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Team 505: Danfoss Stepper Motor Testing Lifecycle Fixture

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Abstract

Danfoss Turbocor designs high-efficiency compressors that help heat or cool large buildings. They tasked us with improving their testing procedure for an important stepper motor in their compressors. This stepper motor controls the amount of air entering the compressor by opening and closing small fins, like an air conditioning vent in a house. Danfoss Turbocor tests the stepper motor's lifecycle to assess the motor quality, the reliability of the motor manufacturer, and the overall performance of the compressor. However, they currently lack an official device for this test, so our project focused on building one.

Our goal was to design a high-quality stepper motor testing fixture and user interface. This came with multiple requirements. The fixture needed to perform tests for months at a time, requiring reliable materials and electronics. It also needed a user-friendly design. This meant including a simple user interface and visual indicators, like LEDs that show when the motor fails. The fixture even needed to follow Danfoss Turbocor's safety standards for machines with moving parts. We implemented all the requirements as we developed our design.

The result was the H-Frame, designed to securely hold and apply a constant resistance torque to the stepper motor over the lifecycle test. The fixture was made of aluminum and secured together with stainless steel bolts. The user interface consists of a screen and control knob, like those in car displays. With this, the user can start the test, input test parameters such as speed and direction, and review the results after the test finishes. A magnetic sensor tracks rotations and detects motor failure to determine the lifecycle of the motor. Overall, the testing procedure measures the motor's limits, ensuring that Danfoss Turbocor stepper motors perform as intended.

Acknowledgement

These remarks thanks those that helped you complete your senior design project. Especially those who have sponsored the project, provided mentorship advice, and materials. 4

- Paragraph 1 thank sponsor!
- Paragraph 2 thank advisors.
- Paragraph 3 thank those that provided you materials and resources.
- Paragraph 4 thank anyone else who helped you.

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Notation

IGV	Inlet Guide Vane
PPS	Pulses Per Second

Chapter One: EML 4551C

1.1 Project Scope

1.1.1 Project Description

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The objective of this project is to design and produce a stepper motor lifecycle test fixture for Danfoss Turbocor to improve user-friendliness and reliability over their current testing procedure. Stepper motors are used within Danfoss compressors to actuate the inlet guide vanes (IGV) and control ~~that control~~ the amount of airflow into the compressor. Therefore~~.~~ their lifecycle is important to verify for customer confidence. ~~The current stepper motor testing procedure involves the~~ The lifecycle test is currently done with the ~~entire~~ IGV assembly, ~~which adds~~ adding undesirable friction ~~losses~~ forces to the stepper motor that lower the test accuracy~~at skew results~~. The new fixture will apply torque resistance to the motor directly, allowing for a more exact result and a simpler process.

1.1.2 Key Goals

The ~~major~~ goal of this project is to accurately track the pulses per second ~~(~~PPS~~)~~, number of rotations, and life cycle of the stepper motor under specified conditions (load and speed) for both clockwise and counterclockwise rotation until failure. This goal represents the quantification of the test parameters and results required to track stepper motor lifecycles. ~~Other key goals~~ Goals for the design include user-friendliness, reliability, automation, and ~~accuracy.~~ ~~User~~accuracy. ~~-friendliness will be quantified in These key goals reflect our intent to produce a fixture that will be implemented by Danfoss in their current design process~~. ~~The u~~ User-friendliness ~~goal~~ incorporates the importance of allowing ~~aa~~an efficient and straightforward process for all operators. Reliability focuses on the design to effectively run each test for the months the motors can last. Automation ensures tests can be run with minimal human intervention. Accuracy reflects the true performance ~~capabilities~~ of the stepper motor.

1.1.3 Markets

The primary market for this product will be Danfoss Turbocor. Project success is determined by our product's usefulness ~~in~~ and improvement over Danfoss Turbocor's current stepper motor testing procedures. Secondary markets include other compressor manufacturing companies, stepper motor manufacturing companies, academia, and 3D printer companies. Compressor manufacturers such as Atlas Copco and Sullair could be interested in our testing procedures for potential stepper motor components. Stepper motor manufacturing companies that prioritize quality assurance in their products could also make use of our product. University laboratories studying stepper motors represent another market for the fixture, as it provides students with an educational example for motor lifecycle testing. One last market is 3D printer companies as they use stepper motors to actuate the movement of their print heads. They would benefit from lifecycle testing to understand the limits their stepper motors have. Our lifecycle testing fixture and methodology can be adapted to the stepper motors our various markets use.

1.1.4 Assumptions

Our assumptions include:

- The stepper motor lifecycle fixture will be in a secluded room in ~~the back room of~~ the Danfoss factory with standard room temperature and conditions.
- We will be provided with the IGV stepper motors, Perma-Tork magnetic breaks, and stepper motor power connectors.
- Only the IGV stepper motor will be tested.

- The fixture will sit on an elevated flat working space.
- A standard 120V outlet will be available.
- The user has knowledge in basic tool operation such as screw drivers, allen wrenches, and knowledge of operating a basic interface consisting of switches or a digital display.
- The resistance torque of the HC3-3J will be verified with a specific torque wrench by a Danfoss operator.

These assumptions help limit our scope to ensure that we complete our project by graduation.

1.1.5 Stakeholders

The primary stakeholders for this project are Danfoss Turbocor and ~~associated contacts~~ Cole Gray, a Danfoss Senior Mechanical Design Engineer~~ and Brandon Pritchard.~~ ~~Their~~Mr. Gray's investment of time, financial resources, and effort throughout the project and his~~their~~ interest in potentially implementing our design make him~~them~~ a key stakeholder~~s~~. Cole Gray has provided the group with parameters and details of the design and will determine if the result is up to standard. Secondary stakeholders include our advisor, Dr. Patrick Hollis, who will invest his effort and time in~~to~~ making sure the group is moving in the right direction and contributing to the design process to see a successful result. Additionally, Dr. Shayne McConomy is investing his expertise and time into preparing and mentoring the group throughout the project and moving the project forward. Our last stakeholder, who is interested in our design, is Dr. Camillo Ordonez at the FAMU-FSU College of Engineering, who teaches students about stepper motors and will provide electronic advice for the project.

	Investors	Decision-Makers	Advisors	Receivers
Sponsor Danfoss (Cole Gray ~~& Brandon Prichard~~)	X	X	X	X
Manager Dr. McConomy			X	
Operators Danfoss Employees & General HVAC & Dr. Ordonez				X
Advisor Dr. Patrick Hollis			X	

Table 1: Stakeholders Matrix

1.2 Customer Needs

1.2.1 Investigation of Needs

Danfoss Turbocor has collaborated with the FAMU-FSU College of Engineering to create a lifecycle testing fixture for their 910098 Stepper Motor to test its limits and reliability. Cole Gray, a senior mechanical design engineer at Danfoss Turbocor, is Team 505's sponsor and point of contact throughout the project duration.

On September 9th at 10:00am and September 18th at 4:00pm, the team toured Danfoss Turbocor's main warehouse, seeing where the stepper motor testing would take place and interviewing Mr. Gray about the specifics of the project. Following the meetings, the team prepared a list of questions for Mr. Gray about the project. The questions were sent via Excel Document for Cole Gray to answer. The responses were recorded and shown in the table below

(Table 1). The interpreted needs describe the requirements needed to begin the next section of the project and confirm design choices before ideation.

Customer Needs Questions and Answers			
Sections	**Questions**	**Answers**	**Interpreted Need**
Design Requirements	Design Requirements	“Device must be able to adjust and display the speed (PPS).”	The user interface of the fixture has a way to adjust and display the speed in PPS.
		“Device must be able to adjust and display the time per cycle (CW and CCW).”	The user interface of the fixture is designed to be able to adjust and display the time per cycle clockwise and counter-clockwise.
		“Device must keep cycle count when motor is operated in a continuous direction or alternating between CW and CCW.”	The fixture is equipped to keep the cycle count when the stepper motor is operating in a continuous direction or cycling between counterclockwise and clockwise directions.
		“Device must be able to adjust load on stepper motor.”	The fixture is designed with capability to adjust the load on stepper motor.
		“Device must be able to test up to 6 motors at once – can be a separate fixture such as 2 fixtures that test 3 each, etc.”	The fixture allows the user to test up to 6 motors at once.
		“Must be compatible with 910098 motor.”	The fixture is designed to be compatible with the 910098 Stepper Motor.
		“Motor must be oriented vertically so that the shaft points towards the ground when under test.”	The fixture is designed to align the motor vertically so that the shaft points towards the ground throughout testing.
		“Must be able to set each motor independently.”	The fixture allows each motor to run lifecycle testing independently.

		“Must be able to see lifecycle count while unit is under test.”	The user interface of the fixture displays the lifecycle count while the motor is under testing.
Design Choices	Does the device need to adjust the load on the Perma-Tork manually or is that something needing to be automated?	“It will be manually set, and torque can be verified with a torque wrench we have on site.”	The device allows for manual adjustment to the torque load on motor, while having external verification with torque wrench.
	Are there any preferred materials you would like us to use?	“Aluminum/Stainless steel (as much non-magnetic and non-corrosive materials as possible).”	Device is fabricated with non-magnetic and non-corrosive materials.
	Does the device need manual switches or digital displays for user interfacing?	“Will need visual feedback (most likely a display) for adjusting the speed and rotation time for each motor individually.”	The fixture includes displays with visual feedback for adjustment to the speed and rotation time for each motor.
	How many different people will be running the tests? Does the design need to be operable without a manual or training?	“The simpler the better, very brief training or a short manual would be ideal.”	The fixture's operation is simple enough to be understood with brief training or a short manual.
	What results need to be tracked (other than cycles)? How should the results of the test be displayed?	“Cycles is a must, and as a nice to have total run hours (not just powered on time but actual run time).”	The device tracks total cycle count and total run time.
Failure	What is considered a failure in the testing process?	“The stepper motor is unable to overcome the resistance torque.”	The device identifies failure of stepper motor to overcome resistance torque.

