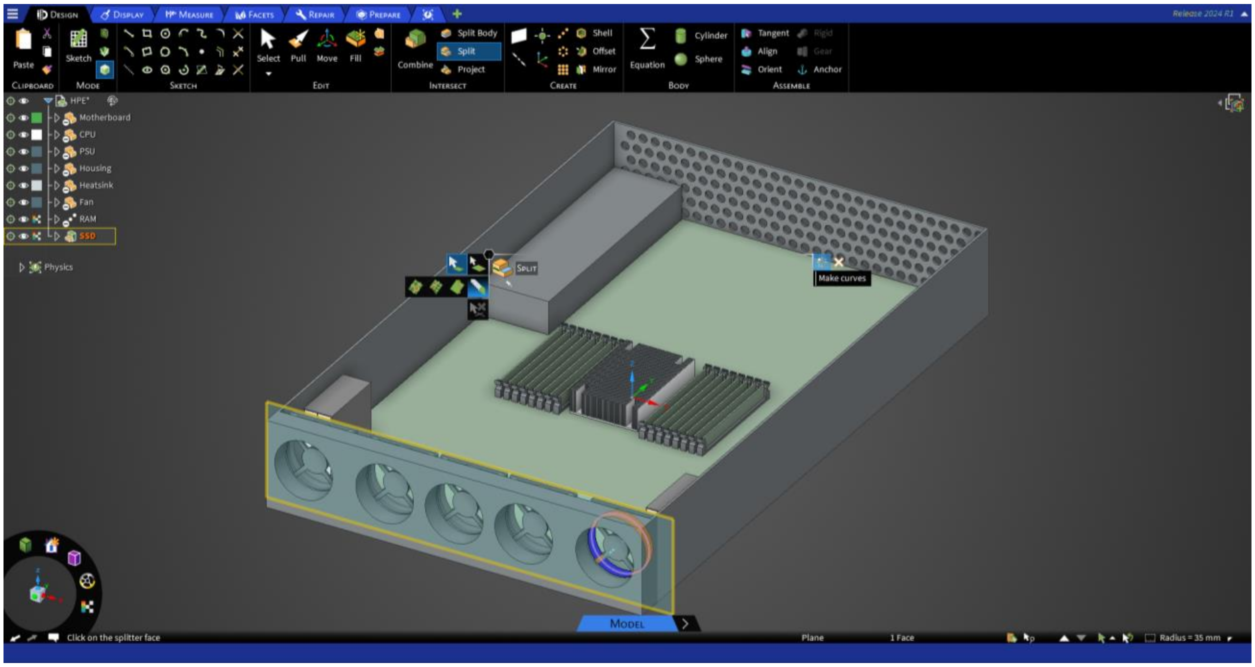
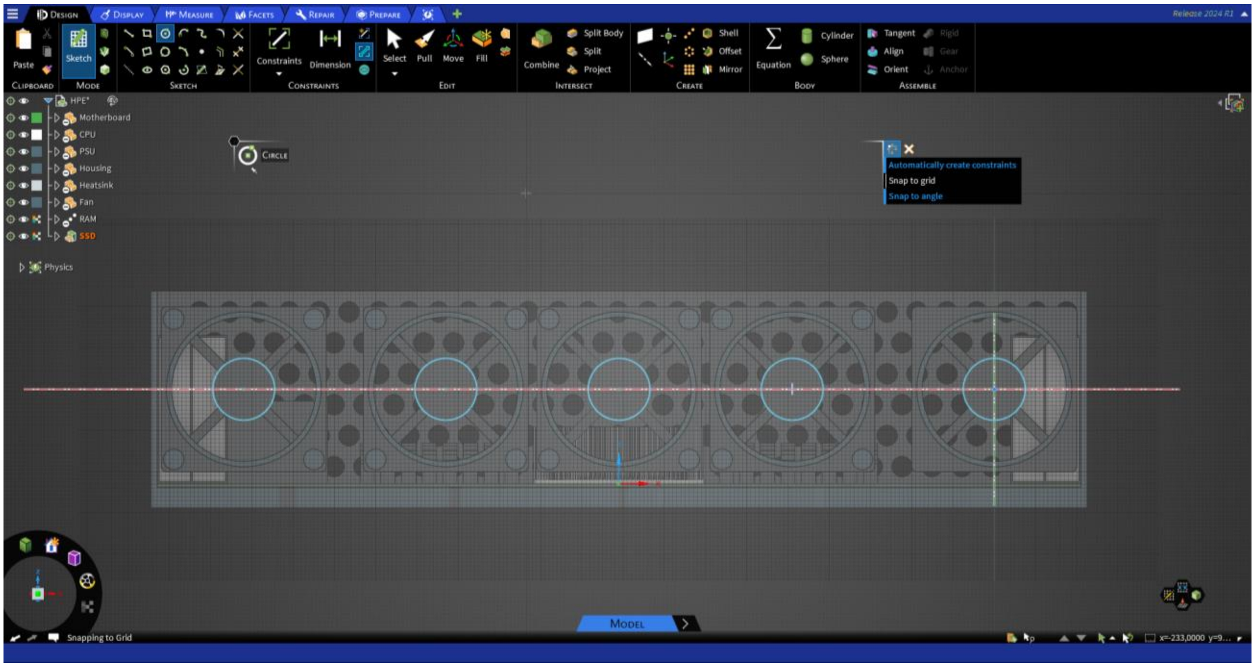
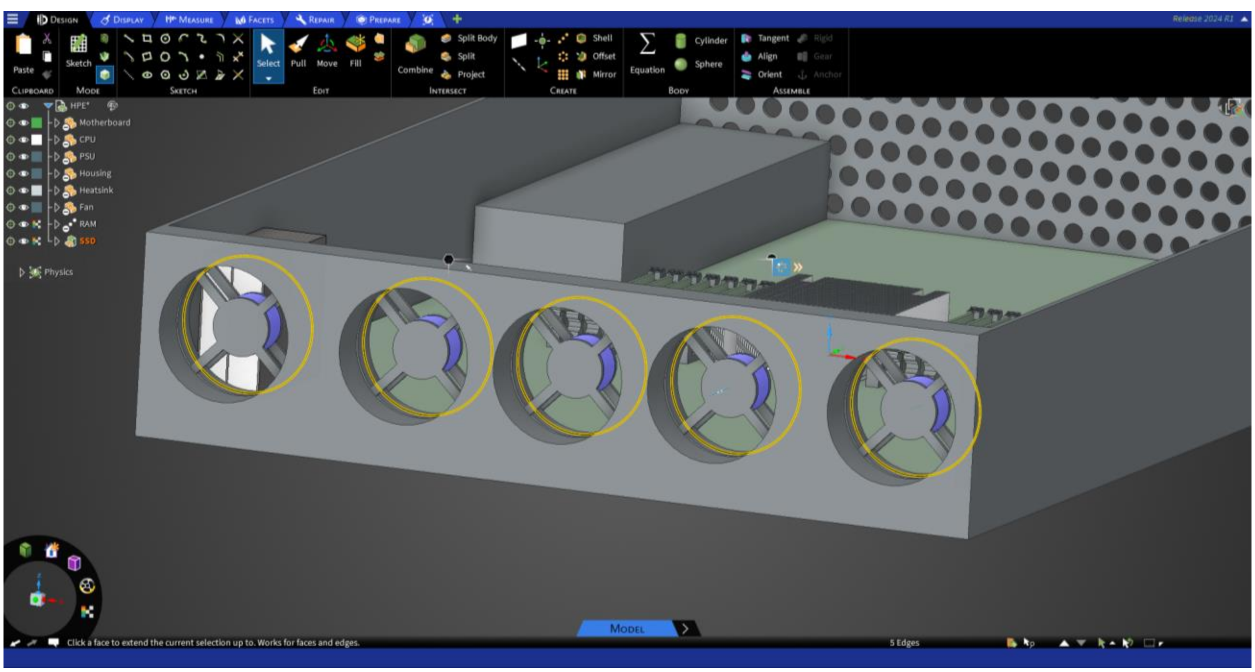


Figure 59. *Fan Array Split Plane Definition*

After deleting the plane, select one fan's planar inner face and use the Sketch Circle tool to create a 30 mm diameter circle extending to the edge of the housing structure. Pull the newly created face to the opposite side of the fan housing, and repeat for the other fans to create the fan hubs.



Next, select the circular edges inside the fans, copy (Ctrl+C) and paste (Ctrl+V) them, then use the Fill tool (F key) to create faces. Pull the resulting disk faces slightly outward using the Pull tool. The inner faces of these disks will define the location and velocity of the air moved by the fans. With this geometry prepared, the next step is to extract the volume of air inside the server, which will define the region of interest for simulating airflow.



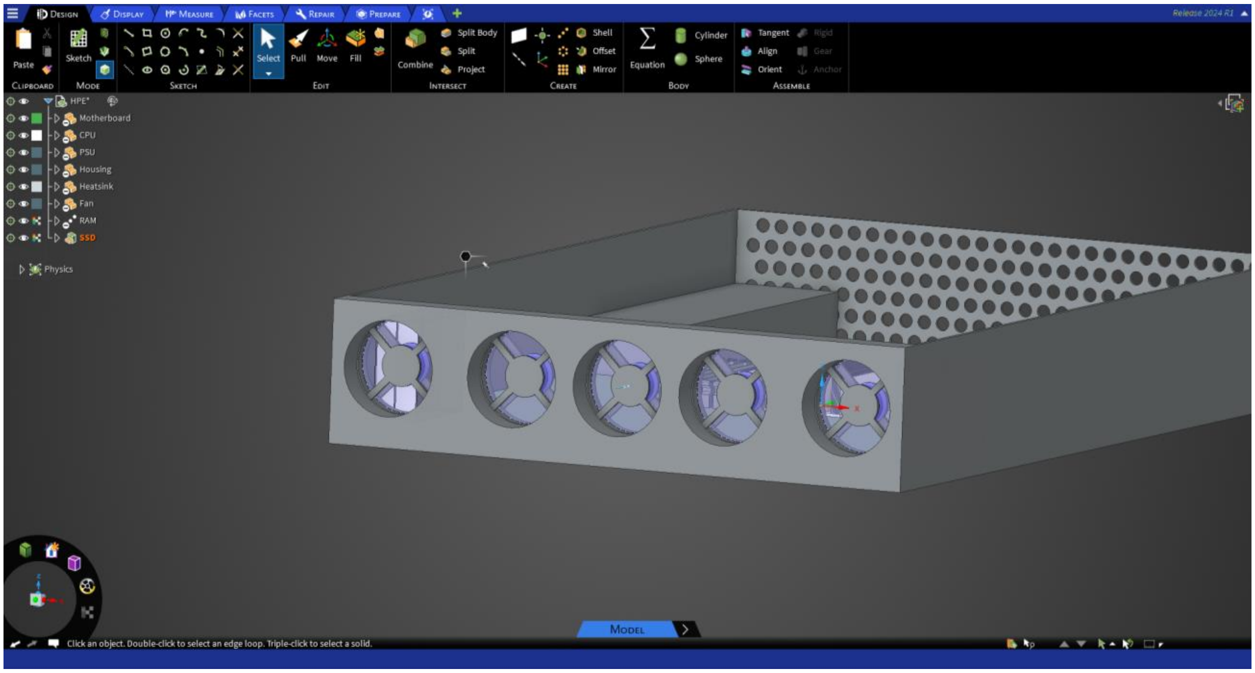


Figure 60. *Final Fan Volume Configuration*

8. Volume Extraction

Preparing the geometry and extracting the fluid volume are crucial steps in setting up a fluid-dynamic simulation to predict airflow within a server enclosure. To optimize the simulation, simplify the geometry by removing small, non-critical elements that have minimal impact on airflow, such as minor protrusions, intricate patterns, or tiny gaps. These features can increase computational complexity without significantly contributing to the overall airflow patterns. Once the geometry is simplified, define and create the volume of air within the enclosure through a process called volume extraction. In the 3D modeling software, navigate to the "Prepare" tab, select the "Volume Extract" tool, and click on the topmost face of the housing and the outer face of the perforated side to define the volume boundaries.

Figure 61. *Fluid Volume Extraction Setup*

Activate the "Seed Face" option and select the inner face of one of the outlet holes, then click the green check mark to complete the volume extraction process.

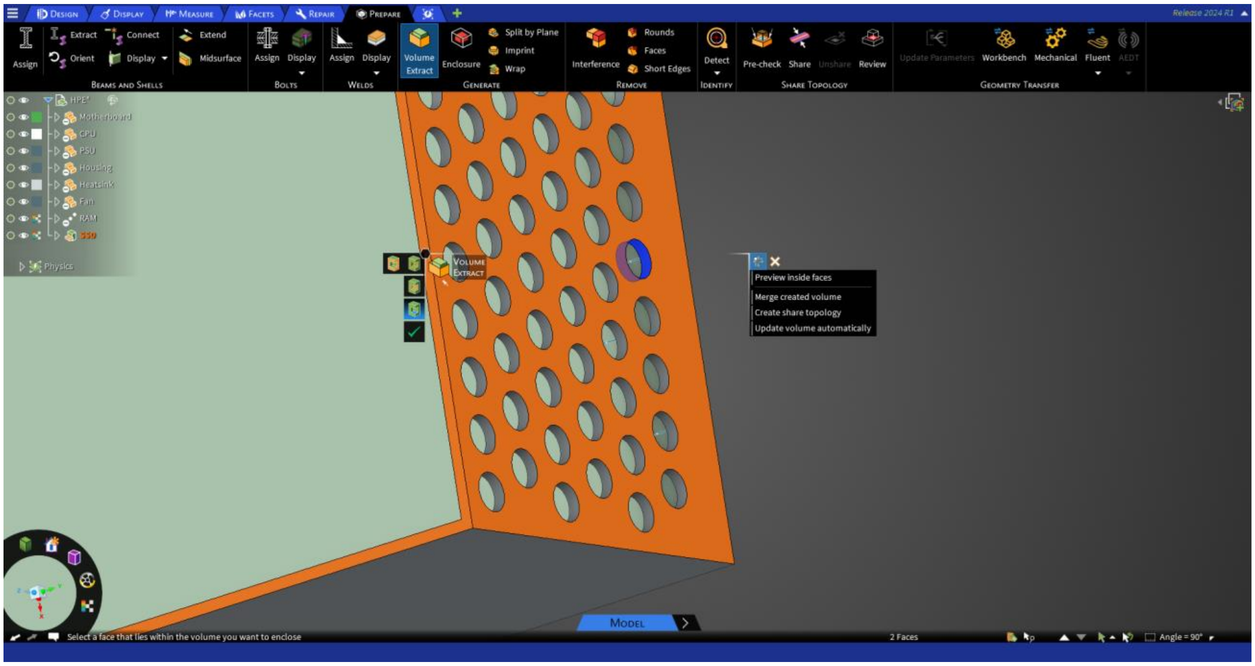


Figure 62. *Volume Boundary Selection*

To visualize the internal geometry of the extracted fluid volume, right-click on the top face of the newly created volume, select "Face" from the context menu, and choose "Hide Face." This process defines the region of interest for the simulation, focusing the airflow analysis on the relevant areas inside the server while allowing for a clear view of the fluid domain in preparation for the subsequent simulation setup.

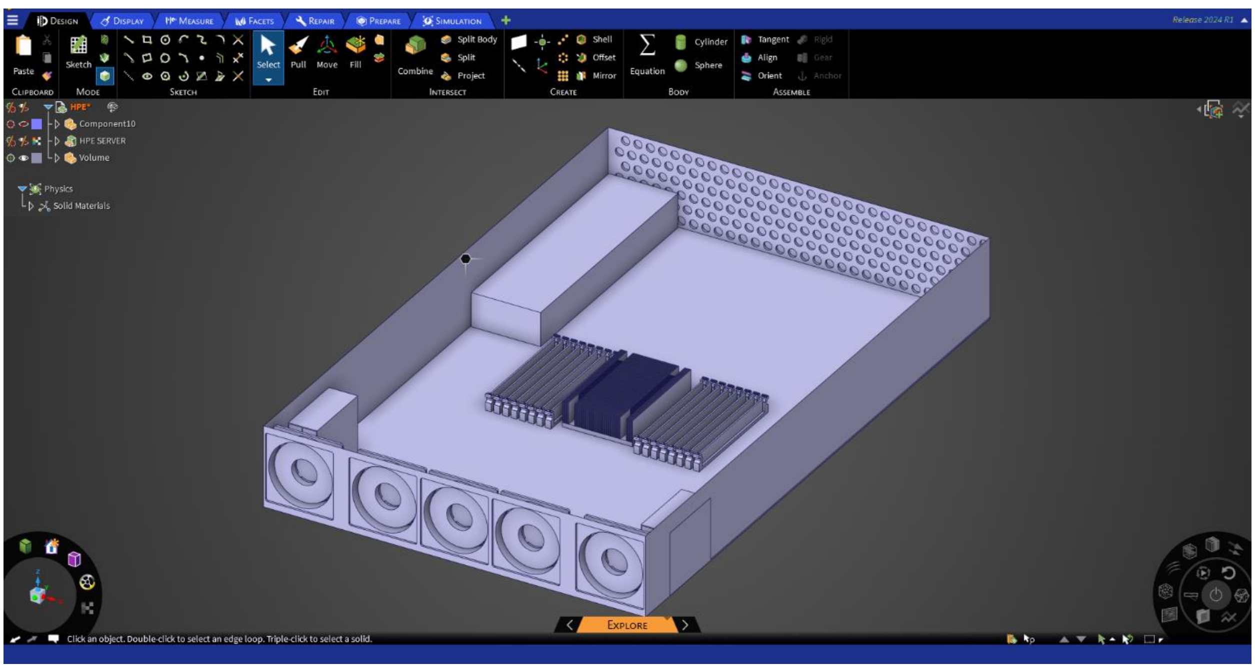


Figure 63. *Completed Fluid Domain Model*

9.1. Material Assignment

Click on the materials tool and select the component. The predefined material is structural steel; we can open the dropdown menu and then assign the materials. Each material's properties are shown in the Images below:

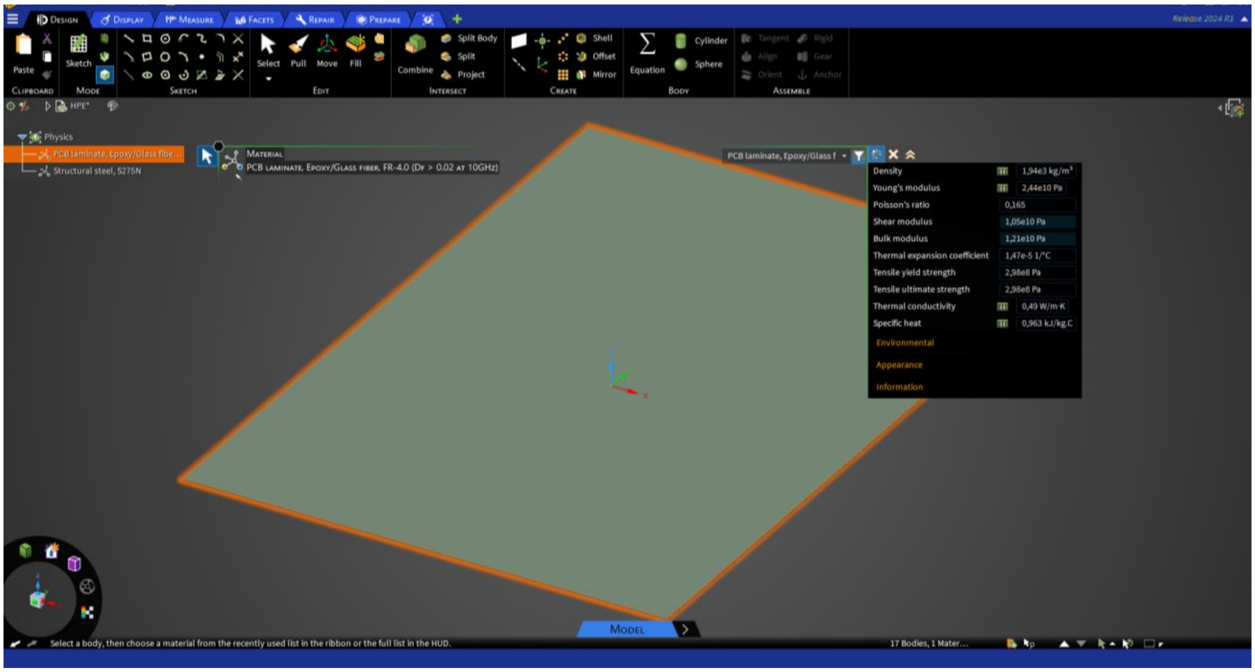


Figure 64. *Motherboard-PCB Laminate, Epoxy/Glass Fiber, FR-4.0*

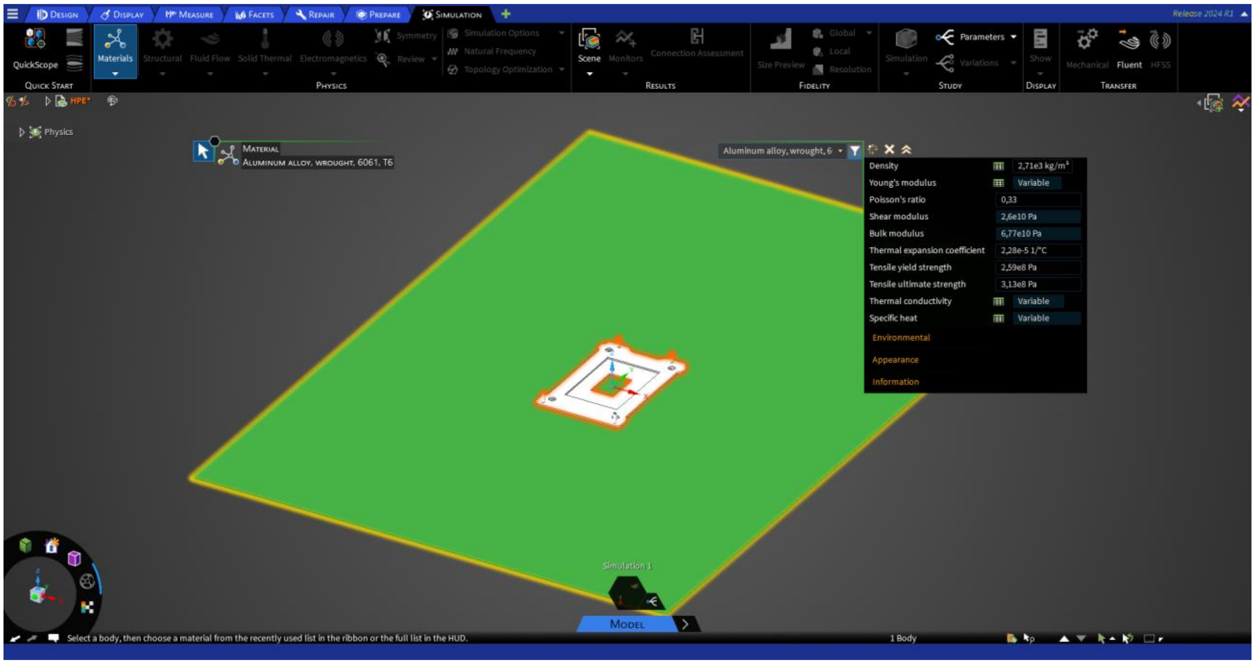


Figure 65. *Stiffener Frame/Heatsink Attachment – Aluminum Alloy, wrought, 6061, T6*

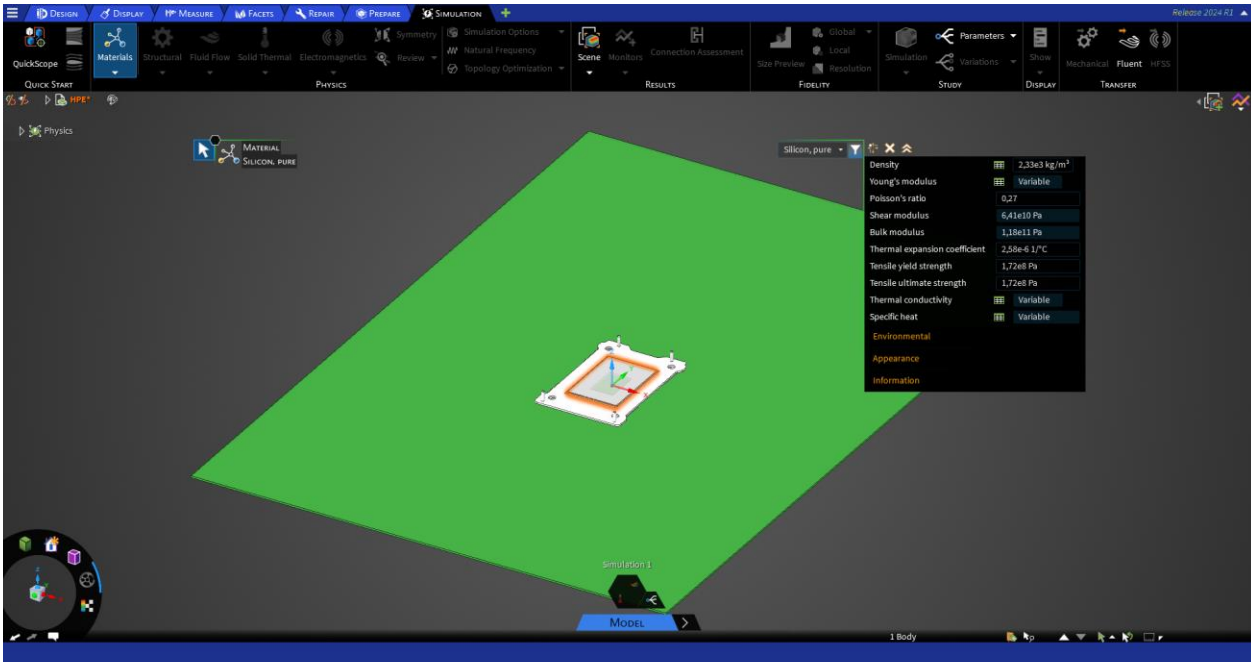


Figure 66. *CPU – Silicon, Pure*

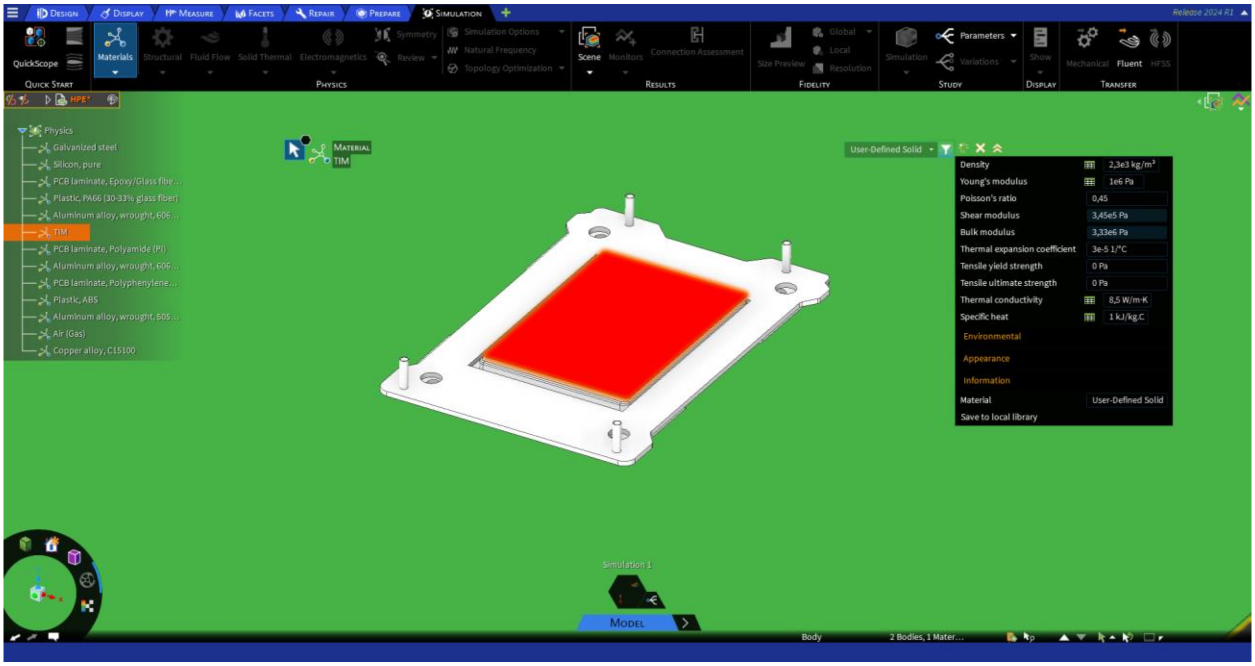


Figure 67. *Thermal Interface Material*

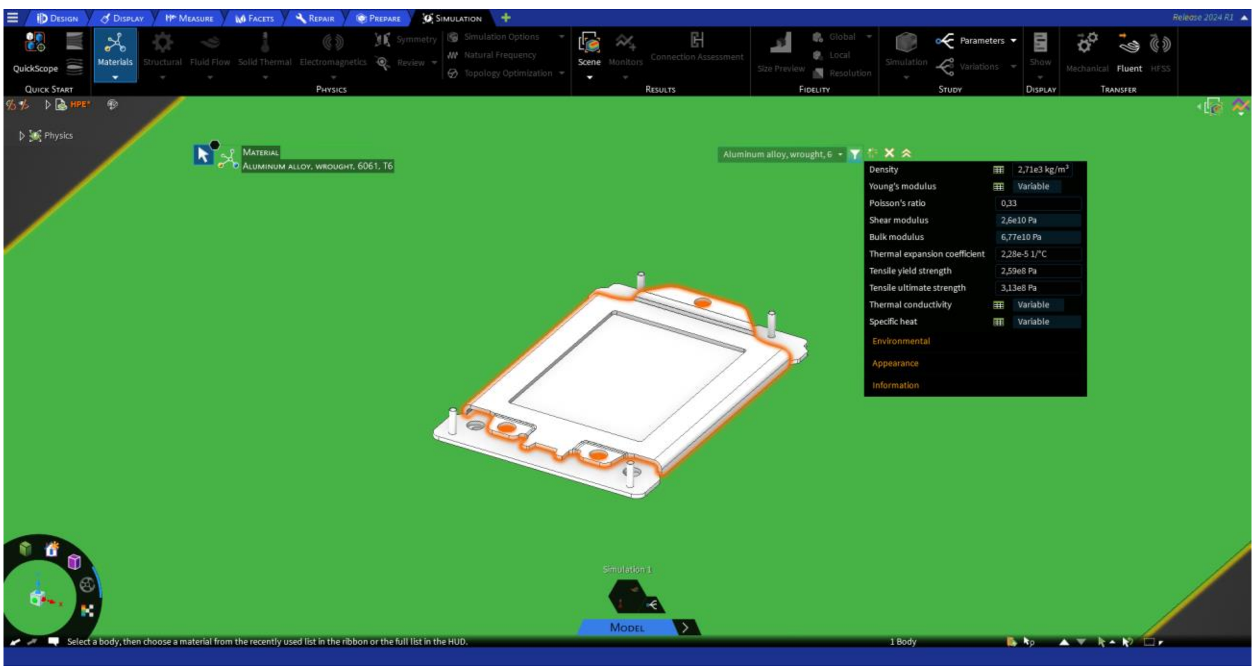


Figure 68. *Force Frame – Aluminum Alloy, wrought, 6061, T6*

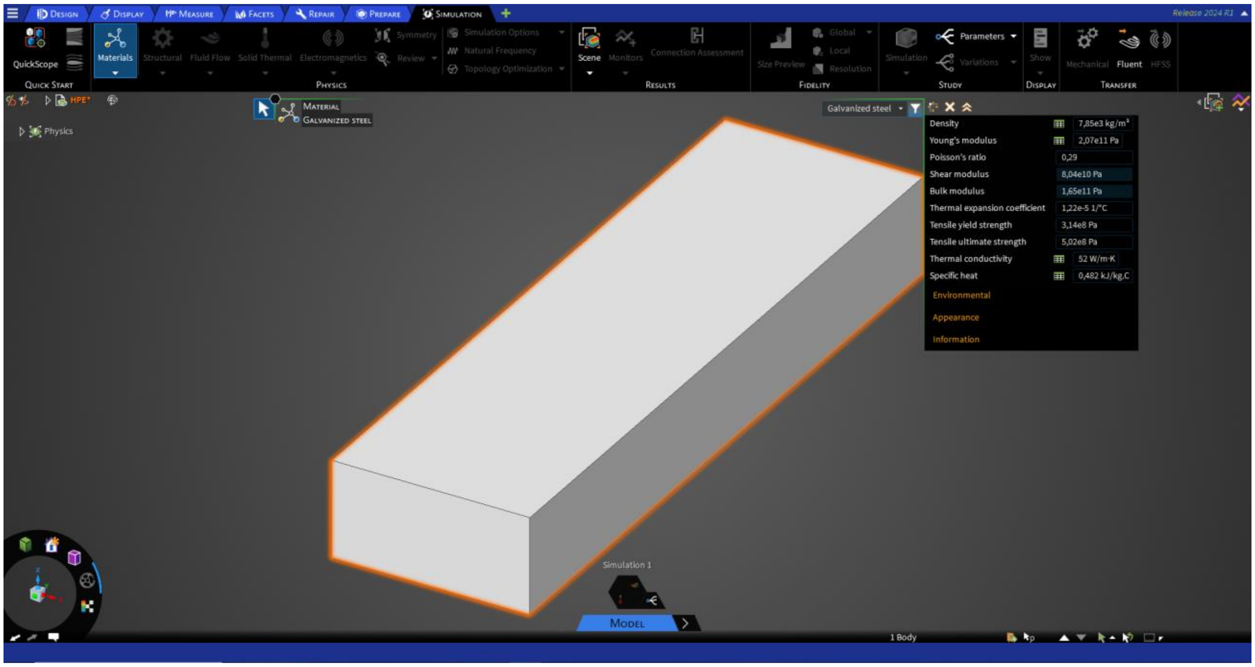


Figure 69. *Power Supply Unit – Galvanized Steel*

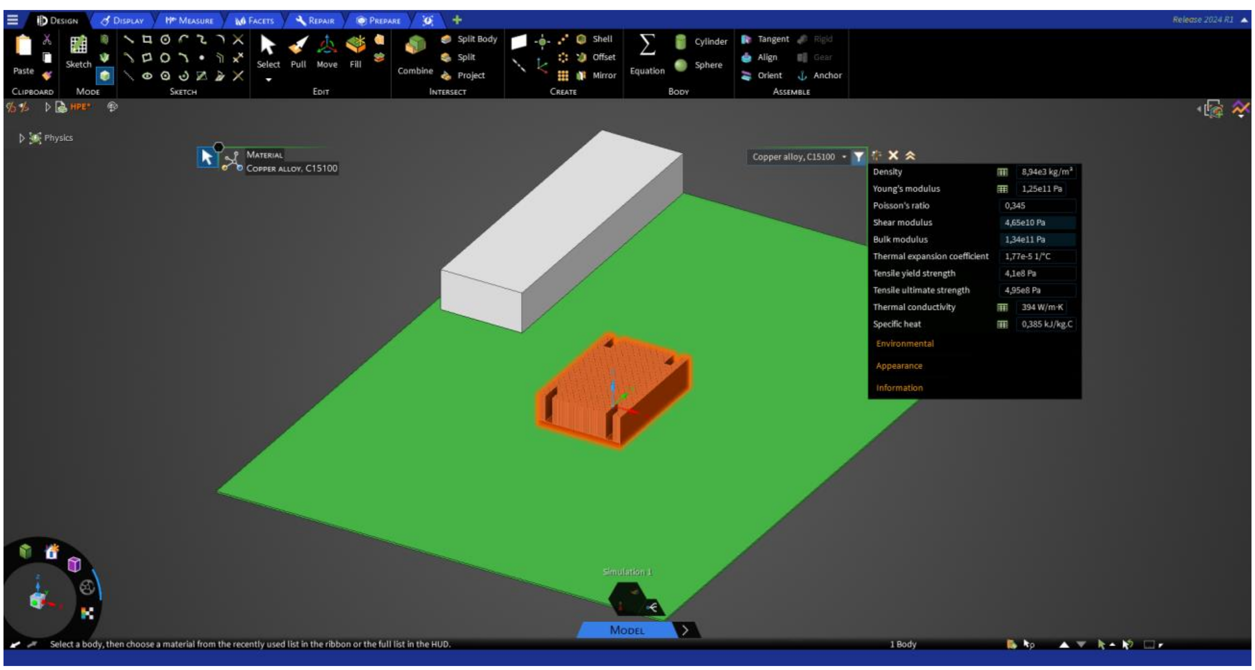


Figure 70. *Heat Sink – Copper alloy, C15100*

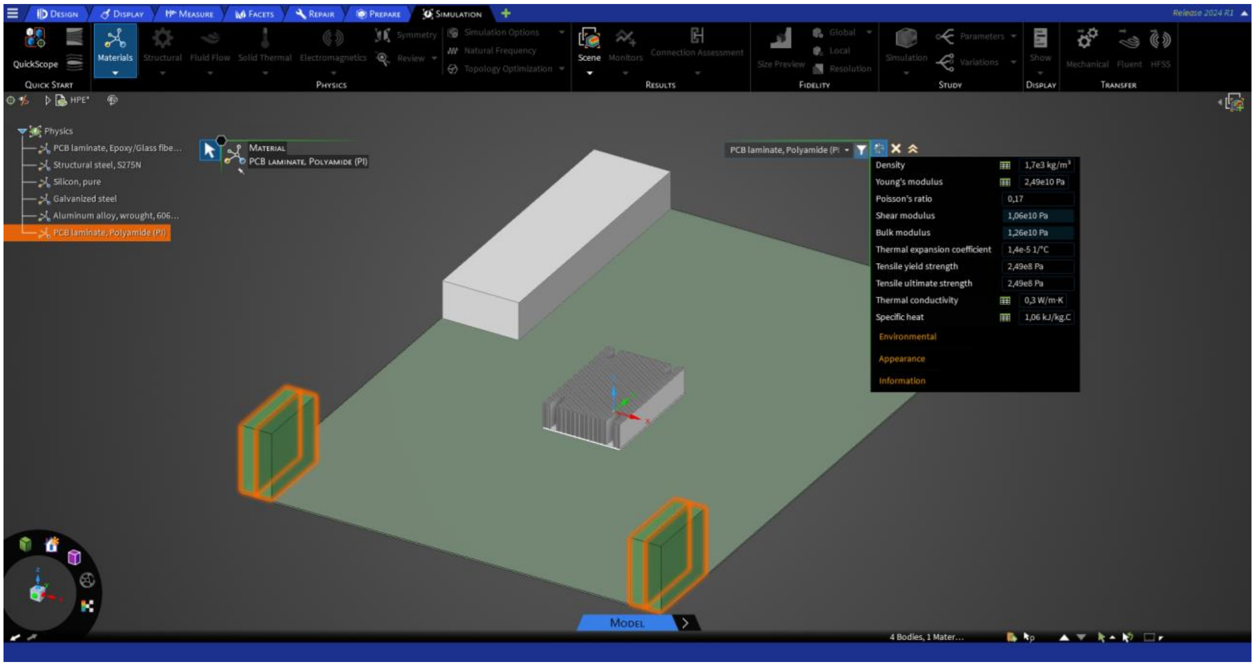


Figure 71. *Solid State Drives – PCB Laminate, Polyamide (PI)*

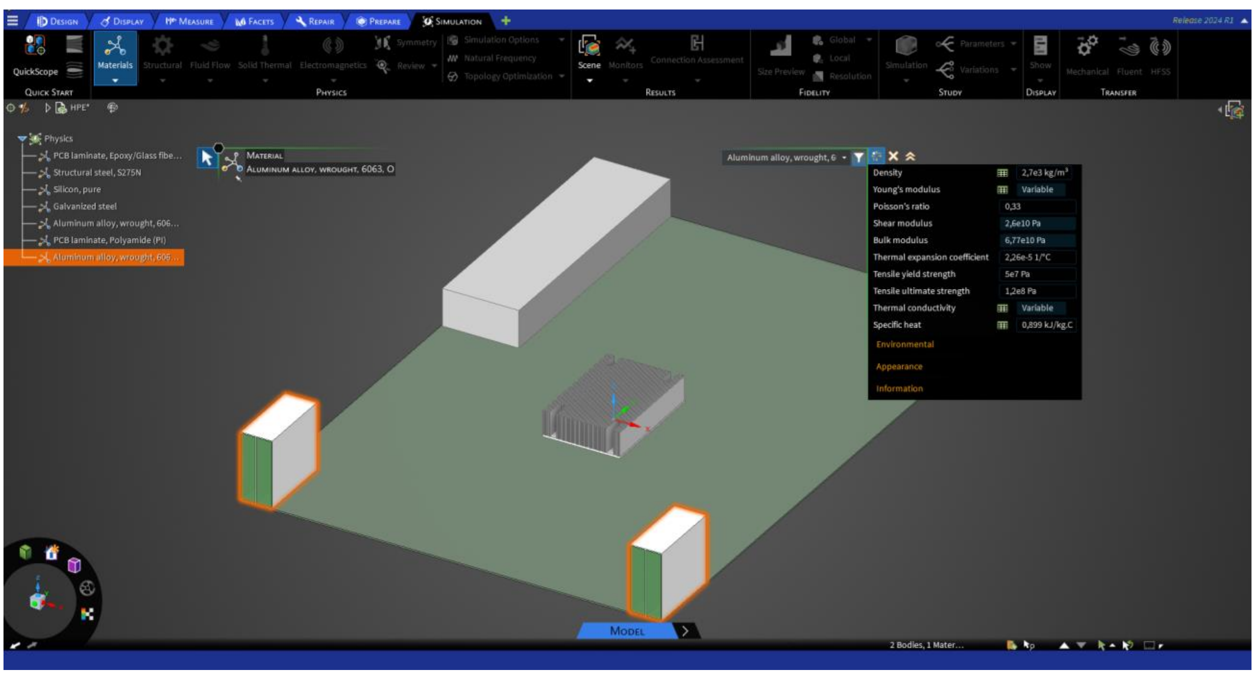


Figure 72. *SSD enablement kit – Aluminum alloy, wrought, 6063, O*

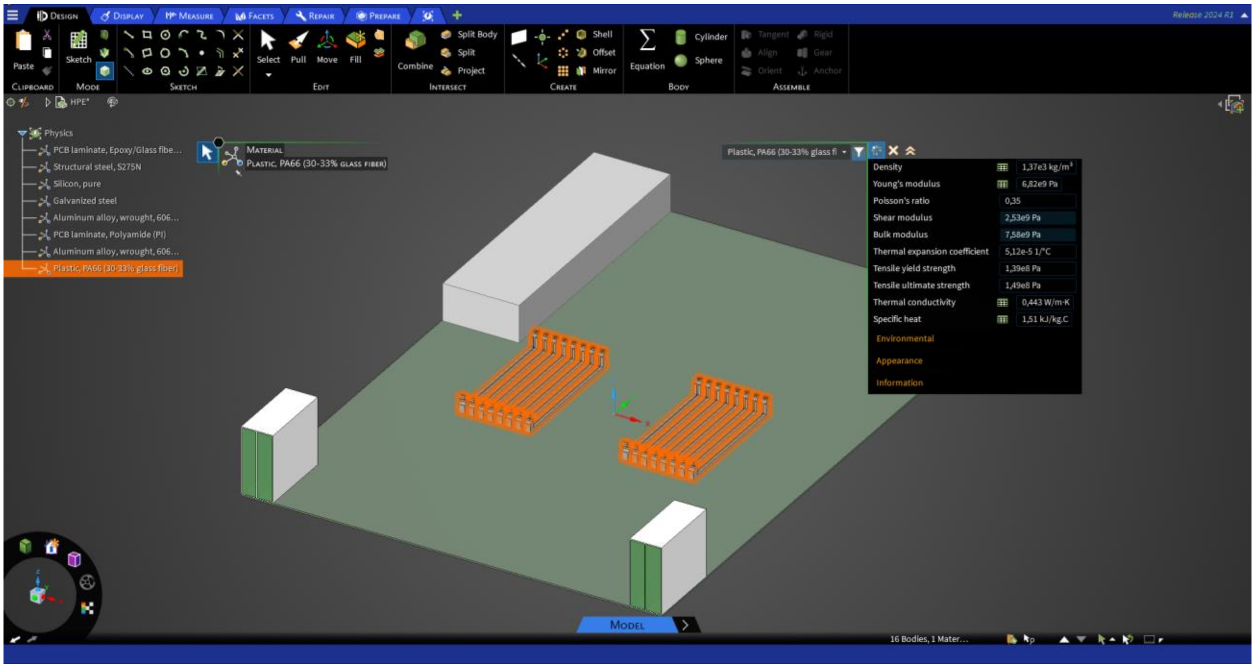


Figure 73. *RAM retention mechanism – Plastic, PA66 (30-33% Glass Fiber)*

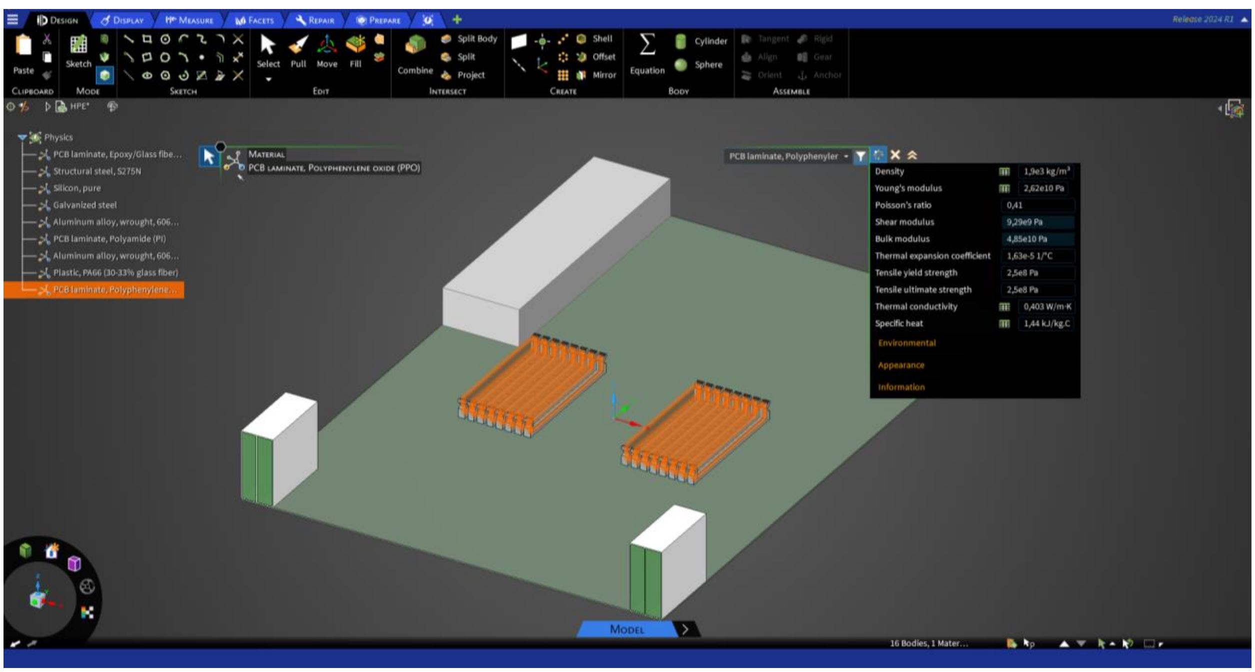


Figure 74. *Random Access Memory – PCB Laminate, Polyphenylene Oxide (PPO)*

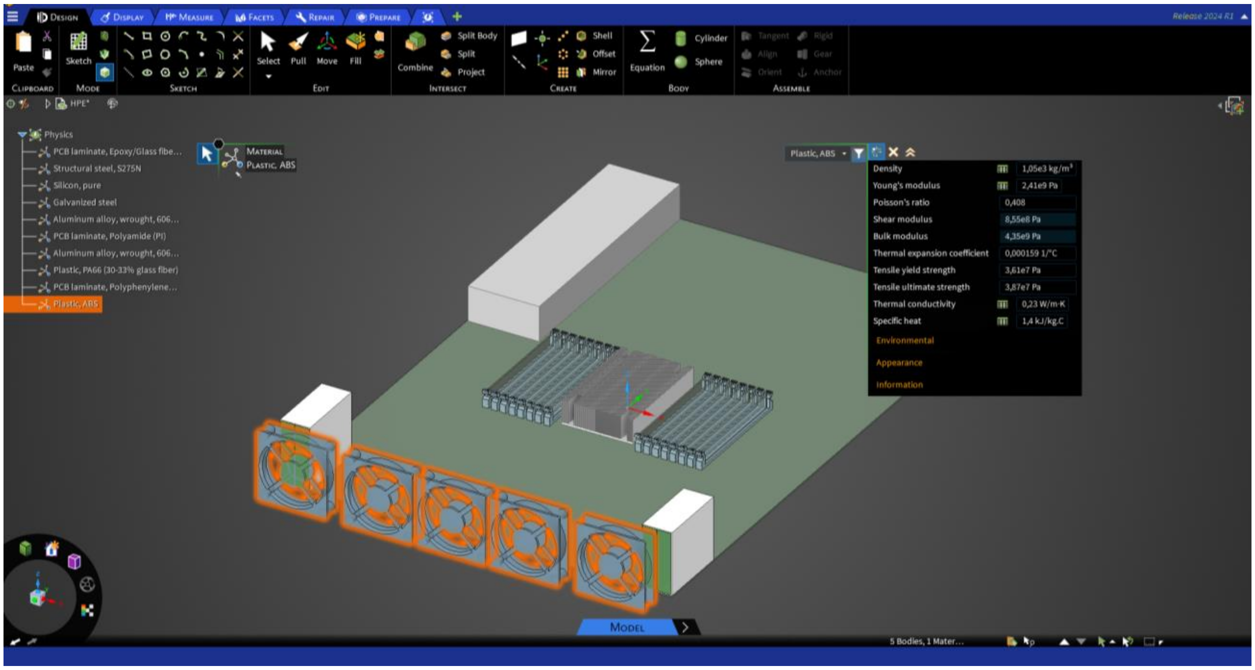


Figure 75. *Fan Housing – Plastic ABS*

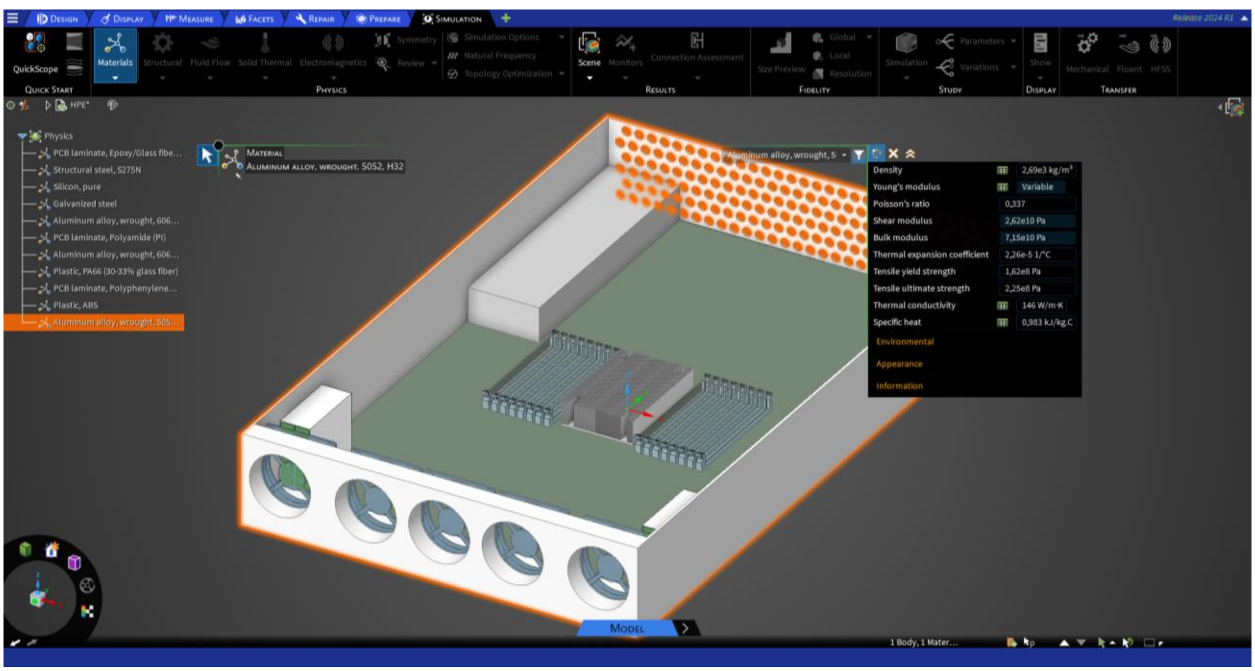


Figure 76. *Server Housing – Aluminum alloy, wrought, 5052, H32*

9.2. Mesh Settings

To specify global and local sizing for the mesh, begin by ensuring that all objects participating in the simulation are visible. Navigate to the global fidelity settings and select "Curvature" to control the size of the cells near curved bodies. In the