Automation	What are all the different cases of test procedures we should automate?	“The only two tests we would run is: 1. motor runs continuously as a specified PPS under the set load until it fails to rotate, this can be recorded as total rotations or total time to failure (preferred but not required). 2. motor rotates CW for say 90 seconds (it ends up completing say 90 rotations as a guess), then stops and rotates CCW for the same time period, then that would count as 1 cycle. This repeats until a full cycle cannot be completed. That is the only 2 configurations we will end up running for now at least.”	The device is capable of running the motor in one direction until failure, alternating the direction of the motor after a specified period of time until failure, and identifying cycle count/time until failure.

	For error analysis of shaft rotation should the device compare PPS to readings from the Hall effect sensor to determine failure?	“Yes, I would say using the PPS, an estimated full motor rotation can be determined, and for continuous running in a single direction, if it doesn't see a full rotation within say double the estimated time, it can stop sending power to the motor and consider the test complete. For the CW/CCW test, the time for each direction would have to be part of the equation, so the pps would have to be converted to a time for 1 full motor rotation, then that can be multiplied by the CW/CCW timing to get the estimated time, then add a decent safety factor on that estimated cycle time before shut down (might be worth adding 2 counters per motor so you can confirm the direction the motor is spinning).”	The device counts PPS for CW and CCW rotation to determine failure against resistance torque. The device implements a double factor of safety to prevent errors from CW/CCW timing, once that safety is exceeded the test will complete.
Environment	Is there a temperature range or environment that the stepper motor is subjected to in the compressor that we should consider in our testing?	“Yes, operation would be 20-80°C, ambient could be -30 to 50°C if the compressor is just cranking up. Normal lifecycle testing will be around 21°C.”	The device is operated in a 21°C environment.

Table 2: *Questions from Team 505 and answers from Cole Gray along with interpreted needs*

1.2.2 Explanation of Results

Based on the interpretation of answers from Table 1, Team 505 has determined the specific areas of focus in the next stages of our project. The customer needs are grouped into five sections, each of which highlights the critical needs of the project.

1.2.2.1 Design Requirements

After receiving feedback from our sponsor Cole Gray, he specified that the design needs to be able to adjust and display the speed (PPS) throughout the test for CW and CCW rotation. Therefore, this highlights how critical user-experience is for the design. The user needs to have an interface to interact and change the variables of the test before it has started. Additionally, the design is capable of being oriented so that the motor is vertically stacked over the Perma-Tork magnetic break. ~~The design also needs to test up to six motors independently~~The design needs to run a single ~~and~~motor and track the number of rotations in each shaft, cycle count, and total run time which will be displayed for each motor during its life cycle test. We interpret this need as the ability to replicate the design and easily produce it. ~~a modular approach to our design, being able to stack testing structures beside or on top of each other.~~

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1.2.2.2 Design Choices

With design choices, Cole Gray specified that the device is to be fabricated with non-magnetic and non-corrosive materials and allows for manual adjustment of the Perma-Tork magnetic break. This customer need simplifies our design and takes away the automation of the Perma-Tork. The customer also needs the device to operate with brief training or a short manual. We interpret this need as the importance of user-friendliness and have simple steps to operate.

1.2.2.3 Failure

The customer needs the device to operate until failure. The failure of the stepper motor was defined as the stepper motor's inability to overcome the resistance torque. This definition narrows down the scope of the project due to the focus on one failure method.

1.2.2.4 Automation

The device's automation will consist of two types of lifecycle tests. This is a critical need for the customer, as it is the basis for how the motor is tested and what is required by the user-interface. The first is a life cycle test where the stepper motor is under a load at a specified speed determined by the set PPS and it will run until failure. The second life cycle test has the same loading conditions but will alternate between clockwise and counterclockwise rotation until failure. Our sponsor defined failure as when the motor fails to overcome the resistance torque. To better improve the user-experience, the test will be completed automatically once the factor of safety is exceeded and the motor is unable to overcome the resistance.

1.2.2.5 Environment

When discussing the environment of the design during operation the standard temperature is 21°C. If possible, it would be helpful to improve the design to allow the fixture to be run in a thermal chamber for testing different loading conditions to better simulate the stresses put on the stepper motor, and it is important to consider the effects of these alternate conditions on the electrical components of the design. However, this need is interpreted as having a fixed temperature for initial device testing. Temperature variations can be implemented into the testing process if time permits.

1.3 Functional Decomposition

Functional decomposition is a technique used to break up the main systems of the project into smaller subsystems and their associated functions based on the interpreted customer needs. The functional decomposition performed by Team 505 is based on the user experience and testing procedures for the IGV stepper motor. It was broken down into three main subsystems of Automation, User Interface, and Structure then split into further subsystems as it relates to the specific functions. There are 20 main functions needed for the project and are grouped below in Figure 1.

To complete the functional decomposition, Team 505 studied the requirements, customer needs, and key goals for the project. Through a series of team meetings and brainstorming sessions, the team walked through how a lifecycle test would go from start to finish and discussed the simplest functions of the design and how they relate to each other. After finalizing these functions, the team worked upwards to group them together into subsystems and then further into the three main subsystems shown in the hierarchy chart below.

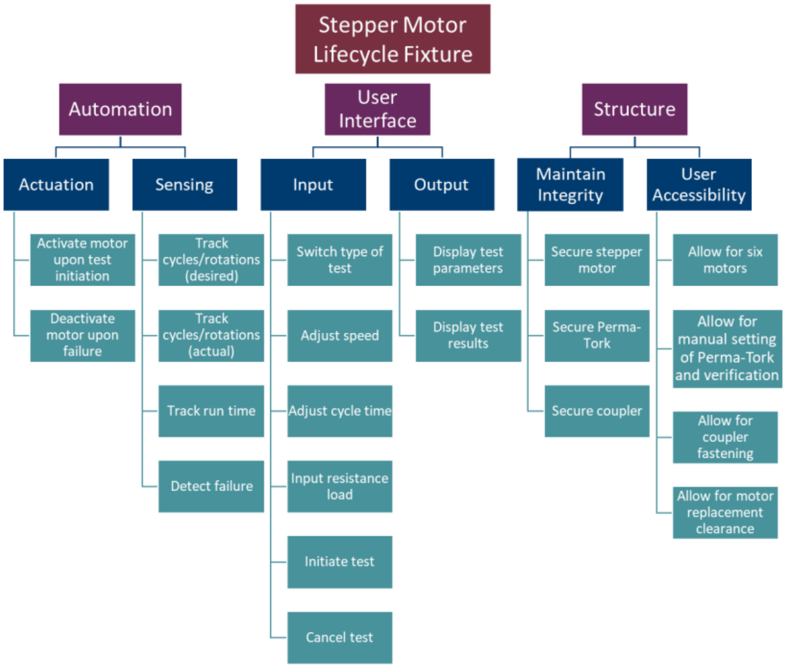

Figure 1: Hierarchy Chart

1.3.1 Hierarchy Chart Explanation

The stepper motor lifecycle fixture is split up into three main subsystems. This is due to the form factor of the design and how the user interacts with it to perform functions. There is the main structure of the fixture, the interface where Danfoss Turbocor will interact with the structure, and there is the control, or Automation, part of the design that diverts power to the motor within a program that is running the test.

In more detail, the Structure houses the components needed to test the stepper motor and keeps them secure. This subsystem is split up into groups, which are called “Maintain Integrity” and “User Accessibility”. The three items that need to be secured to maintain integrity are the stepper motor, the coupler, and the Perma-Tork. To have a stable and accurate test, the structure is designed to eliminate axial forces or any other variables that can skew the results. Additionally, as part of the user accessibility the design must be modular to allow for up to six separate tests at once. Our sponsor has requested for each to have enough room or have a function to manually adjust the Perma-Tork, secure the coupler, and replace the motor. All of these are functions of the structure and form-factor of the design.

The User Interface houses all the controls needed to adjust, start/stop the test, and display data. The functions are further grouped into categories of Input and Output. When starting the test, the user will input the variables of type of test, speed, cycle time, and resistance load before initiating the test. Additionally, there is an option to manually stop or “Cancel test”. These functions are the basis for how the user communicates their test parameters and preferences to the system, ensuring that the design operates correctly. In a similar way, the Output function group includes displaying the test parameters and the test results. These functions are the basis for how the design interface communicates back to the user.

The “Automation” subsystem includes the actuation of the motor and the sensing throughout the test. The actuation includes the functions of activating, deactivating, powering, and turning the motor through instructions set by the input parameters. “Sensing” functions include tracking the desired and actual cycles of the motor, the run time, and detecting failure of the motor. This data is collected then displayed in the output of the user interface.

1.3.2 Connection to Systems

	Subsystems / Subsubsystems						**Function Total**
	Automation		**User Interface**		**Structure**		
Functions	Actuation	Sensing	Input	Output	Maintain Integrity	User Accessibility	
Activate motor upon test initiation	X		X				2
Deactivate motor upon failure	X	X		X			3
Track cycles/rotations (desired)		X					1
Track cycles/rotations (actual)	X	X		X			3
Track run time		X		X			2
Detect failure	X	X		X			3
Switch type of test	X		X				2
Adjust speed	X		X				2
Adjust cycle time	X		X				2
Input resistance load			X	X			2
Initiate test	X		X				2
Cancel Test	X		X				2
Display test parameters			X	X			2
Display test results		X		X			2
Secure stepper motor					X		1
Secure Perma-Tork					X		1
Secure coupler					X		1
Allow for six motors						X	1
Allow for manual setting of Perma-Tork and verification			X			X	2
Allow for coupler fastening						X	1
Allow for motor replacement clearance						X	1
Subsubsystem Totals	9	6	9	7	3	4	

Table 3: *Functional Decomposition Cross-Reference Table*

The Cross-Reference table, shown in Table 3 above, displays how the functions and systems of the fixture relate to each other. The highlighted boxes for each function represent a direct relationship with the subsystem. Non-highlighted "X's" show indication that the function is not directly related but influences the corresponding system. Actuation and Input are the most important systems within functional decomposition which have the largest impact to the design objectives. Actuation has many cross references to Input when determining the parameters of the stepper motor life cycle test. The input parameters include the type of test, the speed (PPS), cycle time, resistance load, and initiating/cancelling the test which directly determines how the motor driver actuates motor for a duration, direction, and voltage to overcome the resistance torque followed by its deactivation. These subsystems are imperative to meeting the design objectives due to them fulfilling the most design requirements in customer needs shown by the subsystems defining the process to meet the objective of accurately measuring the motion of the stepper motor.

Output and Sensing are the next most important subsystems as they determine when the test is complete and compiles the desired information. The desired output information is dependent on the specified inputs set at the beginning of the life cycle test. Sensing is heavily cross referenced with Output as it tracks the information of the test while its running to be compiled and displayed in the output for the user. Sensing motor failure also determines when the cycle is complete to send the result information to the LED display.

User Accessibility is considered a less important subsystem as it has only one cross-reference and deals more with quality rather than functionality. However, user accessibility addresses the quality-of-life aspects of the design specified in the key goals to improve user friendliness and safety by decreasing the necessary user input between life cycle tests. This still has an impact on other systems by allowing the actuation and input systems to operate more efficiently. User Accessibility also addresses the need for a modular system capable of testing up to six stepper motors which impacts the Maintain Integrity system on how it needs to be designed to compensate for the additional motors.

Maintain Integrity has no direct connection to other systems as shown in the cross-reference table but still relates to the other systems due to it specifying how the design will be constructed to secure the stepper motor, Perma-Tork, and coupler. This allows the life cycle test to run while restricting unnecessary motion of the other components of the design which are the key objectives in improving the safety and reliability of the fixture.

1.3.3 Smart Integration

Subsystems and sub-subsystems interact due to the influence individual functions have on them. It is important to know these relationships to identify some of the most critical functions for the overall system. Identifying these functions provides key factors to consider when selecting a concept.

For the Stepper Motor Lifecycle Fixture, three functions were determined critical. “Track cycles/rotations (actual)” has a critical role as the number of rotations completed before failure along with the resistance load characterize the lifecycle of the motor. The difference between actual and desired refers to the physical detection of rotation versus the programmed PPS. The rotations will be sensed by the physical rotation of the shaft, whether on the shaft itself or the coupler. Therefore, it is dependent on Actuation. The function’s relationship to “Output” is straightforward as the running total of the rotations will be displayed throughout the test and after when failure occurs.

“Detect failure” is an extremely important function of the fixture. The purpose of lifecycle testing is to determine the limit of the motor, which is the total number of rotations at failure. If the fixture continues attempting to run the motor past failure, the results will be inaccurate. Because of this role, detecting failure is key to the fixture’s performance. There are multiple solutions for detecting failure, such as comparing programmed cycles to actual cycles.

Once it is detected, the motor driver will cut power to the motor, ceasing Actuation. Then, the test results will be displayed, initiating Output.

“Deactivate motor upon failure” has similar importance to the previous function. If the motor cannot continue to turn against the resistance load but continues to run, it could get dangerously hot. Also, depending on how the fixture tracks rotations, it could cause issues with the running total. This function’s relationships with other sub-subsystems starts with its dependence on the detection of failure under “Sensing”. A task will be programmed into the controller to cut the power once failure is detected. Once the motor is deactivated, the test results will be displayed under “Output”. This will also be done with a task in the programming.

Relationships like those mentioned for the previous critical functions are represented in many of the other functions in the system and add to the system’s complexity.

1.3.4 Action and Outcome

This project encompasses a fixture that will utilize sensors to detect failure as well as tracking speed, lifecycles, and time in a running test of six individual stepper motors. Each stepper motor is connected by a coupler to a resistance device that simulates the load reciprocated from the opposing IGV system. The fixture utilizes a driver that sends power to the stepper motor and continues running with sensors tracking its run time, number of cycles, and status which will be displayed on a display at each motor. The fixture will be able to sense failure to a stepper motor and cut off power to the motor while visually outputting the failure to the operator. The hardware and electronics to this fixture will accommodate the six stepper motors and allow for sensors and displays for each stepper motor. The fixture will test each motor at different loads and track the number of cycles and the run time to receive the needed result of recognizing the stepper motor's life cycle upon failure. The fixture will output information on the runtime, number of cycles and life status on a display at each motor for the user to observe the overall run status for each motor.

1.3.5 Function Resolution

We have determined that the functions presented in the hierarchy chart describe the objective of each subsystem at its finest level. Breaking the functions down further will ultimately be describing "how" our project will accomplish the objective rather than "what" the project is to accomplish. For example, the function "Track rotations/cycles (actual)" states the purpose of what the fixture is to do for the cycle count. Breaking this function down further will result in "how" this function will accomplish this task being through a specific sensor or detection device. Determining "how" our project is to accomplish the desired functions is described in section *1.5 Concept Generation.*

1.4 Targets and Metrics

Through Functional Decomposition, the Stepper Motor Lifecycle Fixture was broken down into its most basic functions. To validate these functions in the final design, our team developed targets and metrics for every function. A metric is a unit of measurement while a target is the value of that measurement that will be used to validate functionality. We used methods like benchmarking and consulting our customers' needs to develop these targets and metrics. Each target and metric will be used to verify the success of our final design.

The following sections contain discussion about our critical targets and metrics, but the full catalog of targets and metrics can be found in Appendix D.

1.4.1 Critical Targets and Metrics

Critical Targets		
Function	**Metric**	**Target**
Adjust Cycle Time	Time (seconds)	0-300 [s]
Adjust Speed	Pulses Per Second (PPS)	1-1000 [PPS]
Deactivate Motor Upon Failure	Voltage (V)	0 [V]
Detect Failure	seconds/cycle	Actual Rotation Time > Expected Rotation Time * FOS
Display Test Results	Number of Results	> 2
Allow for Manual Setting of Perma-Tork	Area	4620 mm^2
Allow for Verification of Perma-Tork Resistance Torque	Newton Meters	0.03-0.45 [N-m]
Track Cycles/Rotations (Actual)	Accuracy	98%

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Table 4: *Critical Targets*

The first critical target for the stepper motor lifecycle fixture is to adjust the cycle time, in seconds, of the alternating test. Our sponsor has requested that the alternating lifecycle test has an adjustable cycle time for up to 300 seconds. Additionally, both the singular direction test and alternating test have a critical target of speed adjustment in Pulses Per Second up to 1000 PPS. Both of these functions are part of the Input subsystem of the design and are a significant part of the testing customizability. With a successful design, the user interface will allow a Danfoss Turbocor operator to adjust these parameters within their constraints to construct a specific test procedure that fits their needs.

The next critical target is to deactivate the motor upon failure. To ensure energy efficiency and shut down the test after the stepper motor fails, the power needs to be cut from the motor. Measured in voltage, a target of 0V is set in place to guarantee that no power is sent to the stepper motor. Failure is detected when the actual rotation time is less than the expected rotation time. This target is measured in Cycles/Second and is represented by the equation:

$$\text{Actual Rotation Time} > \text{Expected Rotation Time} * \text{FOS}$$

The Factor of Safety (FOS) is adjusted to create a threshold above which the actual Rotation Time represents failure. The Actual Rotation Time is measured using the Hall Effect sensor and the Expected Rotation Time is calculated using the input PPS at the beginning of the test. Once the actual rotation time slows to a value under the actual rotation time adjusted by the FOS, failure has occurred in the motor and the test will stop.

After failure, our next critical target is to visually display at least 2 test results. This metric ensures that at the minimum the display screen will show the time elapsed, and the number of rotations completed, both in the alternating and single-direction lifecycle test.

Our next target is to allow for a manual setting of the Perma-Tork with an area greater than 4620 mm^2. This value was calculated using the dimensions of the Perma-Tork. Additionally, another critical target for the design is that the Perma-Tork torque value must be verified using a torque wrench within the same range of 0.03-0.45 N-m to ensure a correct and accurate test. Our next critical target is part of the Sensing subsection and includes tracking the actual cycles and rotations of the stepper motor with 98% accuracy. The 2% error is set to account for unseen circumstances or human error that would lead to inaccurate counting of rotations. The last critical target is in the User Accessibility subsection and references the customer need that the design allows for 6 motors to be tested simultaneously. This target refers to the structure and modularity of the design and is an important requirement for the project to be successful.