Curvature settings, set the minimum size to 0.003 m, maximum face size and maximum size to 0.06 m, growth rate to 1.3, curvature normal angle to 32°, and maximum boundary layers to zero. Next, click and drag a box to select the entire housing, except for the outlets, and while holding the CTRL key, deselect the components inside the server.

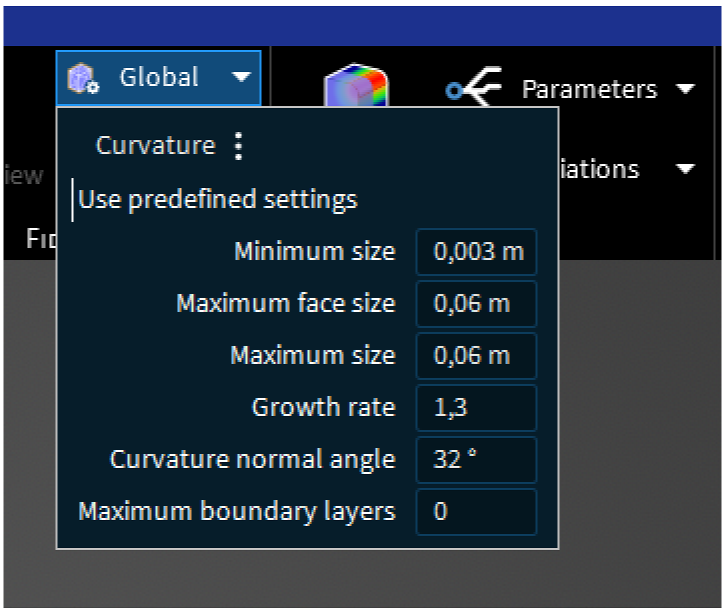


Figure 77. *Global Settings*

Local Fidelity

Click and drag a box to select the entire housing, except for the outlets, and while holding the CTRL key, deselect the components inside the server. Set the local fidelity sizing to 20 mm for the selected housing region. Finally, select the server's internal components and set a local fidelity sizing of 6 mm. By applying these global and local sizing controls, the mesh will be optimized to reduce the total number of cells while maintaining accuracy, striking a balance between solution speed and capturing the important geometric details. This approach will help obtain a faster solution without sacrificing essential flow features and thermal gradients in critical regions.

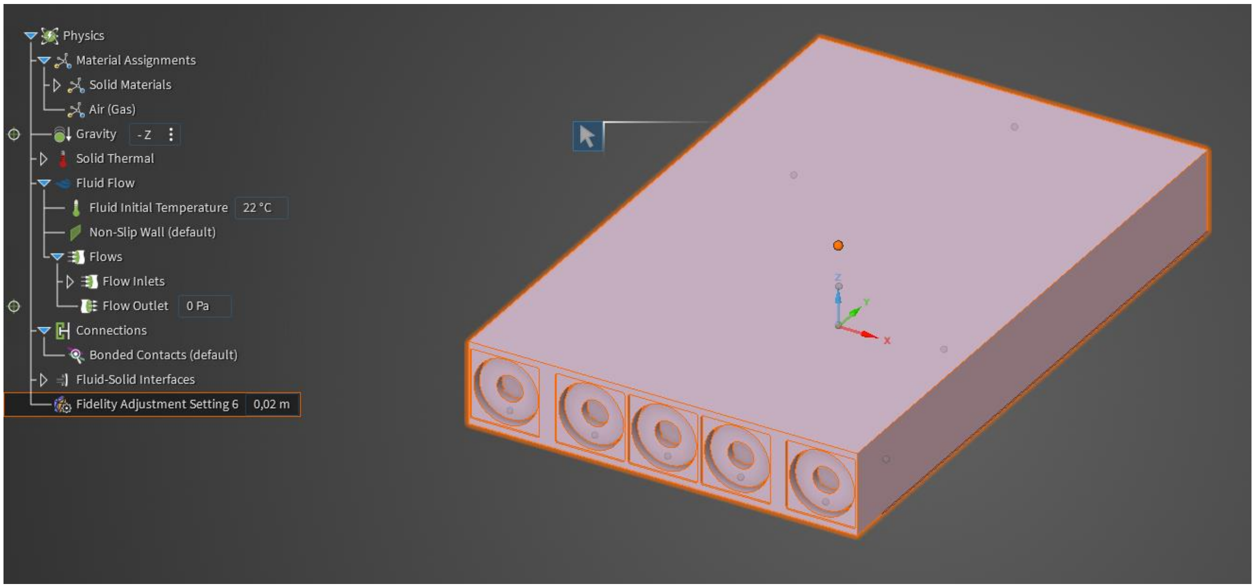


Figure 78. *Extracted volume's local fidelity*

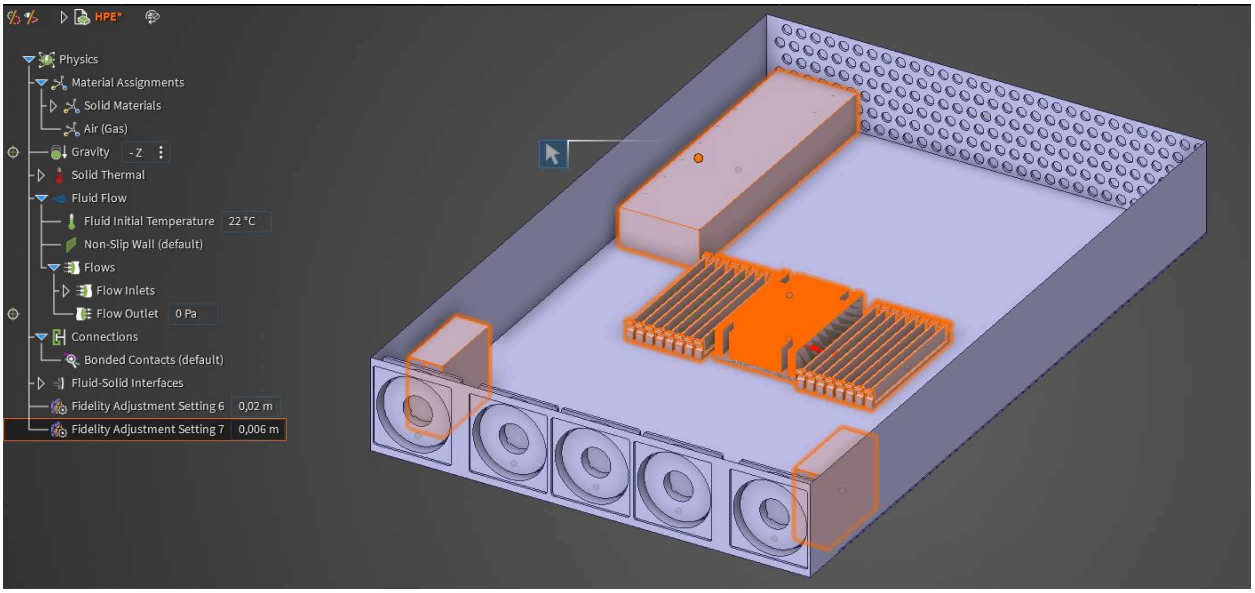


Figure 79. *Server components local fidelity*

Clicking on Generate Mesh, we get the mesh for our geometry (Figure 80)