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1.4.2 Validation of Critical Targets and Metrics

Our first critical target the device will accomplish is to adjust the cycle time. The target is to have a range from 0-90 seconds that the motor can rotate in that direction for. To confirm this time range, we will start a mock test in the alternating test sequence and visually confirm that the motor changes directions at the specified input time.

The next critical target is to adjust the speed the stepper motor is run at. The measurement will be the PPS sent to the motor by a signal from the controller. It can be validated through a Hall Effect sensor. The measured rotations from the Hall Effect sensor are to be compared to the expected rotations for two different speeds. The expected rotations are determined based on the user input speed and the length of time the test is run for.

Critical target 3 is to ensure the motor deactivates upon motor failure. We assigned the target of sending 0 volts to the motor to accomplish this task. We will confirm this target by placing a multimeter in parallel to the input power circuit to the motor and checking that the motor is receiving 0 volts upon deactivation.

The purpose of critical target 4 is to detect failure within the stepper motor. We assigned the target of Actual Time > Expected Time * FOS as stated earlier. Expected Time will be calculated through the motor PPS and Actual Time will be recorded through the Hall-Effect Sensor. Through a variety of testing runs, we will adjust the FOS until it doesn't prematurely indicate a failure. Once the FOS is high enough to represent a failure of the motor, it will be recorded and implemented into the final formula for each test.

Critical target 5 is to display at least two test results. The measurement can be validated through a visual inspection. Once test results are visually presented on the chosen display screen and match outputs from the design's sensors, the target is met.

Critical target 6 is based on the structural function that the user will have ample operating space to manually adjust the torque rating on the Perma-Tork. We will confirm this target by using handheld vernier calipers to measure the access space to the Perma-Tork and verifying that the entire range of torque resistance can be adjusted easily by hand.

Critical target 7 is to verify the resistance on the Perma-Tork device. We will confirm the torque rating given by the manufacturer’s specification using a torque wrench attatched to the main shaft to the Perma-Tork.

Critical target 8 is to accurately track shaft rotations through the use of a Hall Effect sensor. We will confirm the shaft rotations by cross-checking with a separate device such as a manual counter.

~~Critical target 9 is to ensure that the design will incorporate 6 motors for testing. We will confirm this target by a visual inspection and determine whether the fixture does or does not satisfy the requirement of 6 motors.~~

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~~1.4.5~~1.4.3 Summary

Each of the non-critical functions were also given targets and metrics and can be found in Appendix D. Together, these targets and metrics will help our team validate the success of our various subsystems: Automation, Structure, and User Interface. They will help us verify that electronics are powered correctly, the strength of our structure is sufficient, and test parameters are correctly adjusted. Even some functions not resulting from Customer Needs are given targets and metrics. These included functions of non-hazardous materials, magnetism, and weight. First, our design must comply with 2011/65/EU and 2015/863/EU RoHS compliance. This includes not using any hazardous materials within our project that may pose safety risks for the user. Second, our structure or electronics must not induce any magnetic field on the stepper motor or the Perma-Tork, altering their normal operations. Lastly, the weight of our fixture must not exceed 50 pounds, to ensure portability and relatively low weight.

1.5 Concept Generation

During concept generation, Team 505 wanted to layout all possible options for designing our stepper motor lifecycle fixture. To do this, one hundred possible concepts were created and can be seen in Appendix E. We also utilized various idea generating aids such as Forced Analogy, Biomimicry concepts, and general brainstorming amongst team members. The Forced Analogy method involved creating a random list of unrelated items with varying attributes. By connecting these attributes to our project goals, we generated innovative concepts and solutions, fostering creative thinking. The next concept generating tool is to look at features in nature and replicate them in design, also known as Biomimicry. This method is valuable because it leverages design concepts that have been tested in nature over many years, ensuring a solid foundation for innovative ideas. Finally, the team employed general brainstorming tactics to generate ideas that fit the constraints for our design objectives.

1.5.1 Medium Fidelity Concepts

From the list in Appendix E, Team 505 identified five medium fidelity concepts that align with both the project objectives and functions of the device. Medium fidelity concepts are concepts that address most needs for the design but are not as complete as the high-fidelity concepts. Below are the five medium-fidelity concepts, along with their descriptions.

1.5.1.1 Concept 35: Swivel Frame

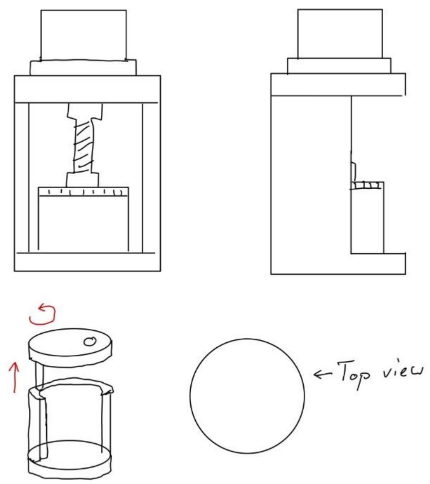


Figure 2: Swivel Frame

Cylindrical open-face structure with a top mount for the motor that lifts and swivels for easy access to adjust and verify the Perma-Tork. The action of lifting is required to release the motor shaft from the coupler. The cylindrical design is intended to best resist the torsional stress on the fixture. This is a modular design and will be connected to a central controller.

1.5.1.2 Concept 19: Hysteresis Break

The Perma-Tork is replaced with a hysteresis break where the torque is adjusted by the input current rather than manual adjustment. A hysteresis break operates by electro-magnets rather than traditional magnets in the Perma-Tork. This concept is medium fidelity because the device controller could implement code for controlling the electro-magnetic resistance force.

This eliminates the need for the user to manually adjust the input resistance torque and can be done through an input current.

1.5.1.3 Concept 29: Tower Tester

The structure of the fixture will model a circular tower that orients each motor vertically allowing the shafts to connect with a rotating spur gear in the center of the tower that is connected to resistance loader. Individual displays will be installed at each motor. The center gear gives the same resistance to all motors during testing in one single motion.

1.5.1.4 Concept 14: StepperLife Pro

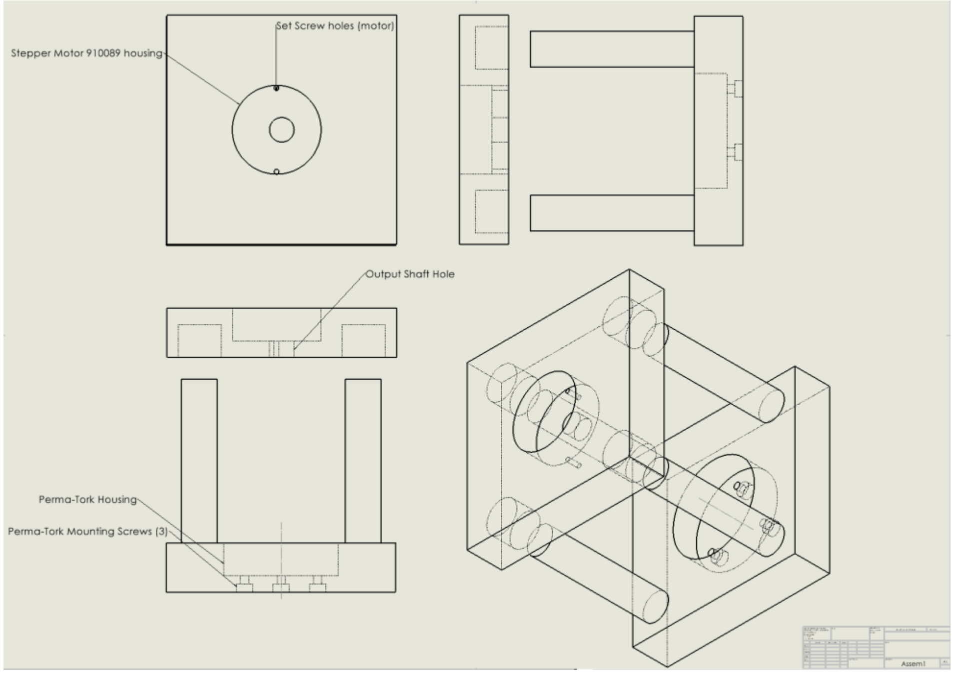


Figure 3: StepperLife Pro

This design is a rectangular prism structure that utilizes the 910089 stepper motor, Perma-Tork, and coupler provided by Danfoss-Turbocor. The Perma-Tork magnetic break is permanently mounted with the bottom mounting screws being inserted into the baseplate leaving clearance for the Perma-Tork set screws when adjusting torque. The coupler is then connected to the mounted Perma-Tork with its own set screws. The top bracket contains the stepper motor securely fastened with two set screws which are then secured to the top cylindrical extrusions from the baseplate. The motor will then press fit into the top section of the coupler. When testing torque, the stepper motor can be easily removed with the two set screws allowing the torque wrench to connect to the coupler for easy measurement, the process is also the same for stepper motor replacement.

1.5.1.5 Concept 75: Torque Master

This design features an open-faced box frame, with a screw hole plate for motor mounting to the frame, a top face mount for the Perma-Tork, a flexible coupler, Perma-Tork lever arm adjustment, an Arduino microcontroller, and individual assemblies. This design is arguably the simplest of our medium fidelity concepts, however simple does not mean poor performance. We rank this design above the rest of the 100 due to the simplicity and ease of manufacturing.