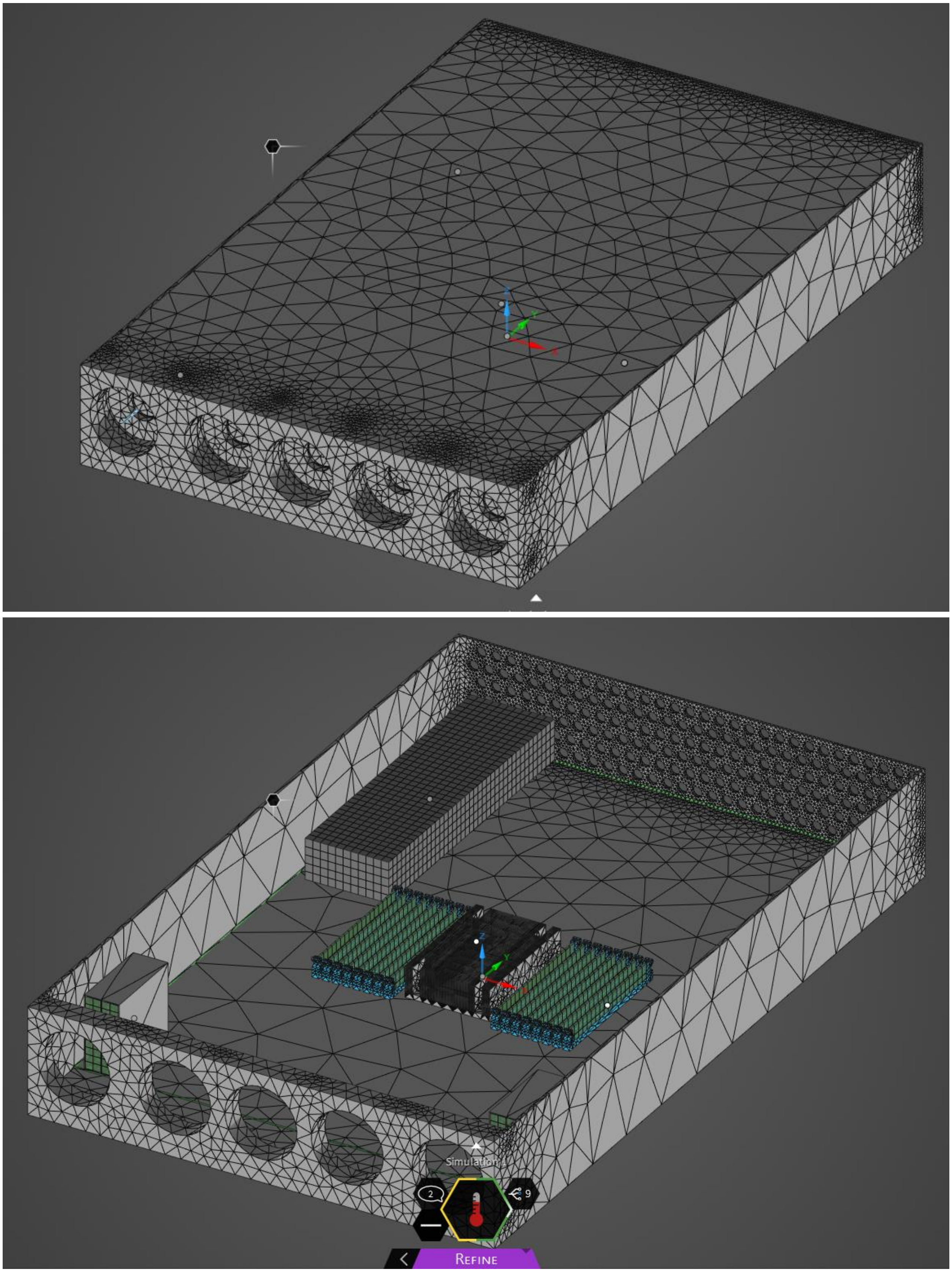


Figure 80. *Final Mesh Quality Assessment*

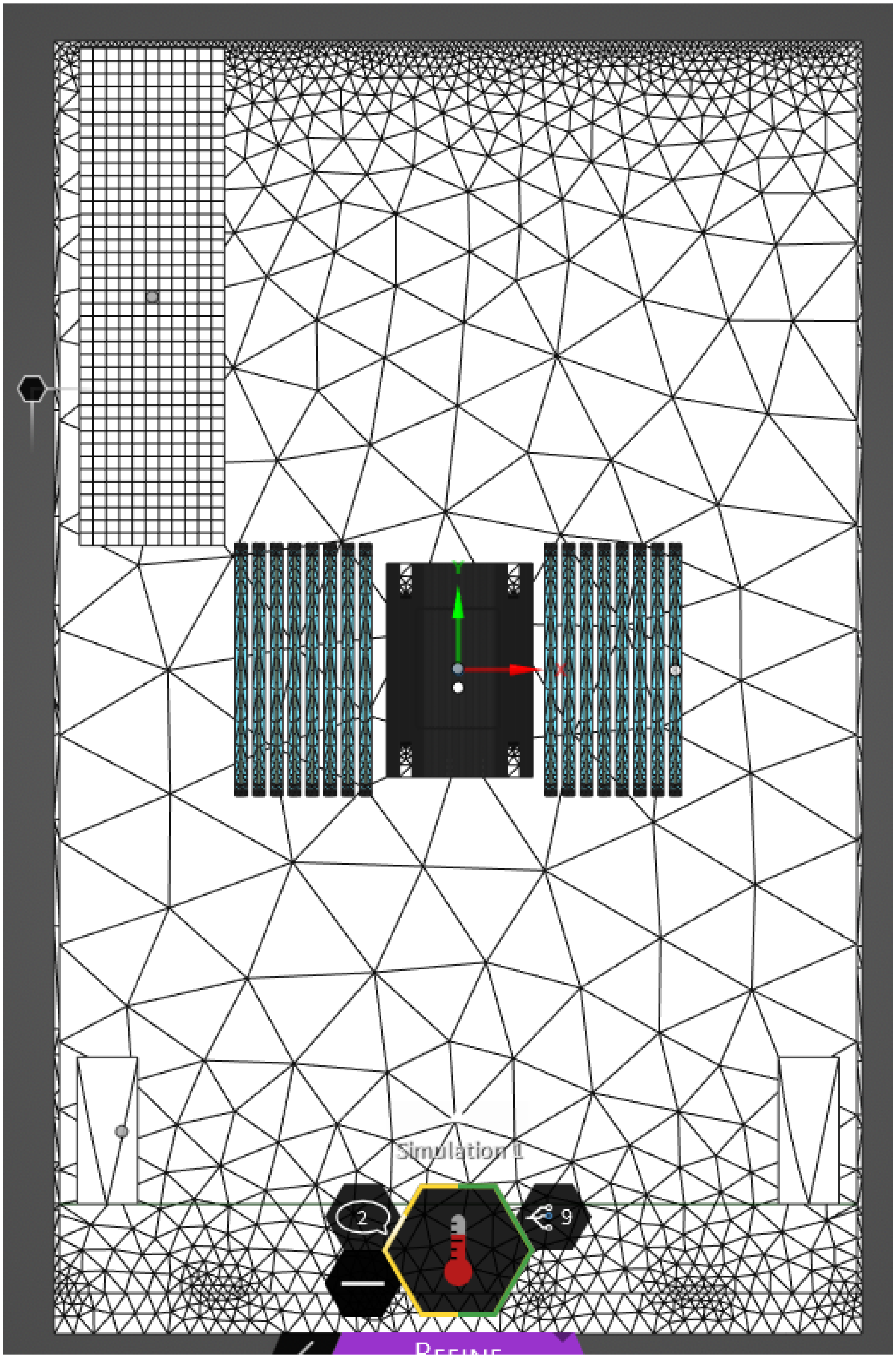


Figure 81. *Server's Mesh, Top View*

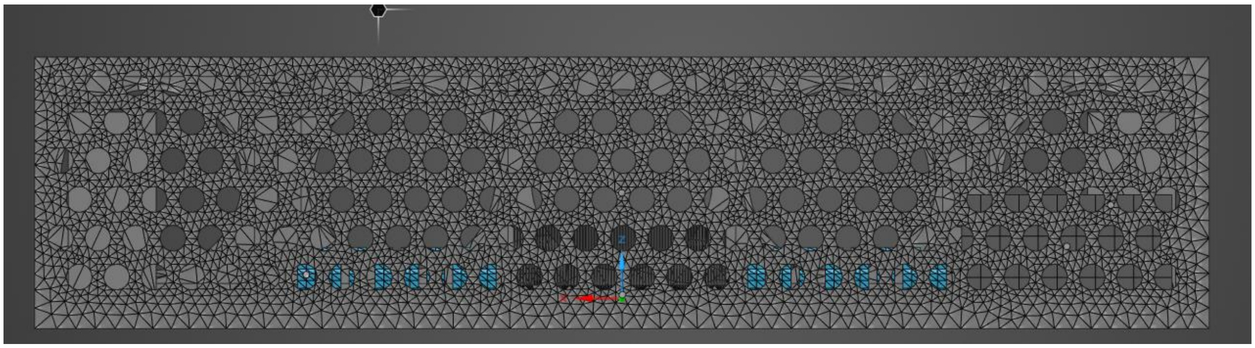


Figure 82. *Server's Mesh, Back View*

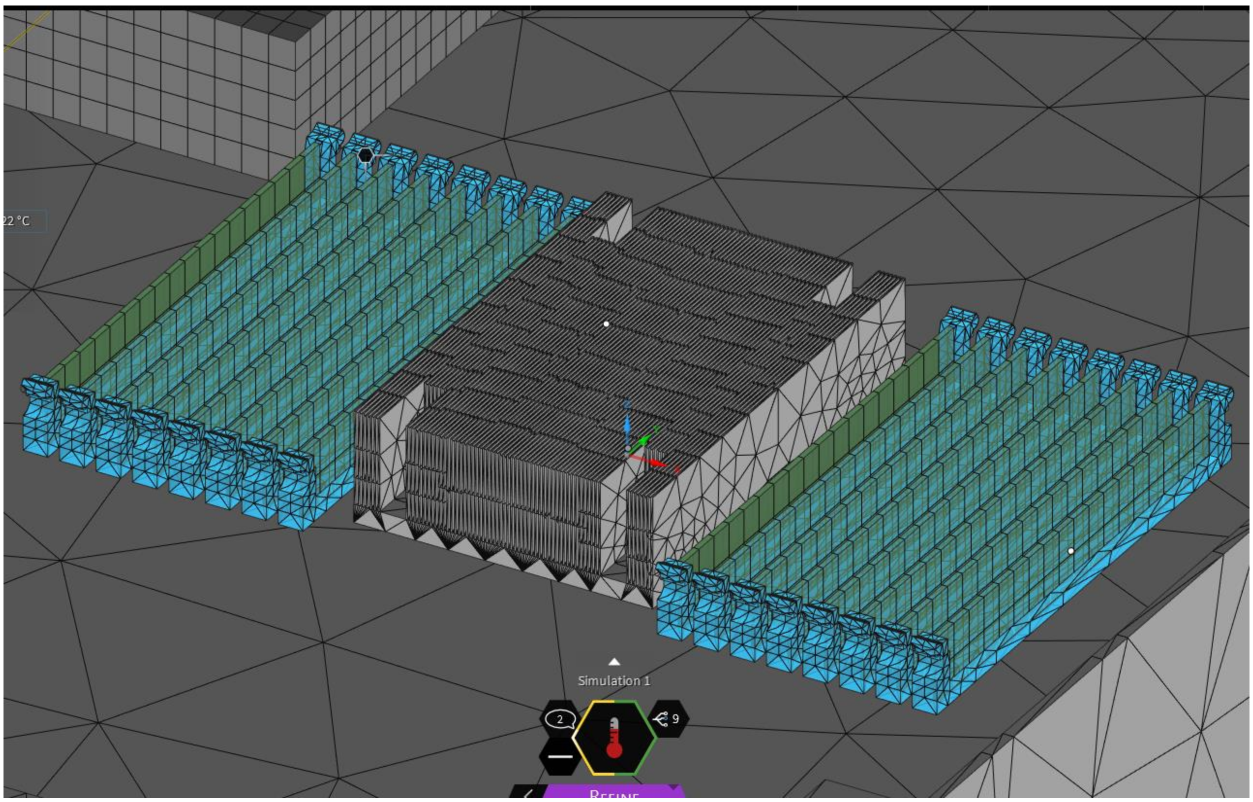


Figure 83. *Component-Specific Mesh Refinement*

9.3. Fluid Flow

To set up the fluid flow simulation, move to the "Explore" stage in the 3D modeling software and select the "Fluid Flow" physics option under the "Simulation" tab. Begin by defining the air inlets by selecting one of the previously created disks representing the fans and setting it as an inlet with a specified air velocity in meters per second (m/s) and a swirl value in revolutions per minute (rpm) to account for the rotating motion of the air.

Figure 84. *Identification of entry boundary conditions*

Next, specify the air outlets by clicking on the x-axis in the bottom left corner to view the model from the side, then click and drag a box to select all the end faces of the outlets in a single operation. Set the boundary condition type for the selected faces as "Outlet".

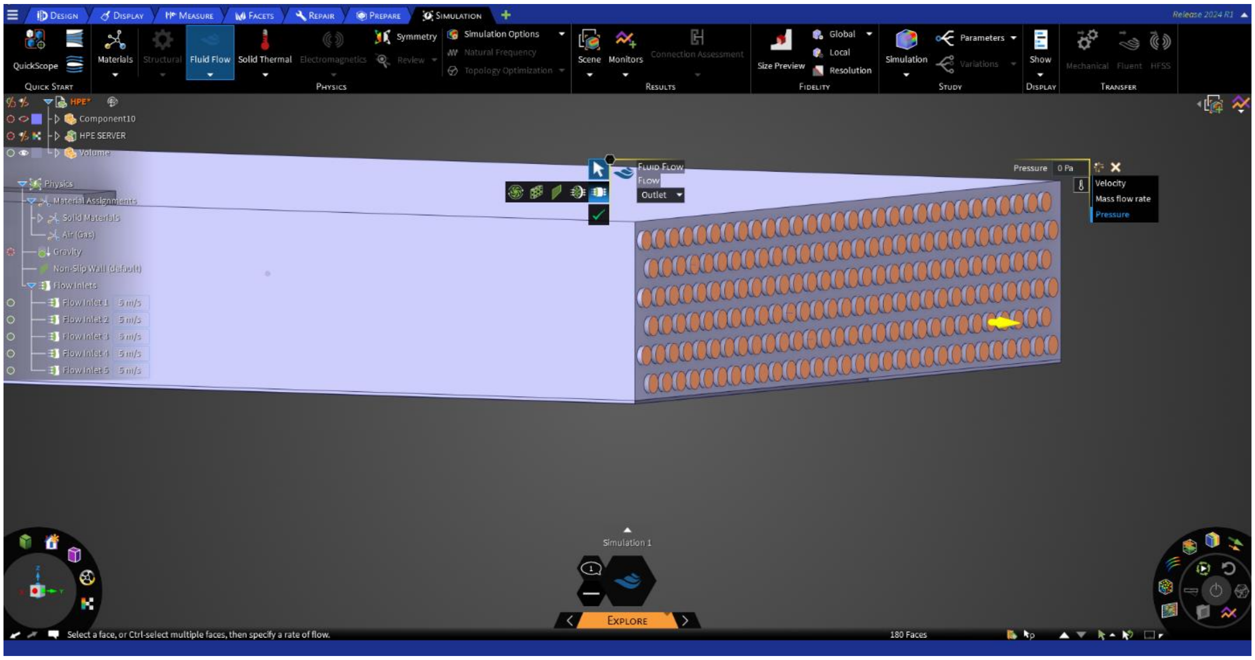
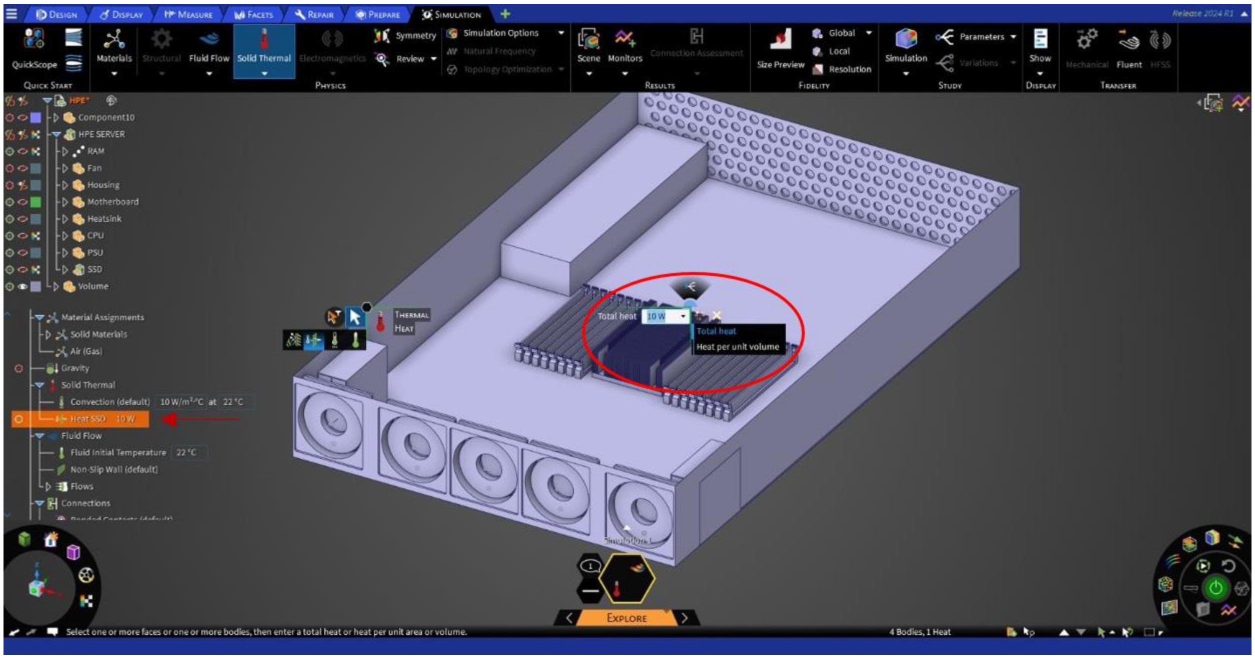


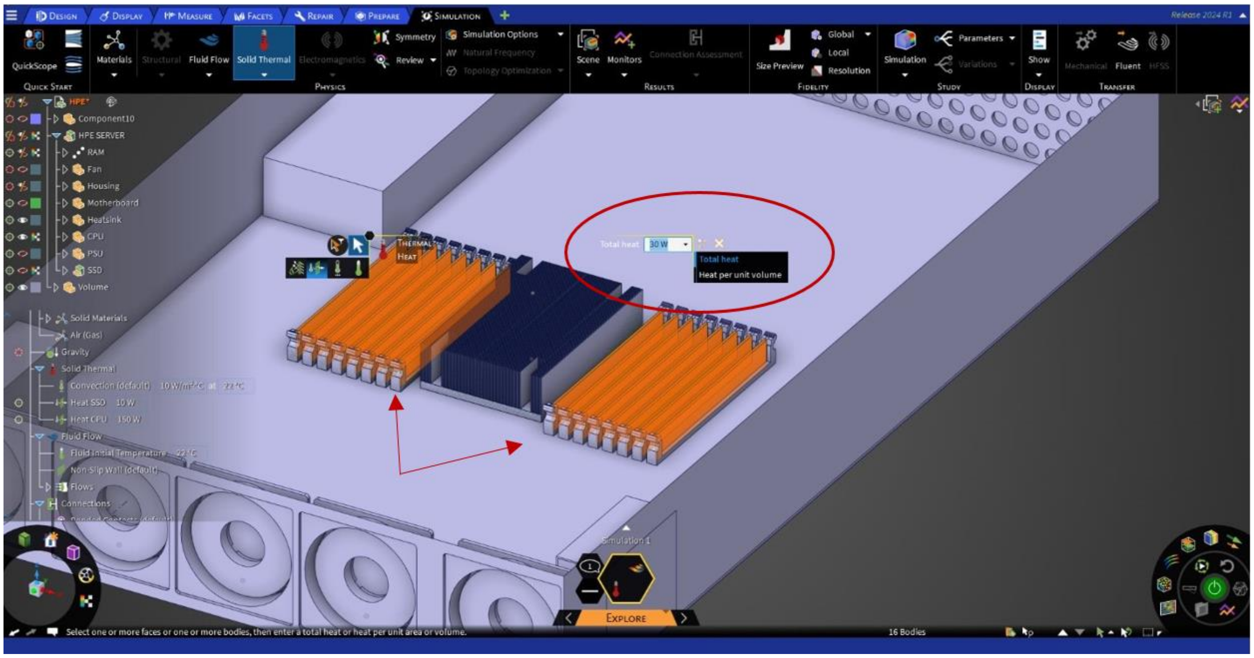
Figure 85. *Identification of exit boundary conditions*

Change the fluid material to "Air" to ensure the simulation uses the appropriate fluid properties. All boundaries not explicitly selected as inlets or outlets are automatically set as solid walls, preventing fluid from crossing them.

9.4. Solid Thermal

To initiate a conjugate heat transfer analysis, which accounts for heat transfer between solids and the surrounding air, click on "Solid Thermal" in the simulation toolbar. Select the relevant component bodies, such as the PSU, CPU, RAM, and SSD, by either dragging a box around them or manually selecting each one.

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Measure
Facets
Repair
Prepare
Simulation
Release 2024 R1
QuickScope
Materials
Structural
Fluid Flow
Solid Thermal
Electromagnetics
Symmetry
Review
Simulation Options
Natural Frequency
Topology Optimization
Scene
Monitors
Connection Assessment
Size Preview
Global
Local
Resolution
Simulation
Parameters
Variations
Show
Mechanical
Fluent
HFSS
Quick Start
Physics
Results
Fidelity
Study
Display
Transfer
HPE*
Component10
HPE SERVER
RAM
Fan
Housing
Motherboard
Heatsink
CPU
PSU
SSD
Volume
Solid Materials
Air (Gas)
Gravity
Solid Thermal
Convection (default) 10 W/m²°C at 22°C
Heat SSD 10 W
Heat CPU 150 W
Fluid Flow
Fluid Initial Temperature 22°C
Non-Slip Wall (default)
Flows
Connections
Thermal
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Total heat 30 W
Total heat
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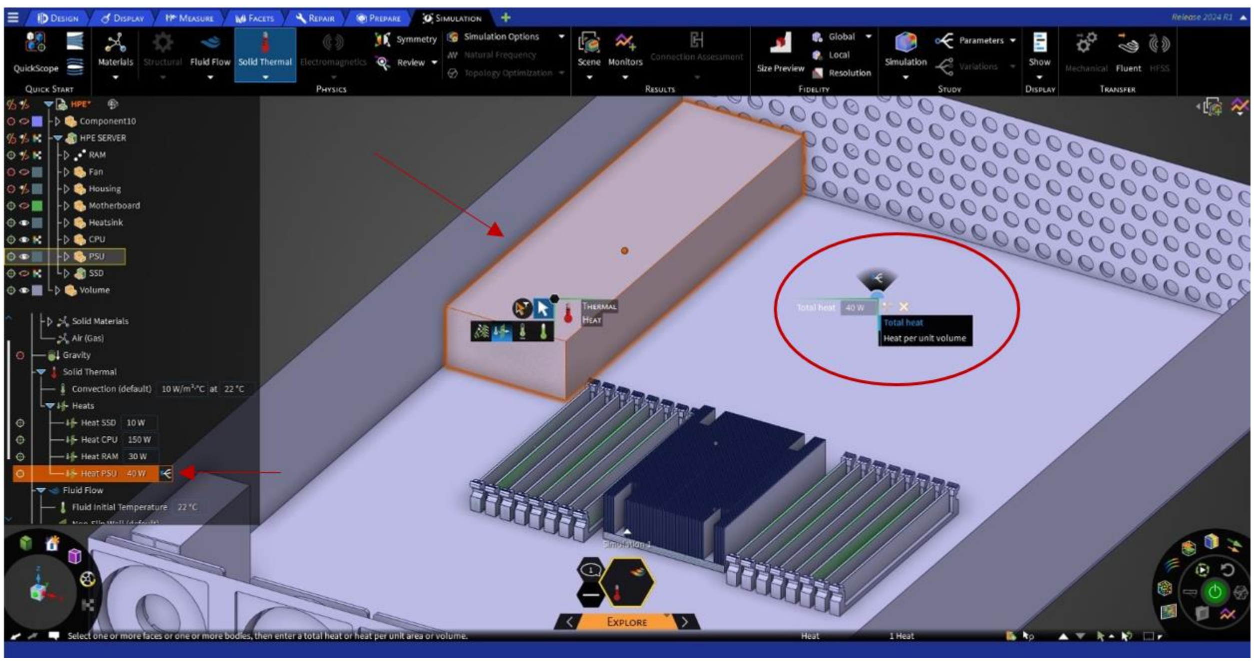
Explore
Select one or more faces or one or more bodies, then enter a total heat or heat per unit area or volume.
16 Bodies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Motherboard
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Convection (default) 10 W/m²°C at 22°C
Heats
Heat SSD 10 W
Heat CPU 150 W
Heat RAM 30 W
Heat PSU 40 W
Fluid Flow
Fluid Initial Temperature 22°C
Thermal
Heat
Total heat 40 W
Total heat
Heat per unit volume
Explore
Select one or more faces or one or more bodies, then enter a total heat or heat per unit area or volume.
Heat
1 Heat

10. Simulation Operating Scenarios

Having established the simulation framework through detailed geometric modeling, material assignments, mesh optimization, and boundary condition specifications, we now proceed to analyze the thermal and fluid dynamic behavior of the server system under various operating conditions. The simulation results are organized into distinct scenarios that represent different operational states commonly encountered in data center environments.

We begin with the baseline scenario, which establishes reference conditions for normal server operation. This scenario serves as a foundation for comparing subsequent configurations and understanding the impact of parameter variations on cooling performance. The analysis encompasses temperature distributions, velocity fields, pressure gradients, and heat transfer characteristics, providing comprehensive insights into the server's thermal behavior.

10.1. Baseline Scenario

In this baseline scenario, we aim to establish the standard operating conditions for the server by considering the key physics principles involved in its thermal management. Heat generation occurs within each component based on its power consumption, with the generated heat then propagating through the system via conduction and convection. Conduction allows heat to travel through solid materials such as heatsinks, PCBs, and thermal interfaces, facilitating the transfer of thermal energy from the heat-generating components to the surrounding environment. Simultaneously, convection enables air to absorb heat from the surfaces it contacts, with the heated air being carried away from the components. The incorporation of fans enhances this convective heat transfer by actively driving airflow through the system. As the server operates, it gradually reaches a steady-state thermal equilibrium, where the heat generation from the components is balanced by the heat dissipation through the various thermal management mechanisms in place. This equilibrium temperature represents the standard operating conditions of the server under the given circumstances.

Table 1. *Baseline Scenario Operating Parameters*

Scenario	Convection [°C]	Component	Heat [W]	Fan Velocity [m/s]	Swirl [rpm]	Temperature (Inlet) [°C]	Temperature (Outlet) [°C]
Baseline	22	CPU	150	5	330	22	23.25
		SSD	10				
		RAM	30				
		PSU	40				

The figures presented in this section display the thermal and fluid dynamic behavior of the 1U rack server under the baseline-operating scenario, as simulated using Ansys Discovery. These visuals provide valuable insights into temperature distributions, airflow patterns, pressure gradients, and other key performance metrics for the server cooling system.

It is important to note that while the images depict the results for the baseline scenario, the same principles and analytical approaches apply to all other operating scenarios explored in this study, such as the energy-saving, peak load, stress test, hotspot analysis, and parametric configurations. The primary difference lies in the specific values of the input parameters, such as ambient temperature, fan speed, and component heat generation, which are adjusted to represent the unique conditions of each scenario.

In Ansys Discovery, when conducting parametric simulations, the results for each configuration are displayed in a separate window, allowing for a focused analysis of the system's behavior under those particular conditions. As the user switches between different scenarios, the virtual model and its associated visualizations dynamically update to reflect the corresponding changes in temperatures, pressures, velocities, and other relevant quantities.

Although the figures in this section focus on the baseline scenario, the insights gained from these visualizations can be extrapolated to other operating scenarios, as the fundamental physics governing the server's thermal and fluid dynamic behavior remain consistent. The variation in input parameters simply alters the magnitude and distribution of the relevant quantities, such as temperature and airflow, while the overall patterns and trends remain largely similar.

By carefully examining the simulation results across all operating scenarios and comparing them against the baseline case, one can develop a comprehensive understanding of the server's cooling system performance and identify the most promising configurations for optimizing energy efficiency and thermal management. This holistic approach ensures that the findings and recommendations derived from this study are robust, reliable, and applicable to a wide range of real-world data center environments.

Thermal and Flow Behavior Analysis

The thermal and flow behavior of the server cooling system exhibits complex interactions between heat transfer and fluid dynamics, as evidenced by the detailed simulation results. The temperature contours displayed in Figures 86-88 reveal the three-dimensional temperature distribution throughout the server chassis. Figure 86 particularly highlights the highest temperature regions, demonstrating how heat concentrates around critical components such as the CPU and power supply unit. Figure 87's inner temperature contours show how the temperature gradually increases along the airflow path from inlet to outlet, indicating effective heat absorption by the cooling medium.

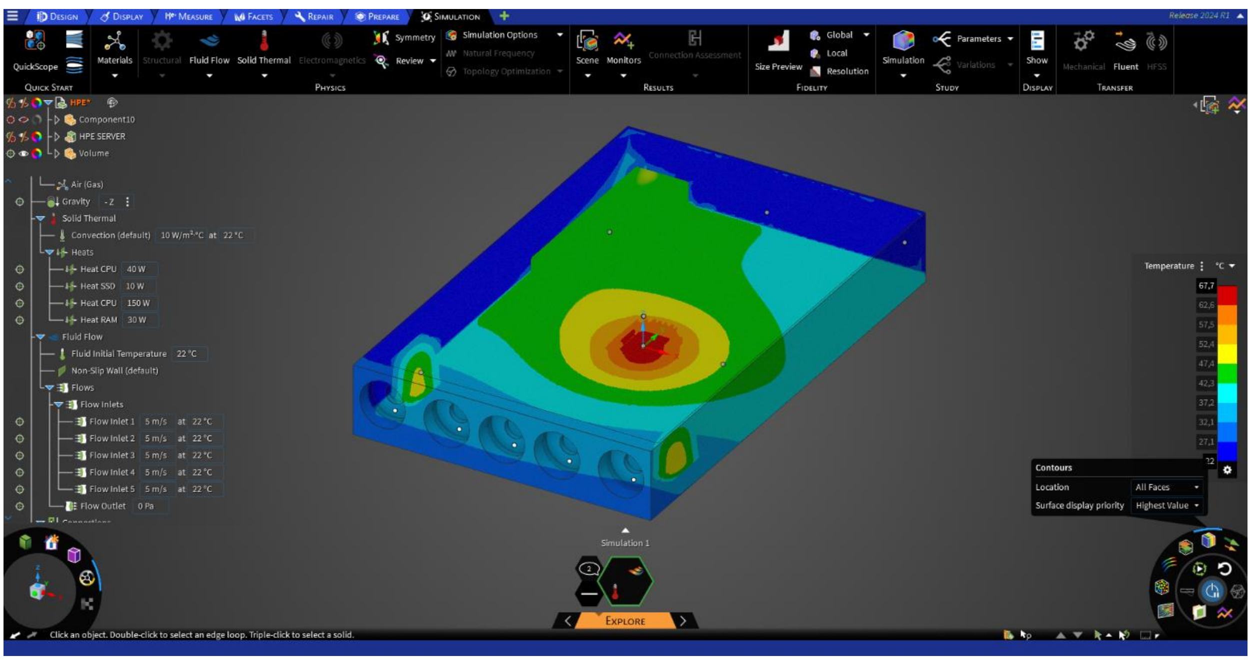


Figure 86. *Temperature Contours (All Faces, Highest Value)*

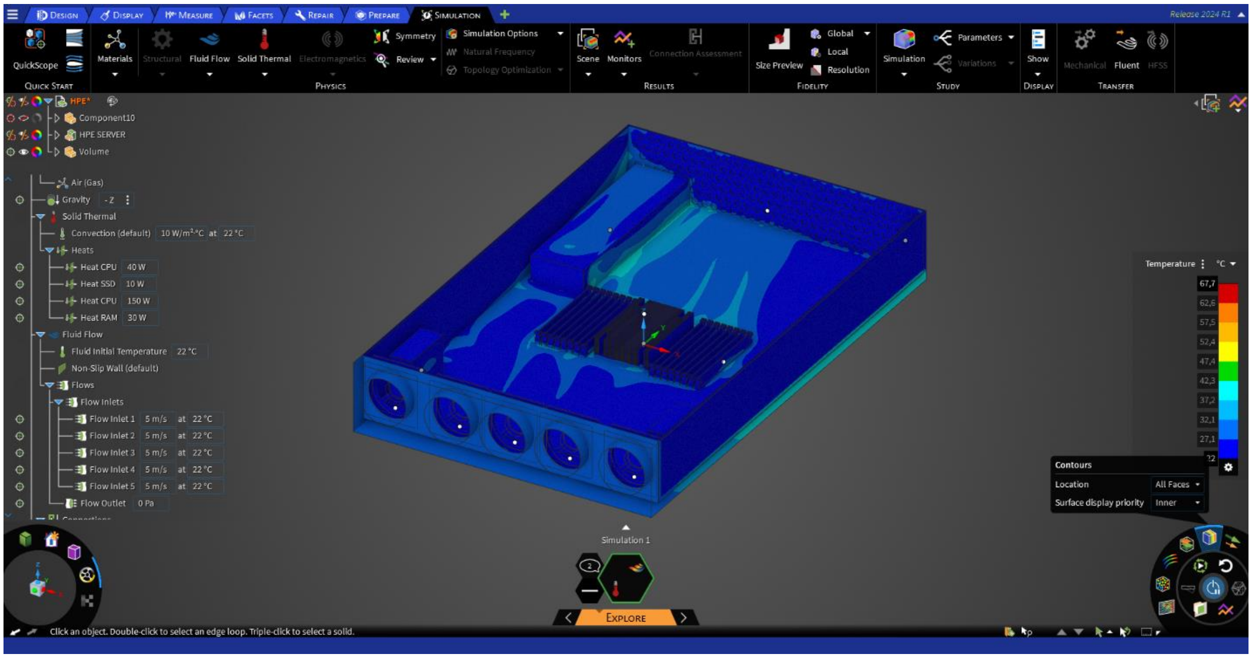


Figure 87. *Temperature Contours (All Faces, Inner)*

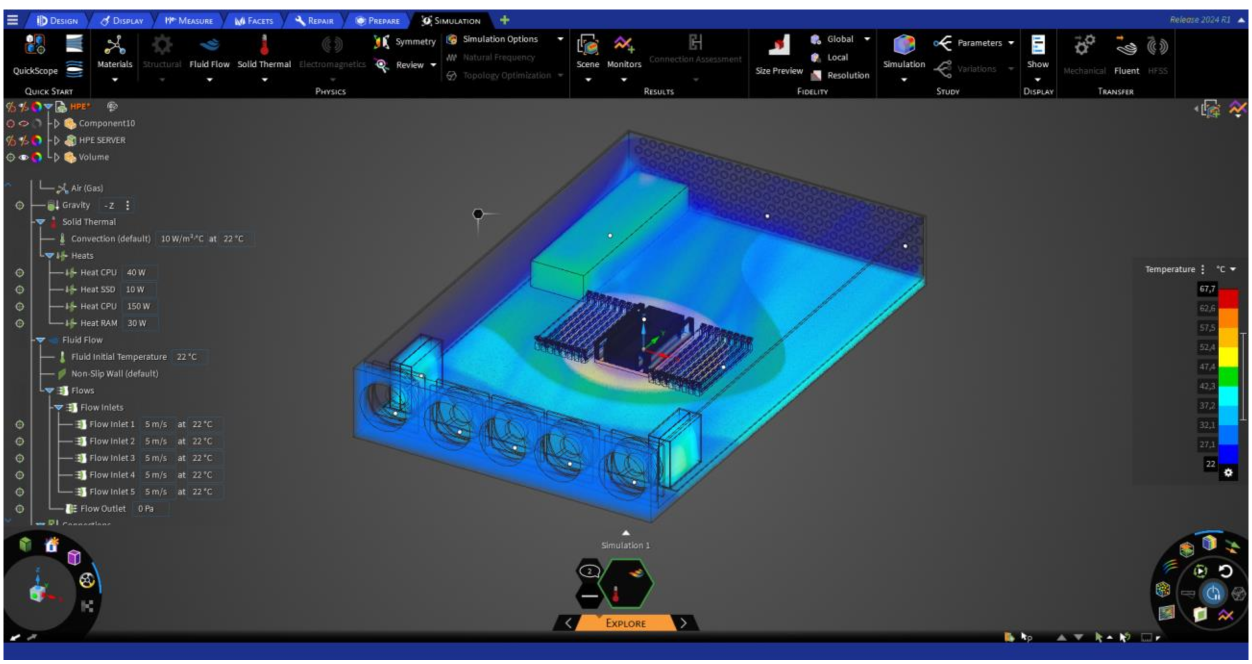


Figure 88. *Temperature Contours (All Bodies), Temperature distribution*

The velocity characteristics, illustrated in Figures 89-91, provide crucial insights into the airflow patterns within the server. Figure 89 shows the inner velocity contours, revealing how the air accelerates through narrower passages between components, creating regions of higher velocity that enhance local heat transfer coefficients. The velocity streamlines visualized in Figure 92 are particularly informative, demonstrating the complex three-dimensional flow paths as air navigates around various server components. These streamlines also highlight potential areas of recirculation and stagnation that could influence cooling effectiveness.

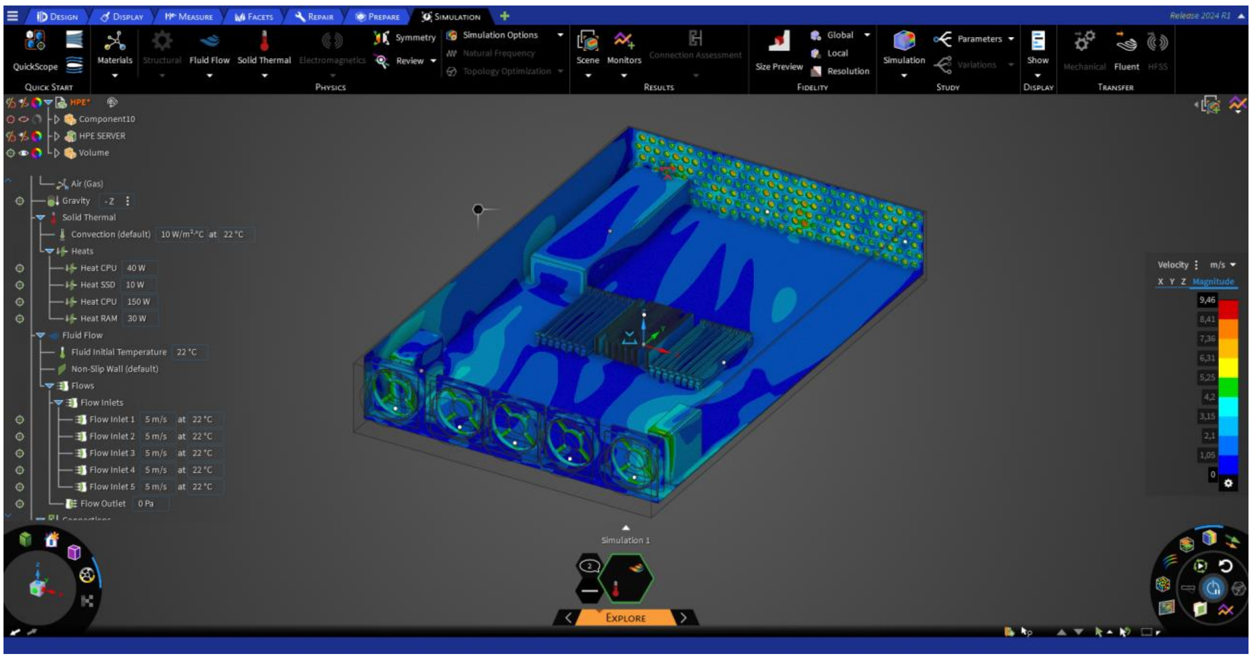


Figure 89. *Velocity Contours (All Faces, Inner)*

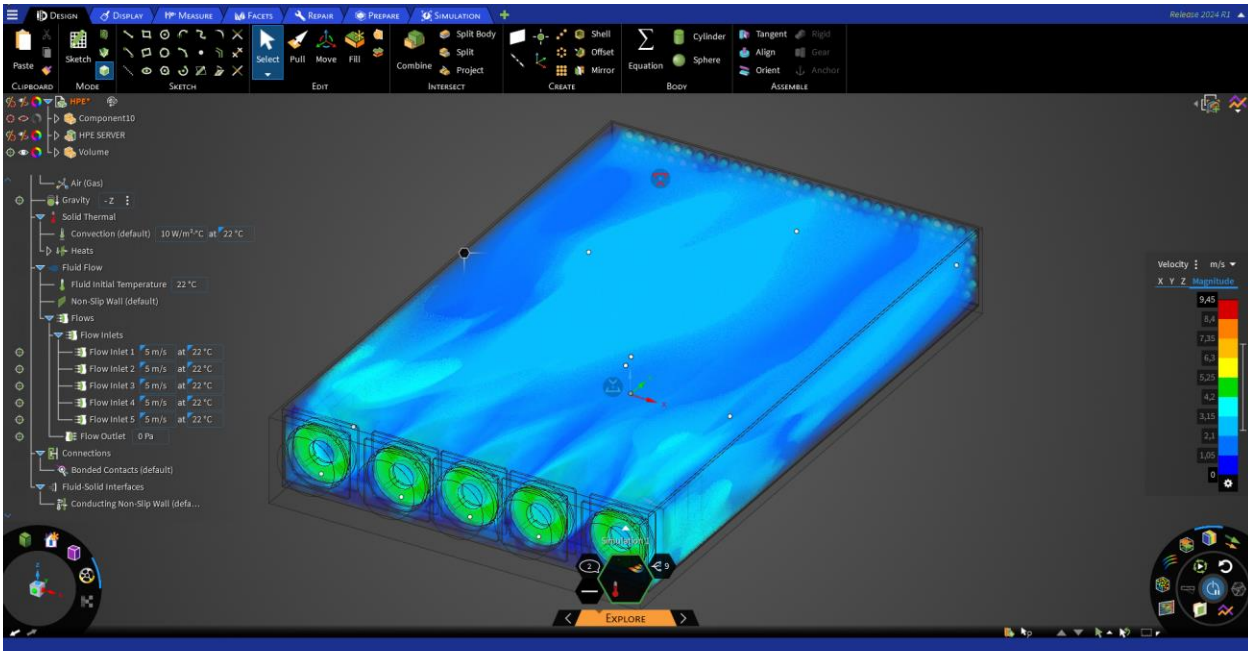


Figure 90. *Velocity Contours (All Bodies)*

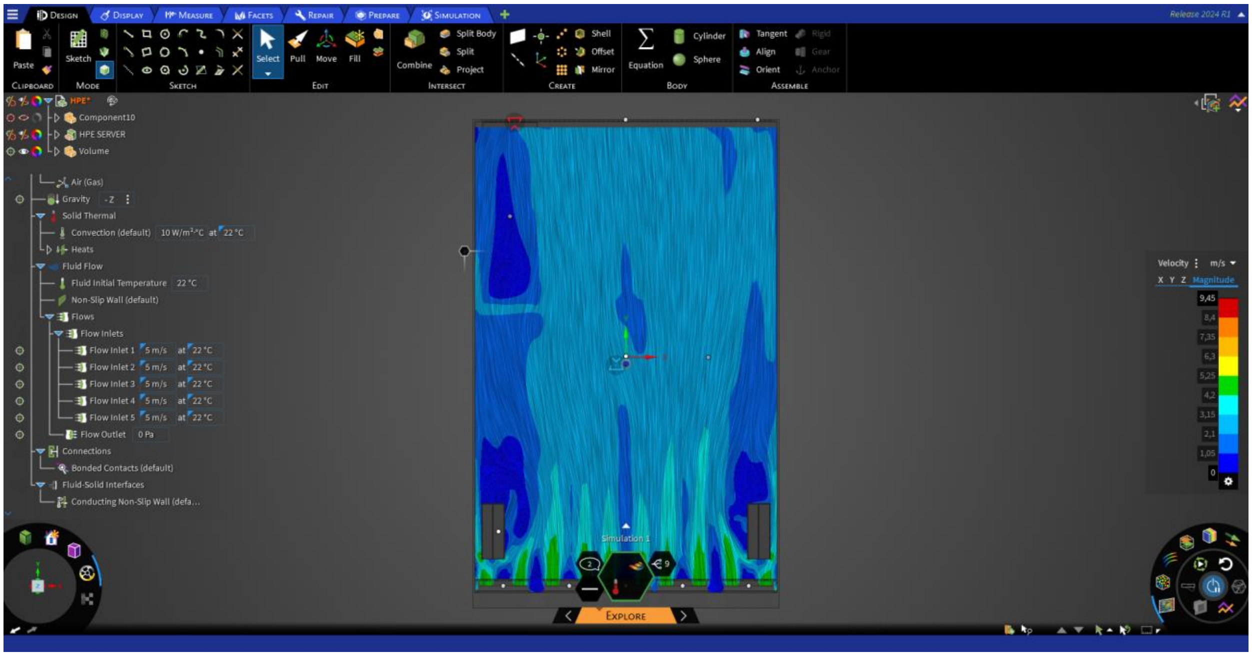


Figure 91. *Velocity Direction Field*

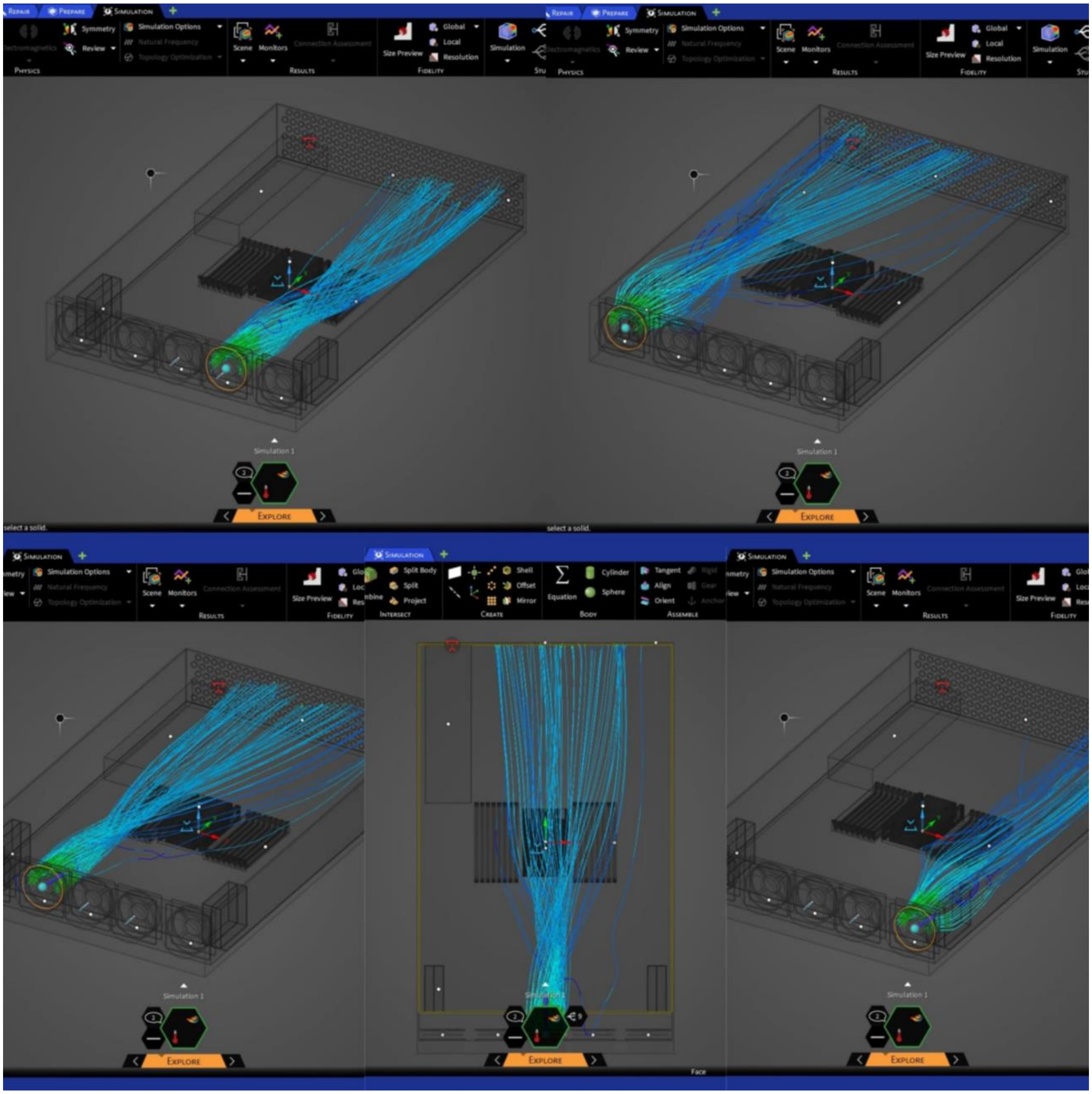


Figure 92. *Velocity Streamlines, Visualization of flow lines within the server*

Pressure distribution, depicted in Figures 93-96, reveals the complex pressure dynamics within the server. The static pressure contours (Figures 93-94) indicate concentrated regions of high pressure near the fan inlets, with distinct pressure zones formed around the cooling components. The total pressure distributions (Figures 95-96), which account for both static and dynamic pressure components, further illustrate these pressure variations and their relationship to the server's airflow patterns. This pressure behavior suggests that the server's cooling design effectively creates targeted flow patterns to address specific cooling needs, rather than relying on a simple front-to-back pressure gradient.