1.5.2 High Fidelity Concepts

The high-fidelity concepts were chosen over others due to their functionality, feasibility, and strong alignment with most, if not all, of the project goals. The team believes that they are the most optimal design choices that can meet the project objectives in a timely manner. These high-fidelity concepts, along with the medium fidelity concepts, will be put through a systematic selection process to decide on the concept that our team will further develop.

1.5.2.1 Concept 1: H-Frame

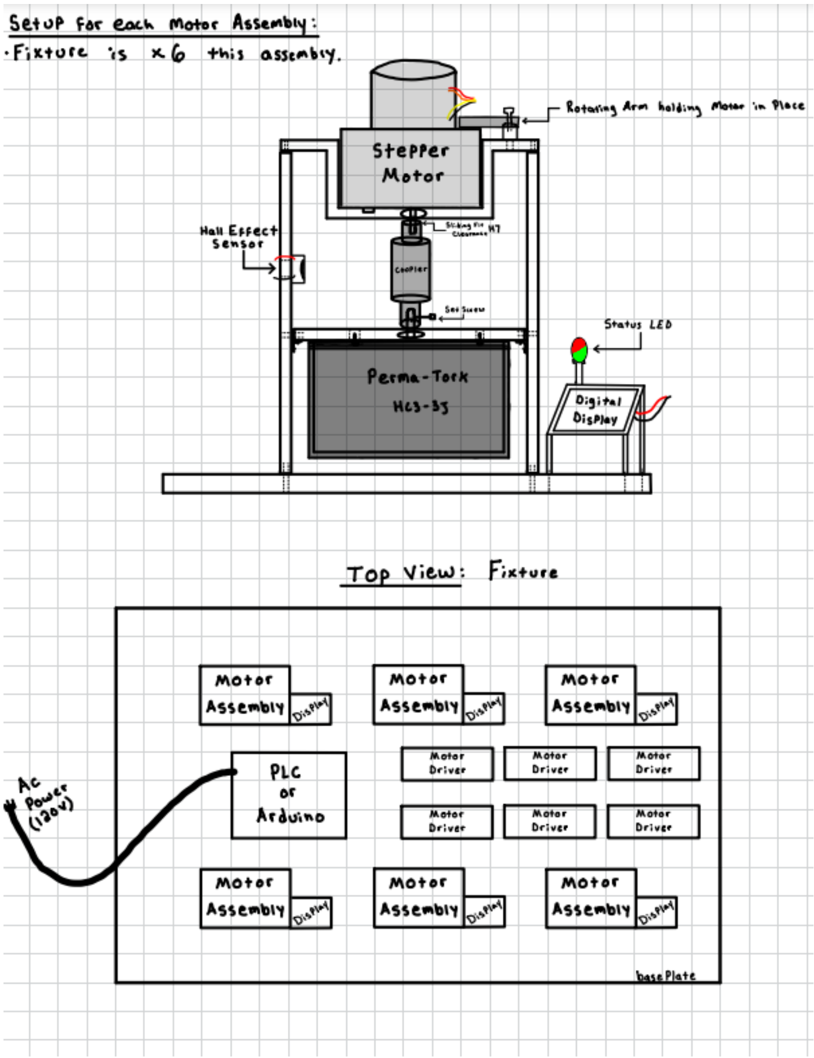


Figure 2: H-Frame

The H-Frame fixture will have a structure with two rows of 3 motors to be tested with 6 in total on one baseplate. Then Perma-Tork resistance loaders will be in parallel to the shaft and orientation of each of the motors. Displays for each motor assembly will output results from each test and a PLC will be used to adjust speed and direction for each assembly. Motor drivers will provide input and PPS for each of the stepper motors being tested. The motor and Perma-Tork are installed in a vertical orientation incorporating a coupler that attaches each component together. The coupler will have a D shape cutout to have a straight and secure alignment between the motor and Perma-Tork. The status and results for each motor assembly will be outputted on a display for the operator to observe for each motor assembly. The layout for the total amount of components in the fixture includes: six Motors, six Perma-Tork's, six Displays, one PLC or Arduino, and six Motor Drivers. A lever arm attachment will be mounted to the base of the Perma-Tork allowing for a manual setting to the torque or resistance put upon the motor.

1.5.2.2 Concept 2: Modular Skeleton

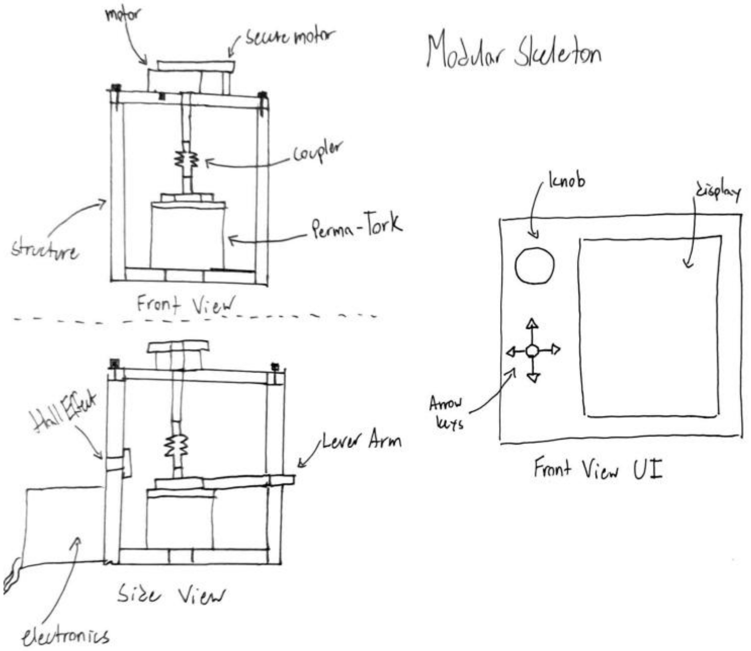


Figure 3: Modular Skeleton

The design consists of a modular structure, where each motor is housed in a skeletal rectangular prism. The stepper motor is aligned and dropped into the top plate, secured using pins that stick up into the motor mounting holes. Motor and pins are held down and in place by a plate that is swung over and secured over the stepper motor. The stepper motor shaft fits into a keyed, flexible joint coupler that is attached to the Perma-Tork. The Perma-Tork is secured to the bottom plate with screws and a lever arm is connected to the top to adjust the torque. Torque can be confirmed by unscrewing the top plate with the screws on each side. Electronics are housed in a box on the side. Hall Effect sensor is placed on the side of the frame. This contains the motor driver, power wire, and connection to the main user interface. The UI is separate from the design and includes the main PLC unit, a screen, knob, and arrow buttons to set parameters for the test. This interface can be connected and control up to 6 motors at a time.

1.5.2.3 Concept 3: Solo C-Frame

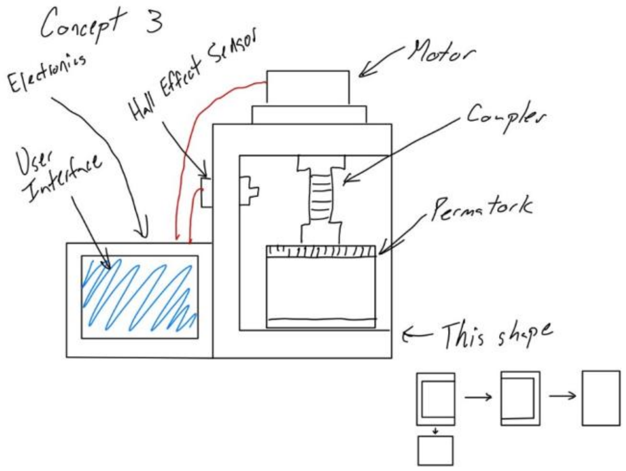


Figure 6: Solo C-Frame

This concept features a rectangular fixture with two adjacent open faces, one on the front and one on the right side. The main benefit of this fixture is accessibility. The adjacent open faces allow for plenty of space to fit fingers to adjust the Perma-Tork resistance after the set screws have been loosened. Then, the motor has easy access as it has a small profile indentation in the top of the frame for it to sit in place. It will be held down axially by the coupler set screw just like the motor is in the IGV assembly. The open concept allows plenty of air flow for any heat dispersion. Attached is a personal controller and user interface for ease of use when testing an individual motor. A Hall Effect sensor is also placed in the frame for the tracking of rotations.

1.6 Concept Selection

The goal of concept selection is to determine the best concept that satisfies all project objectives. To accomplish this goal, selection tools were used to eliminate confirmation bias and ensure that each concept was rated quantitatively under the same selection criteria. The selection tools include a Binary Pairwise Comparison, a House of Quality, Pugh charts, and an Analytical Hierarchy Process. We considered all high and medium fidelity concepts in this system and ranked these concepts against one another. The process certified that the final selection was chosen based on specific customer requirements and design needs rather than internal design bias.