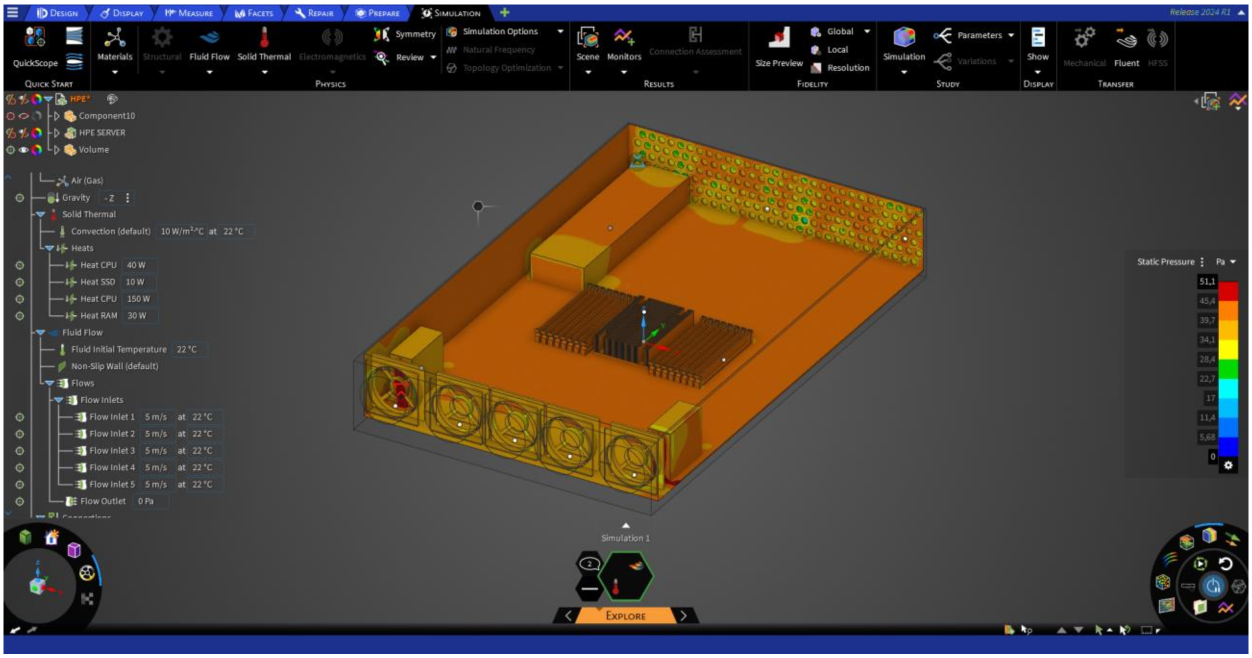


Figure 93. *Static Pressure Contours (Inner)*

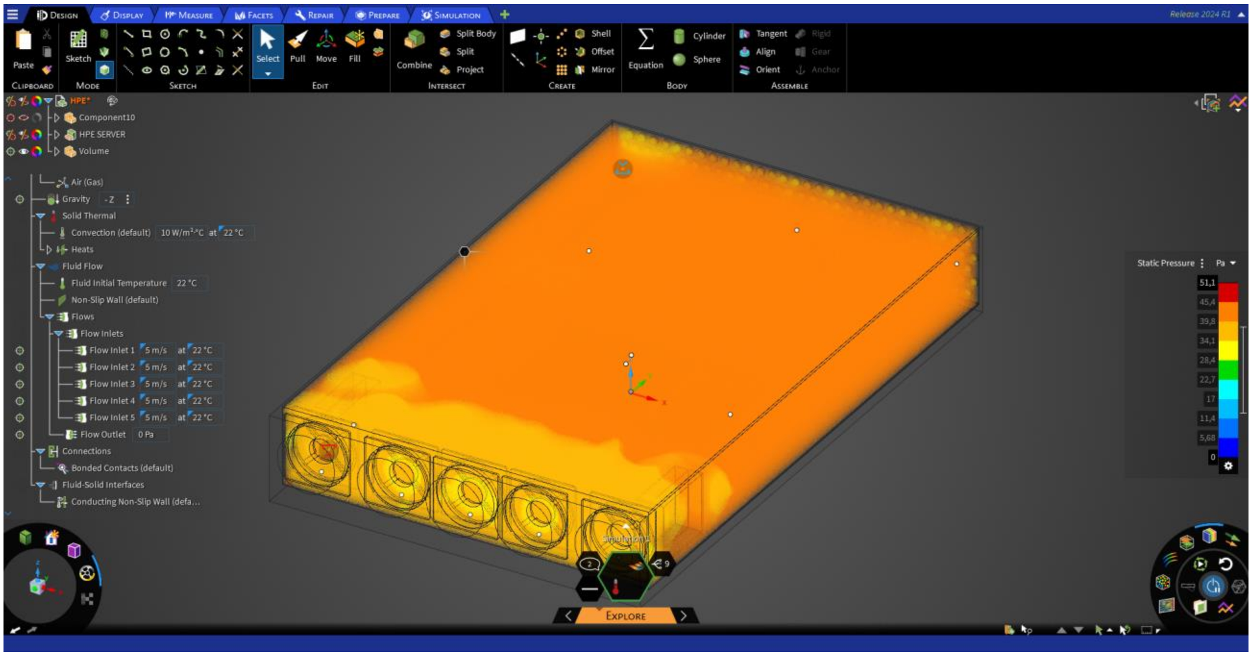


Figure 94. *Static Pressure Contours (All Faces, Highest Value)*

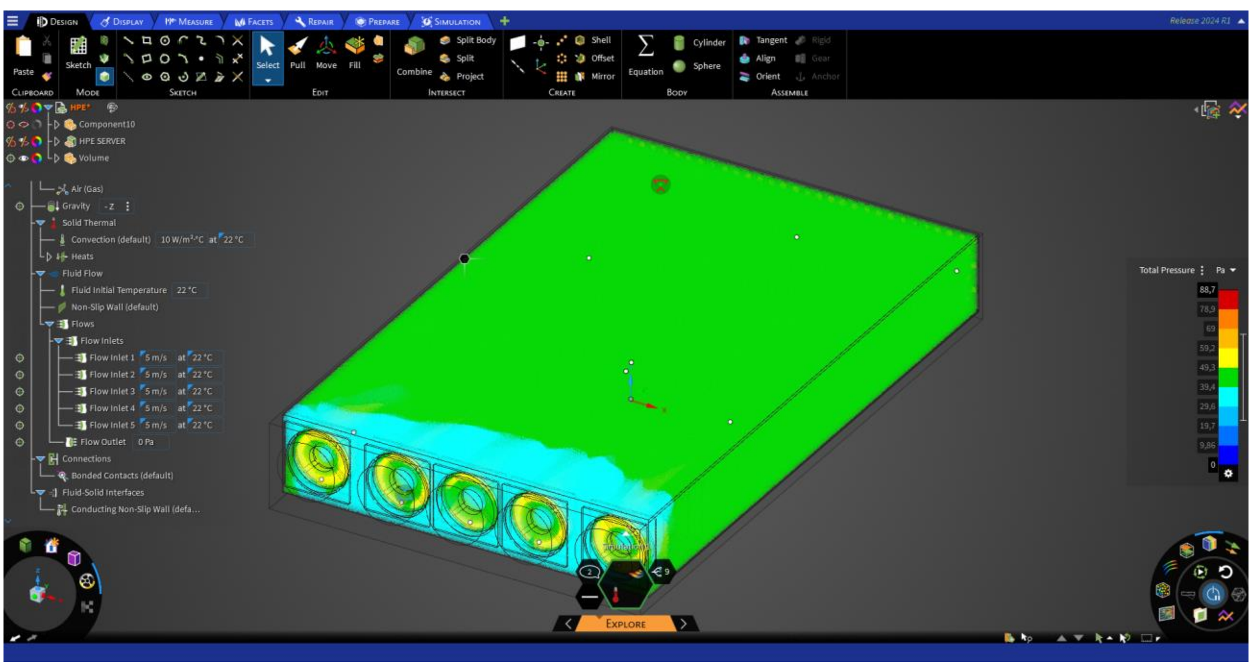


Figure 95. *Total Pressure (All Faces, Highest Value)*

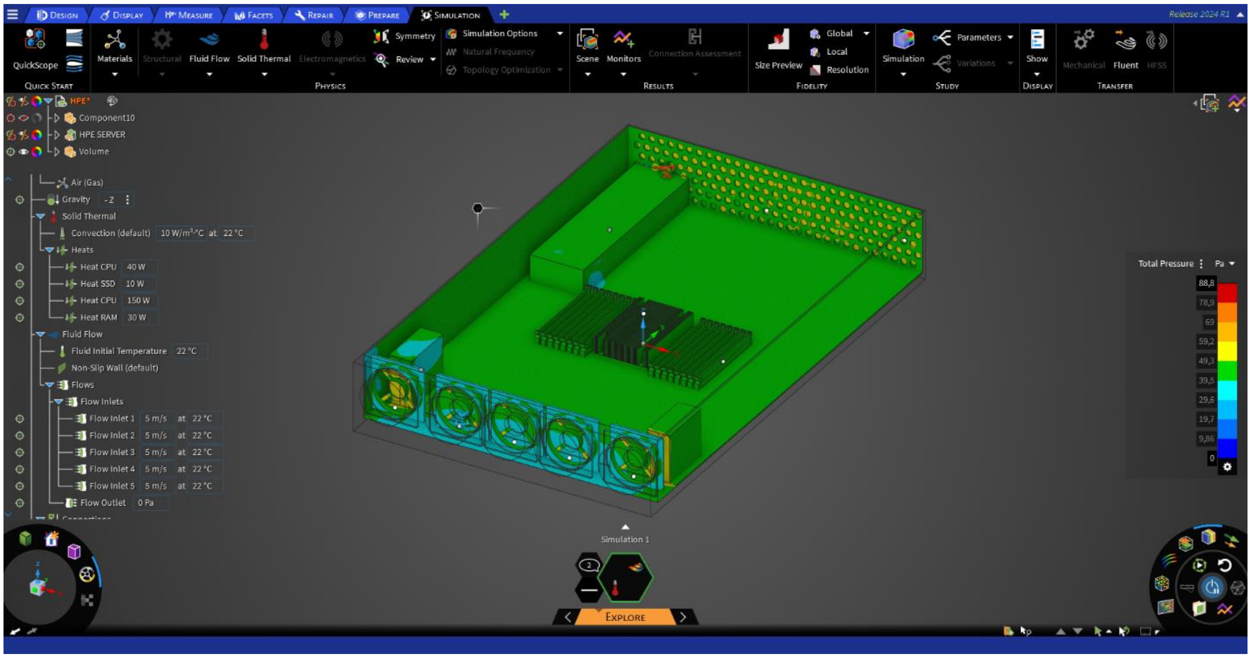


Figure 96. *Total Pressure (All Faces, Inner)*

The heat flux contours presented in Figure 97 are particularly significant as they directly show the rates of heat transfer across component surfaces. These contours identify the most active regions of heat exchange between the solid components and the cooling air, helping to validate the effectiveness of the cooling strategy.

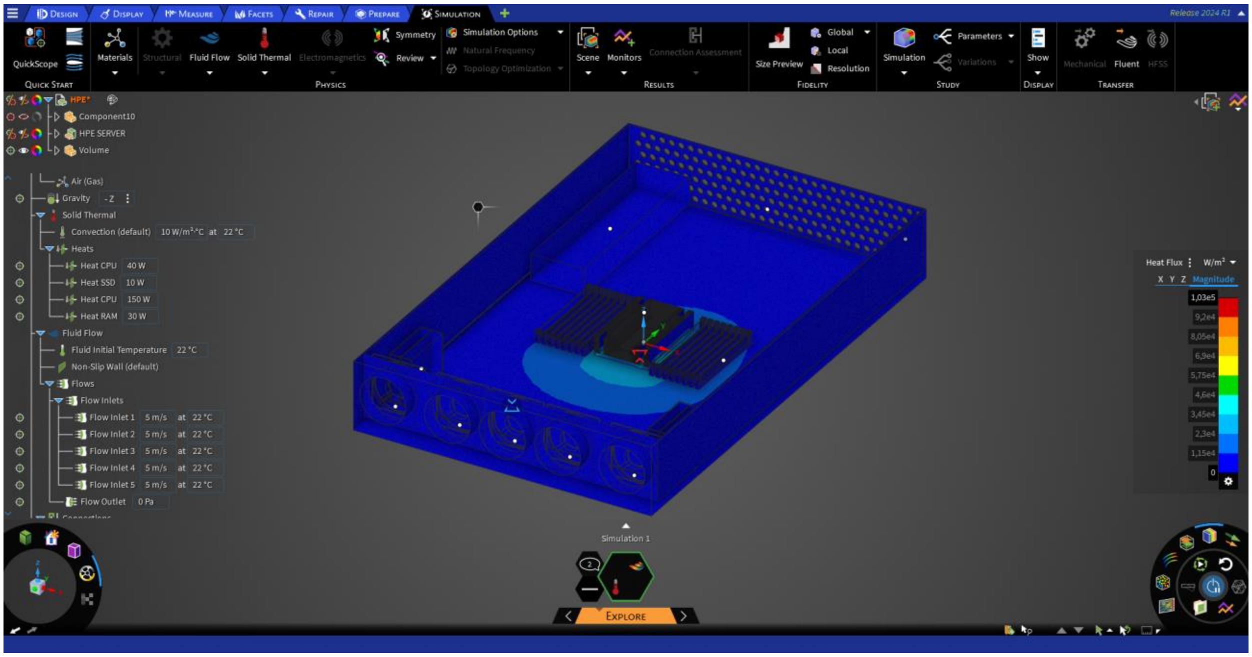
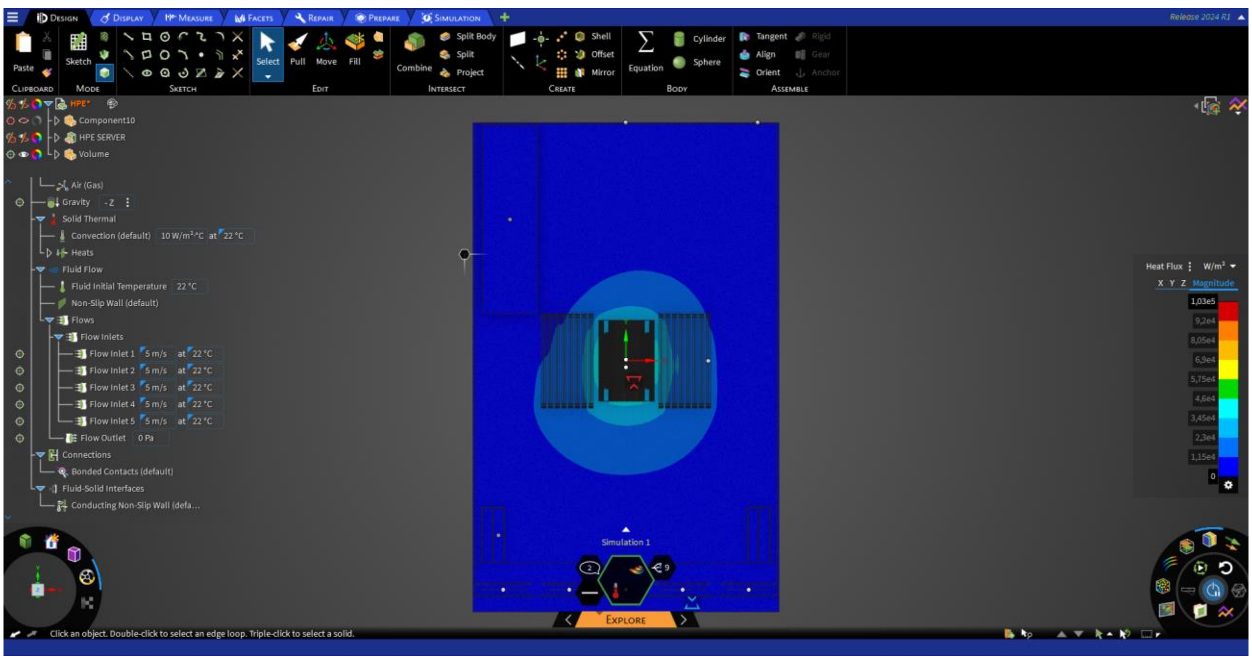


Figure 97. *Heat Flux Contours (All Faces, Inner)*



The Lambda 2 criterion, a widely used method for identifying vortical structures in fluid flows, provides insights into the turbulent characteristics of the airflow within the server. This method identifies regions where rotation dominates strain in the flow field, effectively highlighting coherent vortex cores. Understanding these vortical structures is crucial as they significantly influence heat transfer and mixing efficiency within the server.

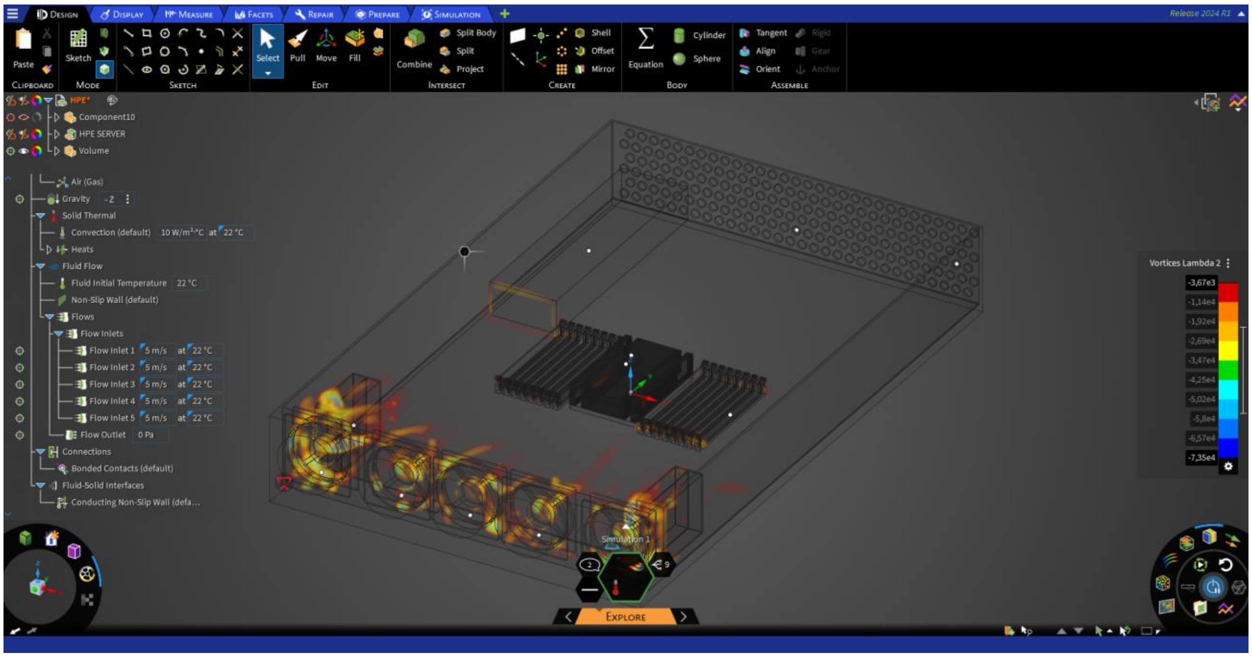


Figure 98. *Vortices Lambda 2 (All Faces, Highest Value)*

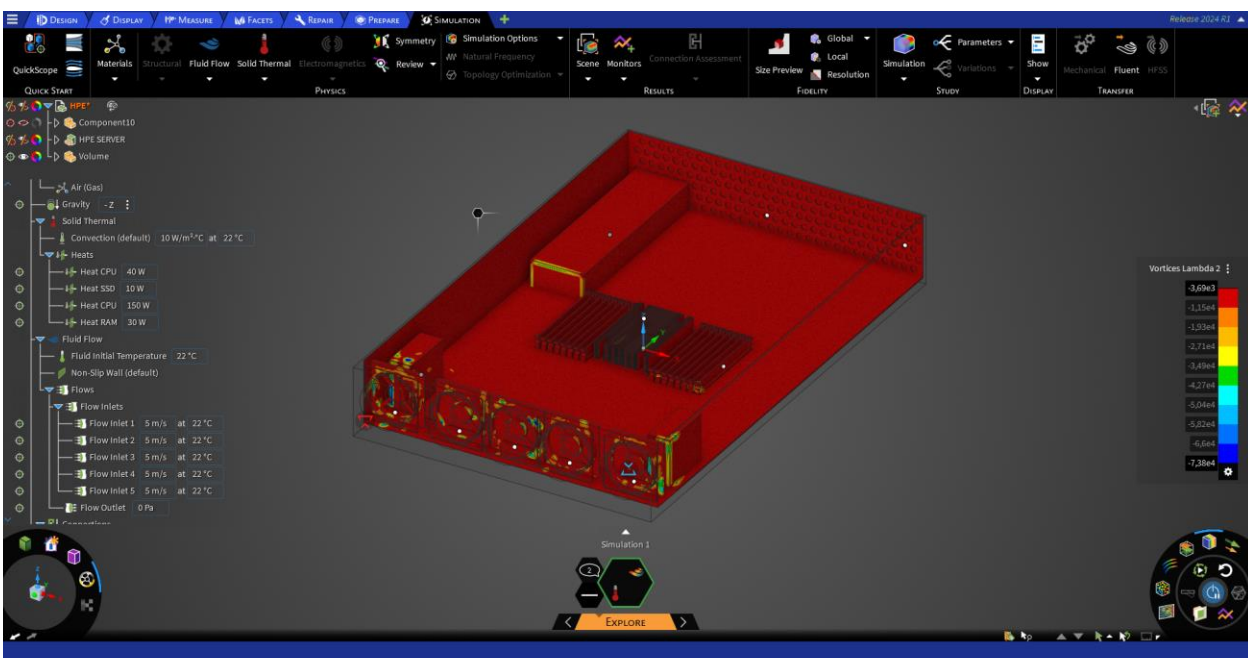


Figure 99. *Vortices Lambda 2 (All Faces, Inner)*

10.2. Energy Saving Scenario

In the energy-saving scenario, we evaluate the server's cooling performance under reduced loads and optimized energy use. Lower CPU and component loads lead to reduced heat generation, which in turn affects the cooling requirements. However, to achieve energy savings, fan speeds are reduced, resulting in lower convection efficiency and a decreased rate of heat dissipation via air. This reduction in fan velocities may cause a larger temperature gradient between the components and the cooling airflow. Consequently, a trade-off analysis becomes necessary to balance fan power consumption and cooling effectiveness. By carefully assessing this balance, we can determine the optimal operating point that minimizes energy consumption while ensuring the components remain within safe temperature ranges.

Table 2. *Energy Saving Scenario Operating Parameters*

`	Convection [°C]	Component	Heat [W]	Fan Velocity [m/s]	Swirl [rpm]	Temperature (Inlet) [°C]	Temperature (Outlet) [°C]
Energy-Saving	25	CPU	100	3	330	25	26.39
	27	SSD	8	4		27	28.04
		RAM	15				
		PSU	25				

Table 3. *Energy Saving Simulation Results*

Convection [°C]	Flow Inlet 1-5 Velocity [m/s]	Flow Inlet 1-5 Temperature [°C]	Max Velocity [m/s]	Pressure Drop [Pa]	Max. Temperature [°C]
25	3	25	4.69	15.1	45.2
25	4	25	5.52	18.2	43.3
27	3	27	4.69	15.1	47.1
27	4	27	5.52	18.2	45.3

10.3. Peak Load Scenario

In the peak load scenario, we test the server's cooling system under the most demanding operational conditions. As the components operate at full power, they generate intense heat loads that push the thermal management system to its limits. The increased heat generation necessitates higher fan speeds to facilitate effective heat dissipation, which can lead to airflow that is more turbulent and potential swirl effects within the server chassis. Under these extreme conditions, key components such as the CPU approach their thermal thresholds, putting significant stress on the cooling system's ability to maintain safe operating temperatures. Localized hotspots may emerge in areas with insufficient airflow or inadequate thermal contact, further exacerbating the challenges faced by the cooling system. This scenario provides critical insights into the server's thermal performance and identifies potential weaknesses that could compromise reliability and longevity under sustained heavy loads.