1.6.1 Binary Pairwise Comparison

Binary Pairwise Comparison (BPC) is a concept selection tool that ranks the customer requirements against each other. Our customer requirements were created by categorizing our functions into five categories including User Interface, Failure Detection, Allow Manual Resistance Load Adjustment, User Friendliness, and Reliability. To create the BPC, the customer requirements were listed in both the column and row headers to form a matrix. If the requirement in the column was more important than the requirement in the row, a 1 was placed in the intersection. If the requirement in the column was less important than the requirement in the row, a zero was placed in the intersection. The corresponding cell across the matrix diagonal received the opposite value. The values were then summed up in the “Total” column on the right and output importance weight factors that were used in the following House of Quality. From the

BPC in Table 5 below, it was determined that Reliability was the most important customer requirement, followed by Failure Detection, User friendliness, User Interface, and Allow Manual Resistance Load Adjustment. Reliability is important to our sponsor as he requested a device that can be running for possibly months at a time and keep the rotation and cycle count even when the power runs out. Failure Detection made sense as the next most important customer requirement because the current IGV assembly testing has no failure detection.

Table 5: Binary Pairwise Comparison

Customer Requirements	User Interface	Failure Detection	Allow Manual Resistance Load Adjustment	User Friendliness	Reliability	Total
User Interface	-	0	1	0	0	1
Failure Detection	1	-	1	1	0	3
Allow Manual Resistance Load Adjustment	0	0	-	0	0	0
User Friendliness	1	0	1	-	0	2
Reliability	1	1	1	1	-	4
Total	3	1	4	2	0	

1.6.2 House of Quality

The House of Quality (HOQ) is used to determine the relative weight of each Engineering Characteristic. The Customer Requirements are rows, with the associated importance weight factor next to them, and the list of Engineering Characteristics are columns. First, each engineering characteristic is evaluated for a relationship with the Customer Requirements on a scale of 0-1-3-5 in order of importance. A 0 indicates no relationship, a 1 indicates a minimal relationship, a 3 indicates a significant relationship, and a 5 indicates a highly significant relationship. The values for each Engineering Characteristic are then multiplied by the importance weight factor for each Customer Requirement and summed up in the “Raw Data” row. Finally, the relative weight for each Engineering Characteristic is produced by dividing the “Raw Data” of each by the “Raw Data Sum”, or the total of all “Raw Data” in the chart. This gives the “Relative Weight %” which ranks each Engineering Characteristic by importance.

From the HOQ in Table 6, it was determined that Tracking Cycles and Rotations (Actual) carried the highest weight and Allowing Resistance Load Adjustment carried the lowest. Ranking these characteristics allows us to understand which criteria to use when evaluating our concepts. In Table 7, four Engineering Characteristics stood out as significantly above the average and moved onto the Pugh chart. Additionally, Rigidity was included as a fifth Engineering Characteristic to expand the ranking criteria, as it was close to the average and is well-backed by our Customer Needs. These Engineering Characteristics stand out for their role in the reliability of the structure because most of them have to do with securing the testing components. Tracking Cycles and Rotations (Actual) is the most important because it has a major role not just in reliability, but also how failure will be detected.

Table 6: House of Quality

		Engineering Characteristic													
Improvement Direction		↑	↓	↑	↓	↑	↑	↑	-	-	-	↑	↑	↑	↓
Units		Pa	# Steps	in^2	lb	oz-in	oz-in	oz-in	Total #	P/F	P/F	in^2	in^2	in^2	in^3
Customer Requirements	**Importance Weight Factor**	**Rigidity**	**Test Prep Steps**	**Allowing Resistance Load Adjustment**	**Weight**	**Secure Stepper Motor**	**Secure Resistance Torque Device**	**Secure Coupler**	**Track Cycles and Rotations (Actual)**	**Display Test Parameters**	**Display Test Results**	**Allow for Resistance Torque Verification**	**Coupler Clearance**	**Allow for Motor Replacement Clearance**	**Size**
User Interface	1	0	5	0	0	0	0	0	3	5	5	0	0	0	3
Failure Detection	3	1	1	0	0	3	3	3	5	1	1	0	0	0	0
Resistance Load	0	5	3	5	1	1	5	1	0	0	0	3	3	1	3
User Friendliness	2	0	5	3	5	3	5	5	1	3	3	5	5	5	5
Reliability	4	5	0	1	3	5	5	5	5	0	1	1	1	1	1
Raw Data		23	18	10	22	35	39	39	40	14	18	14	14	14	17
Relative Weight %		7.26	5.68	3.15	6.94	11.04	12.30	12.30	12.62	4.42	5.68	4.42	4.42	4.42	5.36
Rank Order		5	7	14	6	4	2	2	1	10	7	10	10	10	9

Table 7: House of Quality Output

Engineering Characteristics	Relative Weight (%)	Rank	Criteria (Average)
Rigidity	7.26	5	7.28
Test Prep Steps	5.68	7	
Allowing Resistance Load Adjustment	3.15	14	
Weight	6.94	6	
Secure Stepper Motor	11.04	4	
Secure Resistance Torque Device	12.30	2	
Secure Coupler	12.30	2	
Track Cycles and Rotations (Actual)	12.62	1	
Display Test Parameters	4.42	10	
Display Test Results	5.68	7	
Allow for Resistance Torque Verification	4.42	10	
Coupler Clearance	4.42	10	
Allow for Motor Replacement Clearance	4.42	10	
Size	5.36	9	

1.6.3 Pugh Charts

The Pugh chart is a systematic tool for evaluating high and medium fidelity design concepts by comparing them to a datum, or control concept. Our datum is the current testing method used at Danfoss, which involves the entire IGV assembly. Each high and medium fidelity concept is assessed based on its effectiveness in satisfying the engineering characteristics, receiving ratings of plus (+), minus (-), or satisfactory (S). This iterative evaluation process helps eliminate weaker concepts, ultimately narrowing the options in search for the “best” concept. The chart organizes concepts in columns and key Engineering Characteristics from the House of Quality in rows.

Table 8 shows the results of the initial Pugh chart, with H-Frame, Modular Skeleton, and Solo C-Frame scoring the highest number of pluses. Additionally, StepperLife Pro scored a significant number of pluses and satisfactory ratings, keeping it in the top four concepts.

Table 8: Initial Pugh Chart

		Concepts							
Engineering Characteristics	IGV Assembly	Swivel Frame	Hysteresis Break	Tower Tester	StepperLife Pro	Torque Master	H-Frame	Modular Skeleton	Solo C-Frame
Track Cycles and Rotations (Actual)	- DATUM -	+	+	+	+	+	+	+	+
Secure Coupler		S	S	+	S	S	+	+	+
Secure Resistance Torque Device		+	+	S	+	S	+	+	+
Secure Stepper Motor		S	S	S	S	S	S	+	S
Rigidity		-	-	-	+	+	+	S	+
Total Pluses		2	2	2	3	2	4	4	4
Total Satisfactory		2	2	2	2	3	1	1	1
Total Minuses		1	1	1	0	0	0	0	0
Keep?	No	Yes	No	No	Yes	No	Yes	Yes	Yes

From the initial Pugh Chart, the highest-ranking concept is used as a datum to create a final Pugh Chart. As stated earlier, there were three viable options for our new datum: H-Frame, Modular Skeleton, and Solo C-Frame. All three options had the same ratio of pluses to minuses, thus we decided the H-Frame would be the best concept to choose as our new Pugh Chart datum. From the final Pugh Chart, Modular Skeleton and StepperLife Pro stood out, as they had the greatest number of satisfactory ratings. We also selected the datum, H-Frame concept, because the Pugh Chart determined no concept performs an engineering characteristic better than the H-Frame. All three of these concepts then move on to the Analytical Hierarchy Process for a final selection.

Table 9: Final Pugh Chart

		Concepts			
Engineering Characteristics	H-Frame	Modular Skeleton	Solo C-Frame	StepperLife Pro	Swivel Frame
Track Cycles and Rotations (Actual)	- DATUM -	S	S	S	S
Secure Coupler		S	-	-	-
Secure Resistance Torque Device		-	-	S	-
Secure Stepper Motor		S	-	-	-
Rigidity		-	S	S	-
Total Pluses		0	0	0	0
Total Satisfactory		3	2	3	1
Total Minuses		2	3	2	4
Keep?	Yes	Yes	No	Yes	No

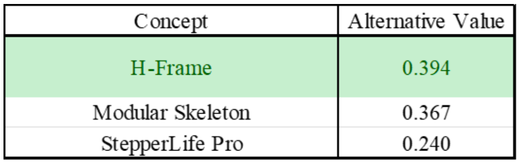
1.6.4 Analytical Hierarchy Process

The Analytical Hierarchy Process (AHP) is used to identify the most critical engineering characteristics for the project's success. Only the top five characteristics from the House of Quality were considered. This process involves comparing each engineering characteristic against itself and ranking their importance using a scale of 1, 3, 5, 7, and 9, where 1 indicates equal importance and 9 signifies that one characteristic is significantly more important than the other. In the [C] Matrix, the ranking goes by comparing the importance of the row (B) to the column (A). The importance value in one cell is used to determine the importance value in the corresponding cell across the diagonal of the matrix by taking its reciprocal value. The values are then normalized in the norm[C] matrix and the rows are summed up to determine each engineering characteristic's critical weight. To ensure there is no bias, a consistency check is performed; a consistency ratio below 0.1 indicates unbiased rankings.

From the AHP for the engineering characteristics it was determined that Track Cycles and Rotations (Actual) was most important, while the least important was Rigidity. The tables for this part of the selection process can be found in Appendix F.

After this we completed the same process five more times but compared each of the concepts to each other based on each of the five engineering characteristics. In those charts, the higher the rating factor was, the better the concept performed at the engineering characteristic. The design alternative priorities that resulted from those tables were then matrix multiplied by the critical weights of each engineering characteristic to determine the alternative value for each concept. The selected concept had the highest alternative value. All tables for this part of AHP can be found in Appendix F as well.

Table 10: Final Selection



Concept	Alternative Value
H-Frame	0.394
Modular Skeleton	0.367
StepperLife Pro	0.240

Our AHP resulted in H-Frame being the selected concept. Its higher alternative value can be attributed to its better performance at securing the coupler, securing the stepper motor, and rigidity.

1.6.4 Final Selection

After determining the most critical engineering characteristics and seeing which concept satisfies these characteristics, we determined that the "H-Frame" concept will perform best. The H-Frame is a concept that has a large base plate where all 6 motor fixtures will sit on. Each of the 6 modular structures will incorporate the needs to secure the stepper motor and Perma-Tork and to track the rotations of the motor under a specified resistance.

The H-Frame is a structurally sound fixture with plenty of space for the operator to adjust components within the fixture (coupler, Perma-Tork, stepper motor). Figure 2 in Concept Generation gives a good idea of how the structure will hold everything in place. This design does not exactly justify where all electronics (wires, HMI, controllers) will be located, which leaves room for adjustability. The concept does however specify the use of a PLC because they are most easily adaptable when compared to an Arduino microcontroller, as well as using a keyed coupler because this secures the coupler the best in comparison to a set screw coupler connection. This concept also utilizes a Hall-Effect sensor to track the rotations of the shaft, this sensor is subject to change however it is the most viable option at this point.

Thus, this concept is best for satisfying all engineering characteristics but is also very adaptable to changes further along in the design process. These changes may arise from scope changes, customer input opinions, and newfound information that can be useful for the design.

1.8 Spring Project Plan

Chapter Two: EML 4552C

2.1 Spring Plan

Project Plan.

Build Plan.

Appendices

Appendix A: Code of Conduct

Code of Conduct

This document will serve as the team code of conduct that will serve as the regulation in which we conduct throughout the duration of the project lasting from Fall 2024 to Spring 2025.

Mission Statement

Team 505 has committed to dedicate the 2024-2025 academic school year towards developing a reliable, user friendly stepper motor lifecycle fixture for Danfoss Turbocor. The team will utilize industry standards and strive to uphold the image of Danfoss Turbocor, our sponsor Cole Gray, and the FAMU-FSU College of Engineering throughout the entirety of the project. We aspire to accomplish all goals with punctuality and dedication. ~~–~~while also behaving in a professional manner. Through ~~having an~~our opportunity ~~of working~~to work with Danfoss Turbocor, we will develop the skills needed to not only succeed in our Senior Design project, but also in our future careers.

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Outside Obligations

Outside obligations and responsibilities are to be recognized as time allocated for that group member. These times are mentioned below and are subject to amendment throughout the project. Amendments to outside obligation times can be made at any time and should be reflected in this document. The group members should notify the group immediately of any changes or emergencies.

Specific member obligations are as follows: (Updated 1~~9~~/9~~13~~/25~~24~~)

Joseph Garvie: No specific time obligations, flexible schedule. Subject to change.

Mason Herbet: Rigid Swim Schedule: (M~~, T, and~~ - F: 7:00am-8:30am, 2:30pm-4:30pm~~;~~ ~~W and Th: 7:00am – 8:30am~~) Weights: (M and W~~, W, and F~~: 10~~9~~:15am- 11~~0~~:00am)

Albert Auer: No specific weekly time obligations, nationals for powerlifting in spring.

Chaney Bushman: No specific time obligations, flexible schedule. Subject to change.

Bradford Andrews: Baptist Collegiate Ministry Involvement (Tuesday 6:30pm-9pm), Church Involvement (Wednesday 5:30pm-8pm)

Team Roles

Team roles are flexible throughout the project and self-assigned based on expertise and interests. Work not related to a specific role will be assigned on a case-by-case basis and collaboration is encouraged.

Team Member	**Team Role**
Joseph Garvie	Systems Engineer
Chaney Bushman	Manufacturing Engineer, Test Engineer
Albert Auer	Mechanical Design Engineer
Bradford Andrews	Mechatronics Engineer
Mason Herbet	CAD Designer

The Systems engineer will be responsible for ensuring that all of the interacting systems of the lifecycle testing fixture are integrated together. Additionally, the Systems engineer will work closely with the Manufacturing and Test engineer to manufacture and fit together electrical components with mechanical components. The systems engineer will also oversee quality control and revise written portions of the project.

The Manufacturing and Test engineer is responsible for designing the main components of the test fixture and adding design changes over time in CAD. Additionally, they are responsible for selecting materials and overseeing the manufacturing process and the ~~of the~~ testing ~~xt~~of the fixture. The Manufacturing and Test engineer will work closely with the Systems engineer to ensure component collaboration.

The Mechanical Design engineer will be responsible for wire management solutions throughout the design, circuit diagrams, and fixture appearance. They will work closely with the CAD Designer to enhance the appearance of the product.

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The Mechatronics engineer will be responsible for initial circuitry design, ~~and~~ electronics selection, ~~as well as~~ and code skeleton development~~frameworks~~. They will work alongside the Mechanical Design engineer to improve wire management and to create and update a circuit diagram. The Mechatronics Engineer will keep the project on a strict timeline and manage the budget.

The CAD Designer will be responsible for the user interface design, HMI structure design, and wire management inside the structure. Additionally, they will work closely with the Manufacturing and Test engineer to iterate the main testing fixture design and manufacture its components. The CAD Designer will also work with the Mechatronics engineer and the Mechanical Design engineer to improve wire management in and around the HMI.

As responsibilities arise, team meetings will be called to assign specific tasks as it relates to their skill set. Group members are expected to communicate their current level of workload and their availability to take on new responsibilities.

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Communication

Communication between team members is to be conducted respectfully and with professional language. A text group chat will be the primary method of day-to-day communication. It will be used to initially set up work sessions to complete the week's assignments or other current tasks at hand. ~~A Microsoft Teams calendar will be updated with meeting times throughout the project to reflect verbal and text group chat agreements or discussions.~~ Email will be used when setting up meetings between the team and our advisor or sponsor, with the entire team being CC'd onto the email thread. Team 505 is expected to respond within 24 hours of a message sent in the primary text group chat. In the event of an unresponsive group member the conflict resolution policy and McConomy/TA intervention policies will be referred to below.

"Communication is the number one contributor to a successful team." (Chaney Bushman, 2024)

How to Notify Group

The primary communication outlet is the text message group chat and email. The group chat is for day-to-day communication and team members are encouraged to update the group on individual progress. Phone calls are used for checking if a team member is late, absent from a meeting, or if there is an emergency. The Teams Calendar is synced with email for scheduling meetings.

How to Respond to People in Professional Meeting

In professional meetings, online or in-person, all communication will be productive and respectful. Group members are expected to be polite and use proper grammar. Members are expected to maintain an appropriate appearance for professional meetings and abide by the Team 505 Dress Code below. In case of a disagreement between the group and an advisor or sponsor, group members are expected to be patient, flexible, and understanding. Team 505 strives to reflect the values of both the FAMU-FSU College of Engineering and Danfoss Turbocor throughout the entirety of the project.

Dress Code

For all formal presentations, including Senior Design Day, suits should be worn for all members. While a specific jacket color is not required for all members, a white dress shirt is required. For sponsor meetings, a polo shirt, long pants, and closed-toed shoes are required. There is no formal dress code for informal team meetings or Advising meetings, but casual dress clothes are expected.

What do we do Before Going to an Advisor or Professor

If a conflict is recognized by the group, a meeting is to be formally scheduled where attendance is mandatory. The meeting will specifically address the issue and seek a resolution. If no resolution is met, the team will refer to the McConomy/TA Intervention Policy below.

McConomy/TA Intervention Policy

In the event of any unresolved issues as described previously, the team will email the TAs for remediation. If they advise contacting Dr. McConomy, the team will then do so through email. Contacting Dr. McConomy for conflict resolution or other issues within the group implies that the final remediation strategy has been resorted to and all other strategies have failed. The team expects

Dr. McConomy to advise the team on a way to resolve the situation. If this advice is ineffective the team is to notify Dr. McConomy and request, via email, a direct intervention with the specific group member. Dr. McConomy is to contact this group member and request a one-on-one meeting to address the persisting issues at a time that most aligns with his schedule.

Attendance Policy

Attendance is expected at all scheduled meetings, especially meetings with the project sponsor or project advisor. Meetings that are reoccurring and, on the Teams, calendar will be scheduled to maximize the number of attendees. For scheduled meetings, 5 meeting absences are permitted per semester. After 5 absences, a discussion between that member and the entire team will be scheduled and held to address the ongoing issue. If no resolution is made in the meeting, the group will refer to the McConomy/TA Intervention Policy.

The group is expected to meet during/after each senior design class time block to tackle the weeks objectives/assignments. Monday, Wednesday, Friday, Saturday, and Sunday meetings can be scheduled in addition to class time blocks. The group can also agree to meet remotely, if necessary, through Microsoft Teams. Members are encouraged to attend meetings outside of the scheduled ones, but not required.

The Lucky Goat Clause

Team 505, to improve group morale, are encouraged to attend coffee outings ~~yearly~~monthly. Meetings are expected to accommodate all members' schedules.

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How to Amend

In the event of an amendment to the Code of Conduct, a meeting is to be held with all team members where specific changes are discussed. All team members must agree to the proposed amendment and re-sign.