Table 4. *Peak Load Scenario Operating Parameters*

Scenario	Convection [°C]	Component	Heat [W]	Fan Velocity [m/s]	Swirl [rpm]	Temperature (Inlet) [°C]	Temperature (Outlet) [°C]
Peak Load	22	CPU	280	5	825	22	23.67
	27	SSD	15	7		27	29.32
		RAM	60				
		PSU	50				

Table 5. *Peak Load Simulation Results*

Convection [°C]	Flow Inlet 1-5 Velocity [m/s]	Flow Inlet 1-5 Temperature [°C]	Max Velocity [m/s]	Pressure Drop [Pa]	Max. Temperature [°C]
22	5	22	7.38	21.97	64.8
22	7	22	10.3	24.52	63.2
27	5	27	7.38	21.97	70.7
27	7	27	10.3	24.52	67.7

10.4. Stress Test Scenario

In the stress test scenario, we evaluate the server's cooling system performance under extreme conditions, with a focus on the impact of high ambient temperatures on heat transfer efficiency and overall system reliability. At higher convection temperatures (e.g., 35–40°C), the efficiency of cooling is reduced due to the decreased temperature gradient between the heat-generating components and the cooling medium. Additionally, thermal interface materials and heatsinks may exhibit nonlinear thermal resistance, losing efficiency at elevated temperatures and impeding heat transfer from the components to the cooling system. The cooling fans must work harder to maintain adequate airflow, leading to increased turbulence, swirl, and potential flow recirculation within the chassis, which can create localized hotspots. Furthermore, exposure to extreme temperatures may cause minor structural deformations, altering the thermal contact resistances between components and their respective cooling solutions, further exacerbating the challenges faced by the cooling system under these adverse conditions.

Table 6. *Stress Test Scenario Operating Parameters*

Scenario	Convection [°C]	Component	Heat [W]	Fan Velocity [m/s]	Swirl [rpm]	Temperature (Inlet) [°C]	Temperature (Outlet) [°C]
Stress Test	30	CPU	280	5	1240	30	31.67
	35	SSD	15	7		35	36.67
	40	RAM	60			40	41.67
		PSU	50				

Table 7. *Stress Test Simulation Results*

Convection [°C]	Flow Inlet 1-5 Velocity [m/s]	Flow Inlet 1-5 Temperature [°C]	Max Velocity [m/s]	Pressure Drop [Pa]	Max. Temperature [°C]
30	5	30	7.38	21.96	75
30	7	30	10.3	24.52	72
35	5	35	7.38	21.96	80
35	7	35	10.3	24.52	77
40	5	40	7.38	21.96	85
40	7	40	10.3	24.52	82

10.5. Hotspot Scenario

In the hotspot analysis scenario, we identify areas of high thermal stress within the server system to pinpoint potential issues and optimize cooling performance. This analysis focuses on several key physics principles that contribute to the formation of hotspots. Firstly, localized heat generation occurs when specific components, such as CPUs, VRMs, or certain RAM modules, generate more heat than the surrounding parts. This uneven heat distribution can lead to concentrated areas of high temperature. Secondly, non-uniform convection arises when airflow is inconsistent throughout the system, particularly in regions shielded by heatsinks or other obstacles. This uneven airflow can result in hotspots where heat accumulates due to insufficient cooling. Thirdly, thermal conductivity limitations of materials like PCBs can trap heat, preventing efficient dissipation and exacerbating hotspot formation. Finally, poorly designed airflow can create vortices and stagnation zones, where air remains stationary and fails to effectively remove heat from critical components. By analyzing these factors and identifying hotspots, we can optimize the cooling system design to ensure more uniform heat dissipation and prevent thermal stress on vulnerable components.

Table 8. *Hotspot Scenario Operating Parameters*

Scenario	Convection [°C]	Component	Heat [W]	Fan Velocity [m/s]	Swirl [rpm]	Temperature (Inlet) [°C]	Temperature (Outlet) [°C]
Hotspot Analysis	22	CPU	280	5	825	22	23.67
	27	SSD	40			27	29.32
		RAM	30				
		PSU	130				

Table 9. *Hotspot Analysis Simulation Results*

Convection [°C]	Flow Inlet 1-5 Velocity [m/s]	Flow Inlet 1-5 Temperature [°C]	Max Velocity [m/s]	Pressure Drop [Pa]	Max. Temperature [°C]
22	5	22	7.38	21.97	70
27	5	27	7.53	21.97	75

10.6. Parametric Scenario

In the parametric sweep scenario, we explore the impact of varying key parameters on the server's cooling performance, providing valuable insights into the system's sensitivity to design factors. By systematically altering parameters such as fan velocity, inlet air temperature, and CPU loads, we can analyze the resulting changes in flow characteristics, convection coefficients, and thermal gradients.

Different fan velocities and swirl patterns influence the laminar-to-turbulent transition in the airflow, directly affecting the effectiveness of heat dissipation. Higher air velocities generally improve heat transfer by increasing the convection coefficient, but this comes at the cost of increased pressure drop and fan power consumption. Careful optimization is necessary to find the ideal balance between cooling performance and energy efficiency.

Variations in inlet air temperature have a direct impact on the temperature difference that drives heat transfer. Cooler inlet temperatures enhance the cooling system's ability to remove heat from components, while warmer temperatures reduce the available thermal gradient and make cooling more challenging.

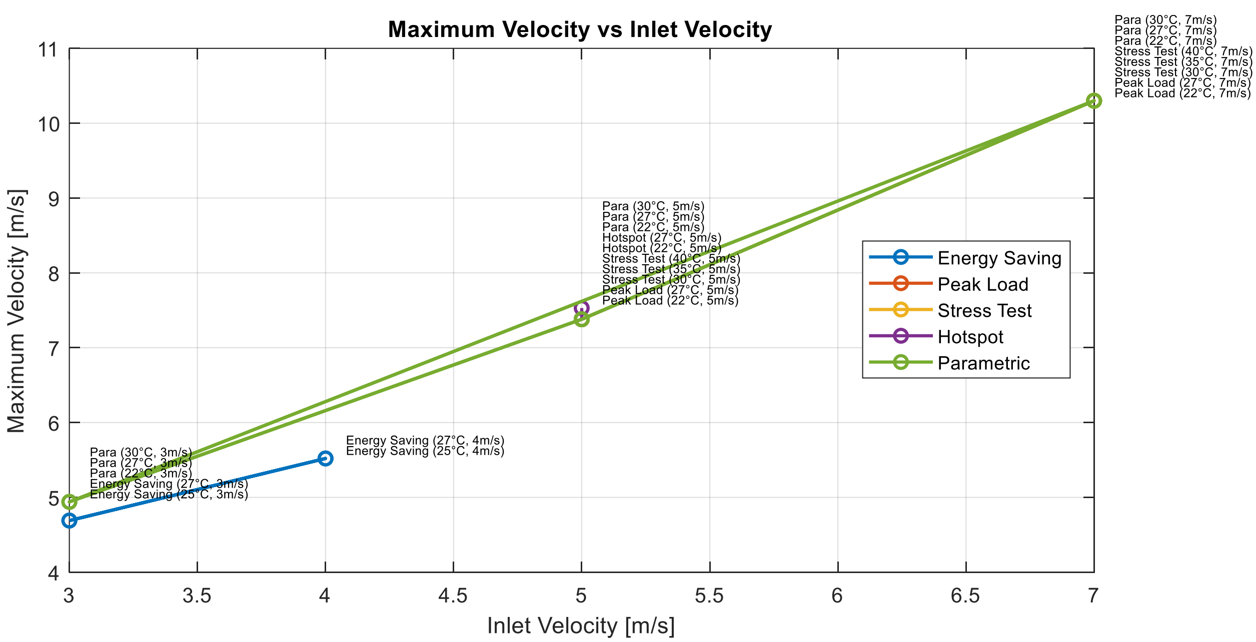
Through sensitivity analysis, we quantify the impact of each parameter on the overall system performance. This analysis highlights the most critical design factors, enabling informed decisions about the allocation of resources and optimization efforts. By understanding the relative importance of fan velocity, inlet temperature, and component loads, we can prioritize design improvements and develop robust cooling solutions that maintain optimal performance across a wide range of operating conditions.

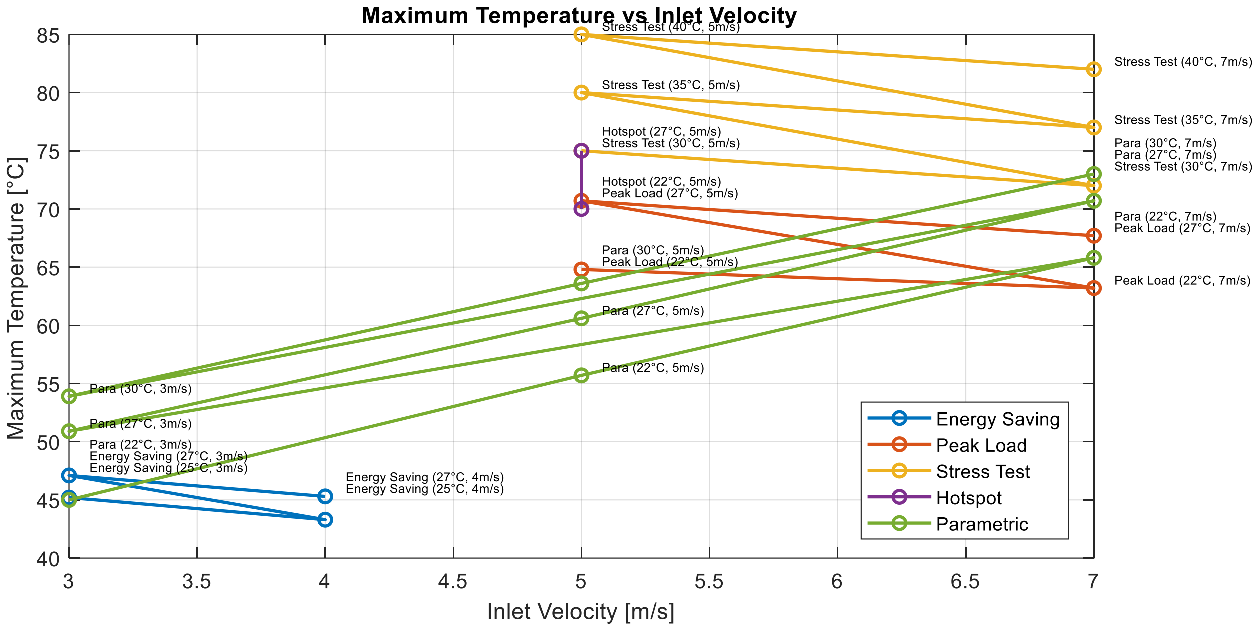
Table 10. *Parametric Scenario Operating Parameters*

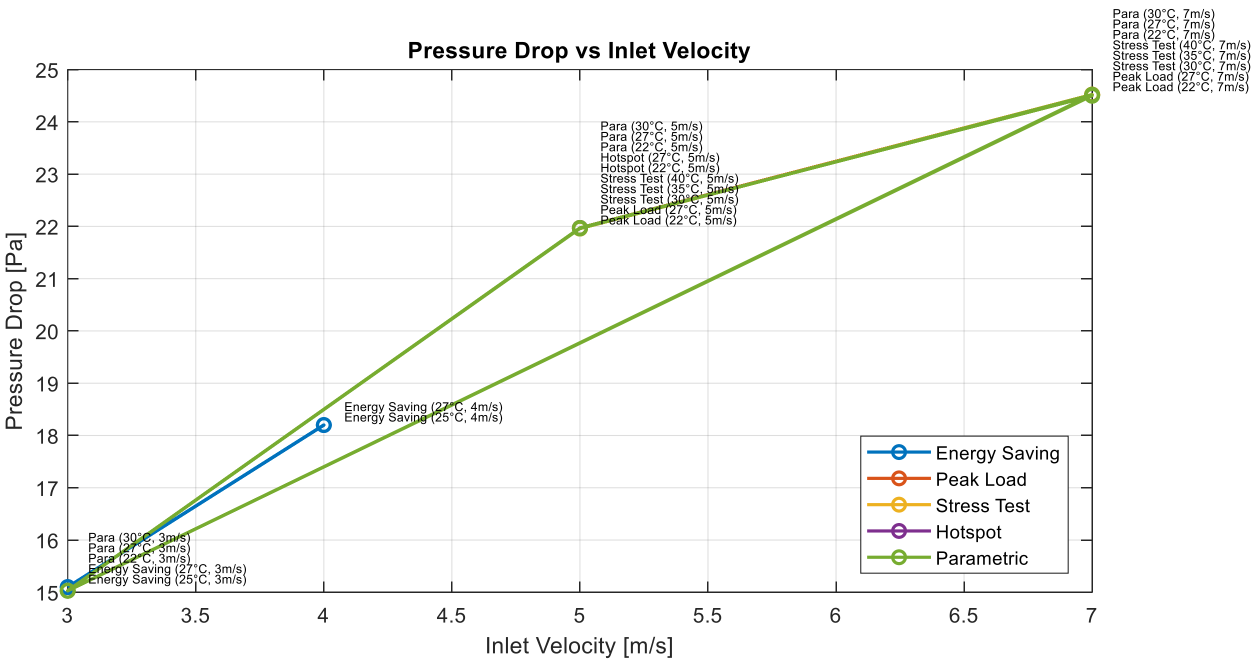
Scenario	Convection [°C]	Component	Heat [W]			Fan Velocity [m/s]	Swirl [rpm]	Temperature (Inlet) [°C]	Temperature (Outlet) [°C]
Parametric	22	CPU	100	150	280	3	330	22	23.67
	27	SSD	40			5		27	29.07
	30	RAM	30			7		30	31.67
		PSU	130						

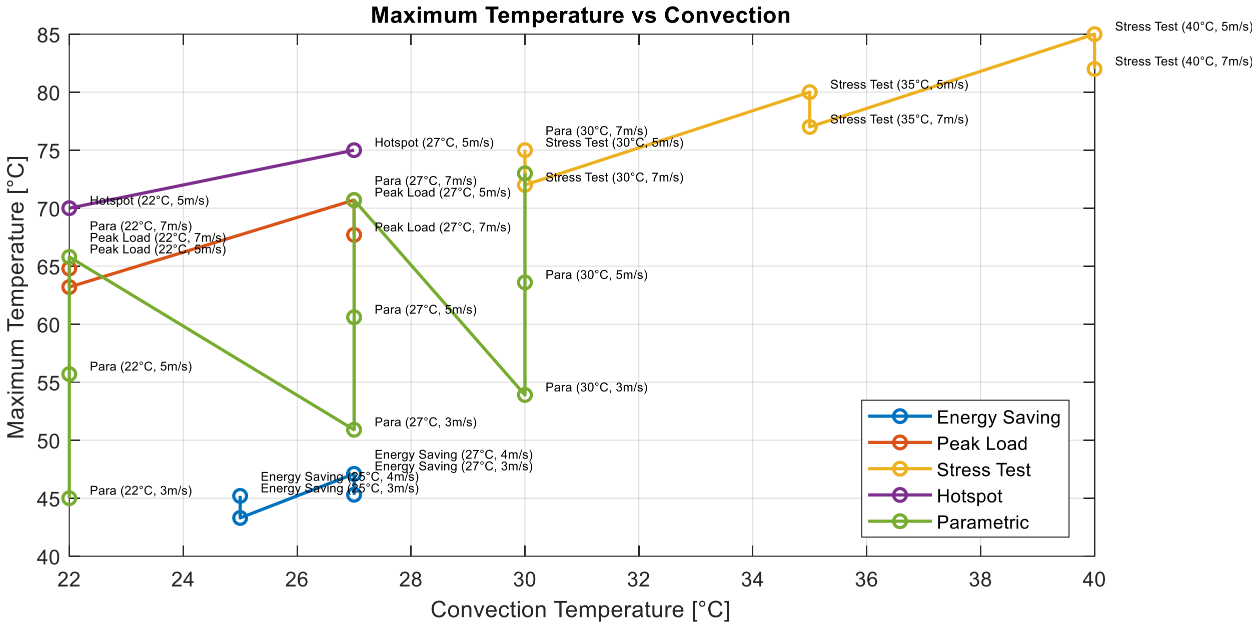
Table 11. *Parametric Scenario Simulation Results*

Convection [°C]	Flow Inlet 1-5 Velocity [m/s]	Flow Inlet 1-5 Temperature [°C]	Heat CPU [W]	Max Velocity [m/s]	Pressure Drop [Pa]	Max. Temperature [°C]
22	3	22	100	4.94	15.03	45
22	5	22	150	7.38	21.97	55.7
22	7	22	280	10.3	24.5	65.8
27	3	27	100	4.94	15.03	50.9
27	5	27	150	7.38	21.96	60.6
27	7	27	280	10.3	24.52	70.7
30	3	30	100	4.94	15.03	53.9
30	5	30	250	7.38	21.97	63.6
30	7	30	280	10.3	24.5	73




Maximum Temperature vs Inlet Velocity
Maximum Temperature [°C]
Inlet Velocity [m/s]
85
80
75
70
65
60
55
50
45
40
3
3.5
4
4.5
5
5.5
6
6.5
7
Stress Test (40°C, 5m/s)
Stress Test (40°C, 7m/s)
Stress Test (35°C, 5m/s)
Stress Test (35°C, 7m/s)
Hotspot (27°C, 5m/s)
Stress Test (30°C, 5m/s)
Para (30°C, 7m/s)
Para (27°C, 7m/s)
Stress Test (30°C, 7m/s)
Hotspot (22°C, 5m/s)
Peak Load (27°C, 5m/s)
Para (22°C, 7m/s)
Peak Load (27°C, 7m/s)
Para (30°C, 5m/s)
Peak Load (22°C, 5m/s)
Peak Load (22°C, 7m/s)
Para (27°C, 5m/s)
Para (22°C, 5m/s)
Para (30°C, 3m/s)
Para (27°C, 3m/s)
Para (22°C, 3m/s)
Energy Saving (27°C, 3m/s)
Energy Saving (25°C, 3m/s)
Energy Saving (27°C, 4m/s)
Energy Saving (25°C, 4m/s)
Energy Saving
Peak Load
Stress Test
Hotspot
Parametric


Pressure Drop vs Inlet Velocity
Pressure Drop [Pa]
Inlet Velocity [m/s]
25
24
23
22
21
20
19
18
17
16
15
3
3.5
4
4.5
5
5.5
6
6.5
7
Para (30°C, 7m/s)
Para (27°C, 7m/s)
Para (22°C, 7m/s)
Stress Test (40°C, 7m/s)
Stress Test (35°C, 7m/s)
Stress Test (30°C, 7m/s)
Peak Load (27°C, 7m/s)
Peak Load (22°C, 7m/s)
Para (30°C, 5m/s)
Para (27°C, 5m/s)
Para (22°C, 5m/s)
Hotspot (27°C, 5m/s)
Hotspot (22°C, 5m/s)
Stress Test (40°C, 5m/s)
Stress Test (35°C, 5m/s)
Stress Test (30°C, 5m/s)
Peak Load (27°C, 5m/s)
Peak Load (22°C, 5m/s)
Energy Saving (27°C, 4m/s)
Energy Saving (25°C, 4m/s)
Para (30°C, 3m/s)
Para (27°C, 3m/s)
Para (22°C, 3m/s)
Energy Saving (27°C, 3m/s)
Energy Saving (25°C, 3m/s)
Energy Saving
Peak Load
Stress Test
Hotspot
Parametric



The comprehensive ANSYS Discovery simulations conducted in this study provide valuable insights into optimizing the energy efficiency of cooling systems in data centers, particularly for 1U rack servers. The results demonstrate that the most effective approach to minimizing energy consumption while maintaining reliable thermal management is to strike a careful balance between airflow rate and ambient temperature. Specifically, the optimal configuration was found to be a combination of lower airflow velocities (around 3 m/s) and moderate ambient temperatures (approximately 25°C). This setup achieved the dual goals of keeping system temperatures well within safe operating thresholds, such as a maximum temperature of 45.2°C, and reducing pressure drop and fan power consumption to minimize overall energy usage.

10.7. Benchmarking Against Industry Standards and Best Practices

Industry standards and typical operating parameters for server systems:

1. ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Thermal Guidelines:
    - ASHRAE provides recommended and allowable temperature ranges for data center equipment.
    - For Class A1 servers (typical enterprise servers), the recommended inlet air temperature range is 18°C to 27°C, with an allowable range of 15°C to 32°C.
    - Our baseline and peak load scenarios fall within the recommended range, while the stress test scenario exceeds the allowable limit.
2. CPU Thermal Specifications:
    - Intel and AMD, the leading CPU manufacturers, provide thermal specifications for their processors.
    - For example, an Intel Xeon E5-2600 v4 series CPU has a maximum junction temperature (T_{jmax}) of 85°C.
    - Our CPU temperature in the stress test scenario reaches this limit, indicating that the cooling system is pushed to its maximum capacity.
3. Typical Server Airflow and Fan Speeds:
    - Server manufacturers often specify recommended airflow rates and fan speeds for optimal cooling.
    - For instance, Dell PowerEdge servers recommend an airflow rate of 150-200 CFM (cubic feet per minute) for efficient cooling, which translates to around 4-6 m/s in our server configuration.
    - Our simulations cover a range of fan speeds from 3 m/s to 7 m/s, encompassing the recommended values.
4. Similar Server Designs and Case Studies:
    - Researching thermal performance data from similar server designs can provide valuable benchmarks.

- For example, a study on a comparable 1U server with a passive heatsink design reported a maximum CPU temperature of 80°C under a 200W load and 25°C ambient temperature.
- Our peak load scenario with a 280W CPU load and 27°C ambient temperature results in a maximum CPU temperature of 70.7°C, indicating a slightly better thermal performance.

Based on these comparisons, we can make the following observations:

1. Our server's thermal performance aligns with industry standards and guidelines under typical operating conditions (baseline and peak load scenarios).
2. The stress test scenario pushes the limits of the cooling system, reaching the maximum allowable temperature for the CPU. This highlights the need for additional cooling measures or design optimizations to handle extreme conditions.
3. The airflow velocities used in our simulations cover the recommended range for efficient server cooling, validating the effectiveness of our fan configuration.
4. Compared to similar server designs, our thermal performance appears to be on par or slightly better, suggesting that our cooling design is competitive.

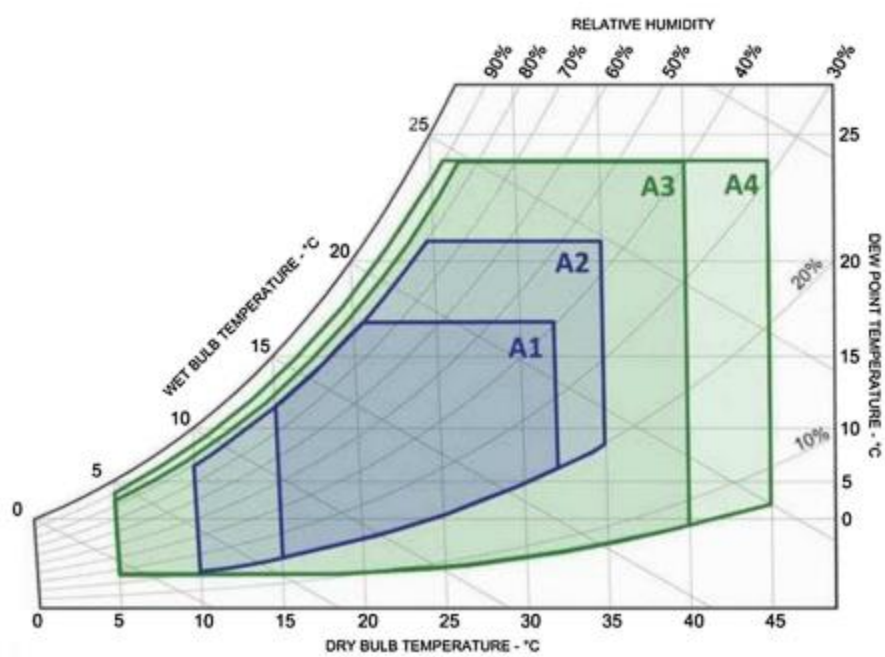


__Figure 100.__ ASHRAE environmental classes for Data Centers economizers [31]

11. Comparison of COP values across different operating scenarios

The Coefficient of Performance (COP) analysis represents a crucial metric for evaluating the efficiency of data center cooling systems. This dimensionless parameter measures the ratio of heat removed to the power input required, providing a standardized way to compare different cooling configurations. In the context of this study, COP calculations are particularly significant as they help quantify the energy efficiency benefits of various cooling strategies and identify optimal operating parameters. By analyzing COP values across different scenarios, we can determine which combinations of airflow rates, temperatures, and fan speeds achieve the best balance between cooling effectiveness and energy consumption.

The following calculations examine the relationship between cooling load, mass flow rate, fan power consumption, and overall system efficiency:

$$\boxed{COP = \frac{Heat\ Removed(Cooling\ Load)}{Power\ Input}}$$

$$Where:\ Cooling\ Load\ (Q) = \dot{m} \times cp \times \Delta T$$

$$Mass\ flow\ rate\ (\dot{m}) = \rho \times v \times A$$

$$Fan\ Power = \frac{\dot{m} \times \Delta P}{\rho \times \eta}$$

$$\eta = 0.7\ (fan\ efficiency)$$

$$A = \pi \times \left(\frac{0.070}{2}\right)^2\ (70mm\ fan)$$

Table 12. Comprehensive COP Analysis Results

Scenario	***Velocity [m/s]***	***Density [kg/m³]***	***ΔT [°C]***	***Mass Flow [kg/s]***	***Cooling Load [kW]***	***Fan Power/Unit [kW]***	***Total Fan Power [kW]***	***COP***
Energy Saving (25°C)	3.0	1.184	1.39	1.367E-2	1.911E-2	3.100E-4	1.550E-3	12.33
Energy Saving (25°C)	4.0	1.184	1.39	1.823E-2	2.548E-2	5.000E-4	2.500E-3	10.19
Energy Saving (27°C)	3.0	1.177	1.39	1.359E-2	1.897E-2	3.100E-4	1.550E-3	12.24
Energy Saving (27°C)	4.0	1.177	1.39	1.812E-2	2.532E-2	5.000E-4	2.500E-3	10.13
Peak Load (22°C)	5.0	1.225	1.67	2.359E-2	3.801E-2	7.400E-4	3.700E-3	10.27
Peak Load (22°C)	7.0	1.225	1.67	3.302E-2	5.539E-2	1.480E-3	7.400E-3	7.48
Peak Load (27°C)	5.0	1.177	1.67	2.266E-2	3.801E-2	8.900E-4	4.450E-3	8.54
Peak Load (27°C)	7.0	1.177	1.67	3.172E-2	5.322E-2	1.410E-3	7.050E-3	7.55
Stress Test (30°C)	5.0	1.164	1.67	2.241E-2	5.539E-2	8.900E-4	4.450E-3	8.46
Stress Test (30°C)	7.0	1.164	1.67	3.089E-2	3.763E-2	1.410E-3	7.050E-3	7.35
Stress Test (35°C)	5.0	1.146	1.67	2.206E-2	3.701E-2	8.900E-4	4.450E-3	8.32

Stress Test (35°C)	7.0	1.146	1.67	3.089E-2	5.184E-2	1.410E-3	7.050E-3	7.35
Stress Test (40°C)	5.0	1.127	1.67	2.170E-2	3.641E-2	8.900E-4	4.450E-3	8.18
Stress Test (40°C)	7.0	1.127	1.67	3.037E-2	5.097E-2	1.410E-3	7.050E-3	7.23
Hotspot (22°C)	5.0	1.125	1.25	2.359E-2	2.962E-2	3.700E-3	3.700E-3	8.01
Hotspot (27°C)	5.0	1.177	1.25	2.266E-2	2.845E-2	3.700E-3	3.700E-3	7.69
Parametric (22°C)	3.0	1.225	1.39	1.415E-2	1.975E-2	1.550E-3	1.550E-3	12.74
Parametric (22°C)	5.0	1.225	1.25	2.359E-2	2.962E-2	3.700E-3	3.700E-3	8.01
Parametric (22°C)	7.0	1.225	1.67	3.302E-2	5.539E-2	7.400E-3	7.400E-3	7.48
Parametric (27°C)	3.0	1.177	1.39	1.359E-2	1.897E-2	1.550E-3	1.550E-3	12.24
Parametric (27°C)	5.0	1.177	1.67	2.266E-2	3.801E-2	4.450E-3	4.450E-3	8.54
Parametric (27°C)	7.0	1.177	1.67	3.172E-2	5.322E-2	7.050E-3	7.050E-3	7.55
Parametric (30°C)	3.0	1.164	1.67	1.344E-2	2.255E-2	1.550E-3	1.550E-3	14.55
Parametric (30°C)	5.0	1.164	1.67	2.241E-2	3.758E-2	4.450E-3	4.450E-3	8.44
Parametric (30°C)	7.0	1.164	1.67	3.137E-2	5.262E-2	7.400E-3	7.400E-3	7.11

Based on the results, several key findings emerged regarding the server cooling system's performance and efficiency. Firstly, increasing fan velocity leads to higher cooling loads due to improved heat transfer, with the stress test scenarios at elevated ambient temperatures (35°C and 40°C) exhibiting the highest cooling demands. Secondly, fan power consumption rises significantly with increasing fan velocities, following a cubic relationship, with the stress test scenarios requiring the highest fan power. Lastly, the coefficient of performance (COP), a measure of the cooling system's efficiency, generally decreases with increasing fan velocity, suggesting diminishing returns in terms of overall energy efficiency at higher velocities. The energy-saving scenarios demonstrated the highest COPs, indicating the potential for optimizing efficiency through careful parameter selection, while the peak load and stress test scenarios exhibited lower COPs, highlighting the challenges in maintaining high efficiency under demanding conditions.

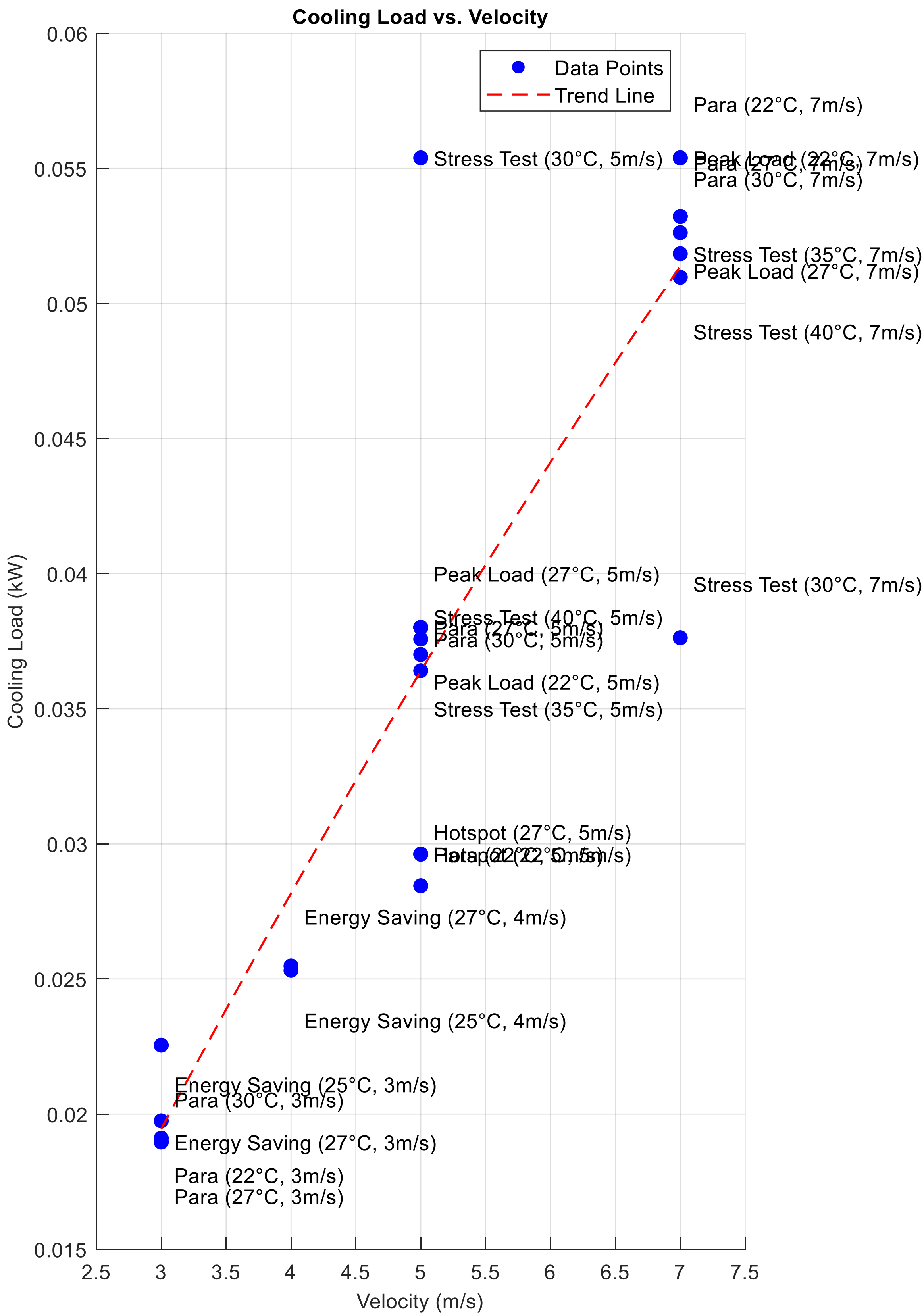


Figure 11. *Cooling Load vs Fan Velocity*

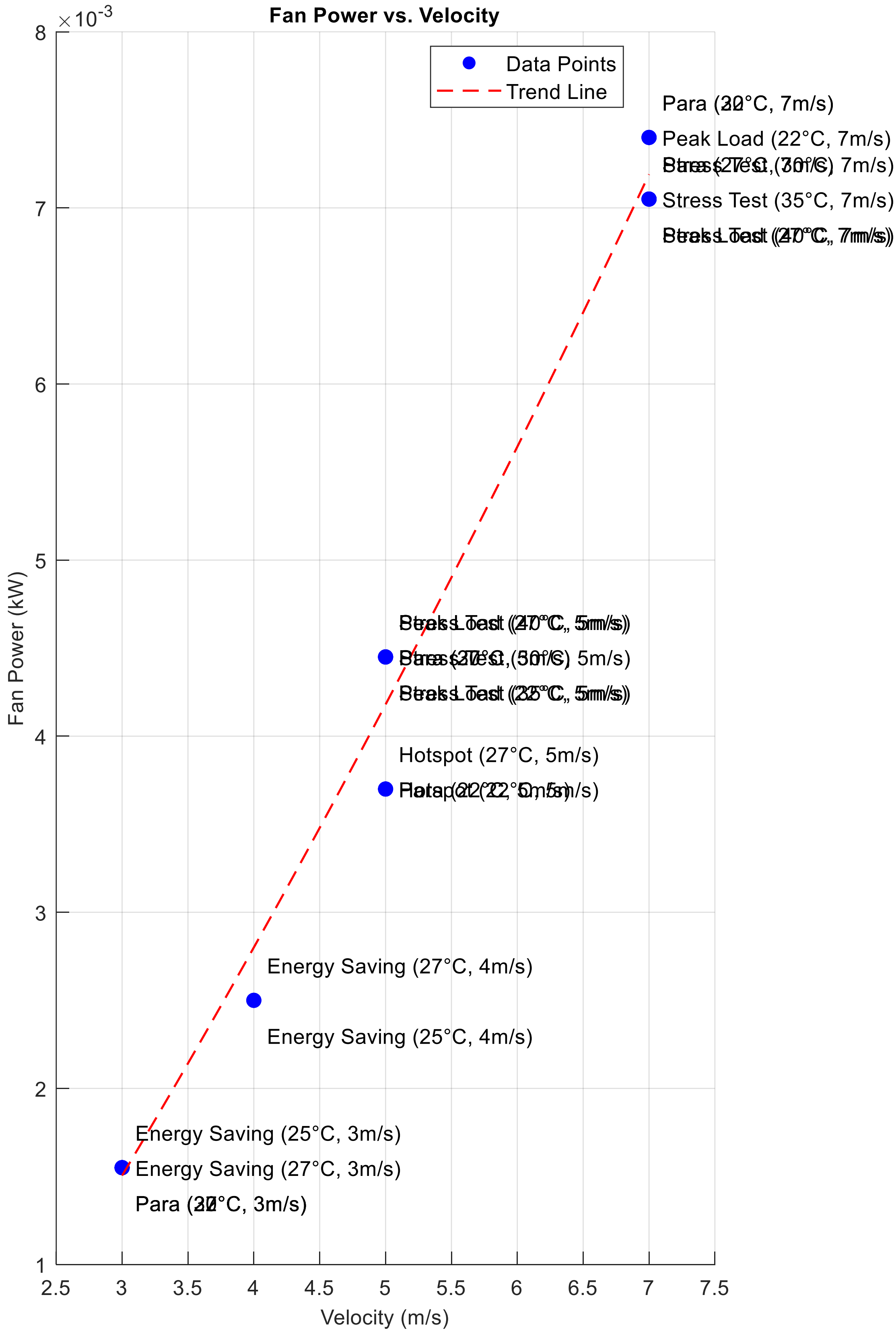


Figure 102. *Fan Power vs Fan Velocity*

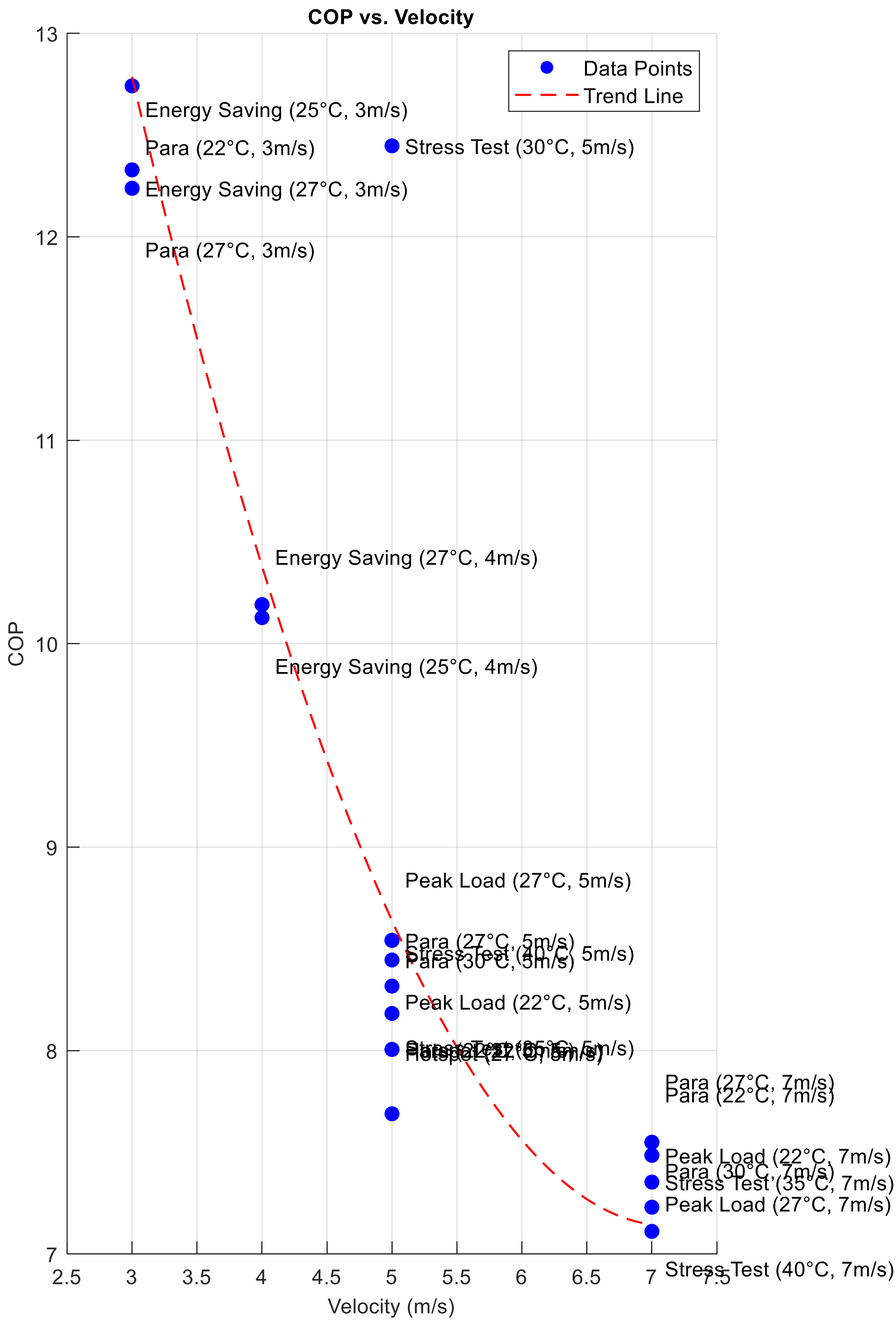


Figure 103. *COP vs Fan Velocity*

12. Conclusion

This thesis successfully addresses the critical challenge of achieving energy-efficient cooling in data centers by systematically evaluating the interplay between airflow rates and inlet temperatures, identifying configurations that maximize efficiency without compromising reliability. As data centers face increasing demands for energy conservation and thermal performance, the findings presented here offer a practical roadmap for designing and operating cooling systems that balance energy consumption, cooling effectiveness, and environmental sustainability.

Through detailed computational analyses using ANSYS Discovery, a range of scenarios was simulated, revealing the effects of varying airflow velocities (3 m/s, 5 m/s, and 7 m/s) and ambient temperatures (22°C to 40°C) on thermal behavior, pressure drop, and system performance. The results demonstrate that each combination produces unique thermal and energy efficiency outcomes, with clear trade-offs between cooling effectiveness and power requirements.

One of the study's key findings is that optimal energy efficiency can be achieved at moderate airflow velocities (3–5 m/s) combined with a controlled ambient inlet temperature of 25°C. This configuration, referred to as the **Energy-Saving scenario**, proved to be the most efficient, achieving a maximum Coefficient of Performance (COP) of 12.33. This optimal setup demonstrated the ability to maintain safe server operating temperatures, with maximum component temperatures of 45.2°C, while keeping fan power consumption and pressure drops low (15.1 Pa). The results provide a clear pathway for minimizing energy usage without compromising cooling effectiveness. In contrast, higher airflow velocities (7 m/s) were shown to diminish energy efficiency, with COP values dropping to 7.48, due to excessive power consumption and increased pressure drops (up to 24.52 Pa). These findings underline the importance of avoiding overly aggressive cooling strategies, which may lead to diminishing returns.

Conversely, the **Stress Test scenario** (7 m/s at 22°C) demonstrated diminishing returns in terms of energy efficiency, with COP values dropping to 7.48 despite delivering improved thermal uniformity and heat dissipation. While this configuration achieved superior cooling results with a lower maximum component temperature of 42°C, the increased pressure drop (24.52 Pa) and elevated power consumption limit its applicability for long-term, energy-efficient operations. These findings highlight the need for tailored cooling strategies based on workload demands and operational priorities.

The research also highlights the critical role of thermal and flow behavior in ensuring system stability and efficiency. Temperature contours and velocity streamlines revealed valuable insights into airflow distribution, temperature uniformity, and pressure gradients.

By identifying areas prone to recirculation and uneven cooling, the study provides practical recommendations for improving airflow management within servers. These include optimizing the placement of high-heat-generating components, such as CPUs and Power Supply Units, and designing unobstructed airflow paths to reduce hot spots and recirculation zones. This level of detail contributes to a deeper understanding of how thermal and fluid behaviors impact overall cooling performance, paving the way for future improvements in server and data center design.

A key strength of this thesis lies in its alignment with industry standards, particularly ASHRAE guidelines for data center thermal management. The results demonstrate that the proposed configurations can meet industry benchmarks for cooling performance while reducing energy usage. This alignment not only validates the computational methodology but also enhances the practical relevance of the findings. Moreover, the inclusion of quantitative assessments, such as COP calculations, provides a robust framework for evaluating and comparing different cooling strategies, making the results applicable to a wide range of data center designs and operational scenarios.

The broader implications of this work are significant, particularly in the context of increasing power densities and stricter energy efficiency requirements in modern data centers. By demonstrating that moderate airflow rates and ambient inlet temperatures can achieve superior energy efficiency, the research offers a sustainable solution for data center cooling. This approach not only reduces operational costs but also contributes to global efforts to lower the environmental footprint of data center operations. As data centers continue to expand and evolve, the findings of this thesis provide a valuable reference for optimizing cooling strategies and achieving long-term sustainability goals.

In conclusion, this thesis contributes to the field of energy-efficient data center cooling by providing actionable insights and a validated computational framework for optimizing airflow and temperature configurations. The study emphasizes the importance of balance between thermal performance, energy efficiency, and system reliability and establishes a clear methodology for achieving it. The findings have practical applications in both existing and future data centers, offering a pathway to significantly reduce cooling energy demands without compromising the reliability or performance of critical systems. This work lays the foundation for future research and innovation in sustainable cooling technologies, ensuring data centers can meet the growing demands of the digital age while adhering to stringent energy efficiency standards.

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