Vacation Days

Vacation days are encouraged for use as a group. If a member must take a vacation day for personal reasons, they must communicate it with the group before usage. If a situation arises where a vacation day could potentially be used for group purposes, a team vote will determine if it is necessary.

Code of Conduct Acknowledgment

Each member of the team has discussed and reviewed this contract and agrees to uphold everything provided in this document. Each member understands that all procedures outlined in the Code of Conduct are expected. Each member understands that the Code of Conduct is subject to amendments. Each member agrees that signing this document is a binding agreement to adhere to the standards detailed above.

Statement of Understanding

I, Mason Herbet, understand and agree to the terms of this Code of Conduct.

I, Albert Auer, understand and agree to the terms of this Code of Conduct.

I, Bradford Andrews, understand and agree to the terms of this Code of Conduct.

I, Chaney Bushman, understand and agree to the terms of this Code of Conduct.

I, Joseph Garvie, understand and agree to the terms of this Code of Conduct.

Albert Auer : x Albert Auer

Mason Herbert : x Mason Herbert

Joseph Garvie : x Joseph Garvie

Chaney Bushman : x

Bradford Andrews : x Bradford Andrews

Signatures (1~~9~~/9~~13~~/25~~24~~)

Appendix B: Work Breakdown Structure

T505: Work Breakdown Structure

Item Number	Task	Assignee	Due Date	Complete	Date Completed
1	**Code of Conduct**	Mason	9/13/2024	yes	9/12/2024
1.1	Schedule Team Meeting	Joseph		yes	9/12/2024
1.2	Plan of Action	Brad		yes	9/12/2024
1.3	Finish Document	Chaney		yes	9/12/2024
1.4	Submit Assignment	Joseph		yes	9/12/2024
2	**Work Breakdown Structure**	Brad	9/13/2024	yes	
2.1	Enter Tasks	Brad		yes	
2.2	Assign Tasks	Brad		yes	
2.3	Review Document	Brad		yes	
2.4	Submit Assignment	Brad		yes	
2.5	Revision After Grading	Brad		no	
3	**Project Scope**	Chaney	9/20/2024	yes	

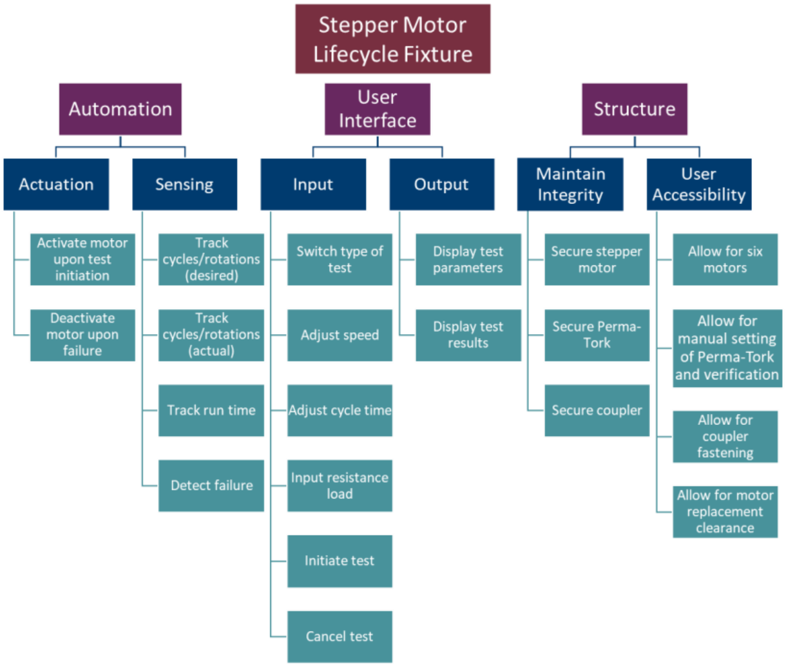
3.1	Project Description	Joseph		yes	
3.2	Key Goals	Albert		yes	
3.3	Market	Joseph		yes	
3.4	Assumptions	Albert		yes	
3.5	Stakeholders	Mason		yes	
3.6	Review Grammar / Formatting	Mason		yes	
3.7	Review Rubric	Brad		yes	
3.8	Submit Assignment	Chaney		no	
3.9	Revision After Grading	Brad		no	
4	**Customer Needs**	Albert	9/27/2024	no	
4.1	Meet With Sponsor	Joseph		no	
4.2	Interpret Needs	Chaney		no	
4.3	Verify Needs	Mason		no	
4.4	Finish Document	Joseph		no	
4.4	Review Grammar / Formatting	Brad		no	
4.5	Review Rubric	Mason		no	
4.6	Submit Assignment	Albert		no	
4.7	Revision After Grading	Chaney		no	
5	**Submit VDR1**	Mason	9/30/2024	no	
5.1	Create Powerpoint	Joseph		no	
5.2	Introduction	Chaney		no	
5.3	Project Brief	Mason		no	
5.4	Background	Joseph		no	
5.5	Project Scope	Albert		no	
5.6	Customer Needs	Albert		no	
5.7	Functional Decomposition	Brad		no	
5.8	References	Joseph		no	
5.9	Review Rubric/Grammar	Joseph		no	
5.10	Submit Assignment	Mason		no	
6	**Functional Decomposition**	Brad	10/4/2024	no	
6.1	Start With a Verb	Joseph		no	
6.2	Cross-Reference Table	Albert		no	
6.3	Creation of Hierarchy Chart	Joseph		no	
6.4	Explanation of Results	Albert		no	
6.5	Connection to Systems	Mason		no	

6.6	Smart Integration	Mason		no
6.7	Ensure Action and Outcome	Chaney		no
6.8	Review Function Resolution	Brad		no
6.9	Check Grammar	Chaney		no
6.10	Submit Assignment	Brad		no
6.11	Revision After Grading	Joseph		no
7	**VDR1**	Joseph	10/8/2024	no
7.1	Revise Powerpoint Based on Feedback	Joseph		no
7.2	Review Rubric/Grammar	Chaney		no
7.3	Submit Assignment	Joseph		no
7.4	Schedule Presentation Practice	Mason		no
8	**Web Master**	Brad	10/11/2024	no
8.1	Select Web Master	Mason		no
8.2	Fill Out Spreadsheet	Joseph		no
8.3	Submit Assignment	Brad		no
9	**Targets**	Mason	10/18/2024	no
9.1	Match Metrics to Functions	Albert		no
9.2	Find Methods of Validation	Mason		no
9.3	Determine Targets	Chaney		no
9.4	Derivations of Targets and Metrics	Albert		no
9.5	Discussion of Measurement	Joseph		no
9.6	Critical Targets/Metrics	Joseph		no
9.7	Summary and Catalog	Brad		no
9.8	Review Rubric/Grammar	Chaney		no
9.9	Submit Assignment	Mason		no
9.10	Revision After Grading	Brad		no
10	**Research**	Brad	10/18/2024	no
10.1	Gather Stepper Motor Info	Mason		no
10.2	Gather Compressor Info	Albert		no
10.3	Gather Perma-Tork Info	Joseph		no
10.4	Gather Electronics Info	Brad		no

10.5	Outsource Possible Parts	Chaney		no	
10.6	Further Benchmarking	Mason		no	
10.7	Schedule Meeting to Discuss Findings	Brad		no	
11	**Concept Generation**	Joseph	10/25/2024	no	
11.1	Gather All 100 Concepts	Chaney		no	
11.2	Medium Fidelity Concepts	Joseph		no	
11.3	High Fidelity Concepts	Mason		no	
11.4	Concept Generation Tools	Chaney		no	
11.5	Review Rubric/Grammar	Albert		no	
11.6	Submit Assignment	Albert		no	
11.7	Revision After Grading	Mason		no	
12	**Concept Selection**	Brad	11/1/2024	no	
12.1	House of Quality	Joseph		no	
12.2	Pugh Charts	Brad		no	
12.3	AHP	Albert		no	
12.4	Final Selection	Chaney		no	
12.5	Review Rubric/Grammar	Mason		no	
12.6	Submit Assignment	Brad		no	
12.7	Revision After Grading	Brad		no	
13	**Risk Assessment**	Albert	11/8/2024	no	
13.1	Brainstorm What Can Go Wrong	Mason		no	
13.2	Accidents Identified	Joseph		no	
13.3	Steps to Avoid Hazards	Chaney		no	
13.4	Safety Measures	Mason		no	
13.5	Emergency Response	Brad		no	
13.6	Emergency Contacts	Brad		no	
13.7	Review Rubric/Grammar	Joseph		no	
13.8	Submit Assignment	Albert		no	
13.9	Revision After Grading	Brad		no	
14	**VDR2**	Brad	11/12/2024	no	
14.1	Create Powerpoint	Joseph		no	
14.2	Title/Introduction	Joseph		no	
14.3	Project Brief Summary	Albert		no	
14.4	Targets and Metrics	Brad		no	
14.5	Concept Generation	Mason		no	

14.6	Concept Selection	Chaney		no	
14.7	Review Rubric/Grammar	Mason		no	
14.8	Submit Assignment	Brad		no	
14.9	Schedule Presentation Practice	Brad		no	
15	**Bill of Materials**	Chaney	11/15/2024	no	
15.1	Line Items	Joseph		no	
15.2	Order Needs	Joseph		no	
15.3	Check for Thoroughness	Mason		no	
15.4	Identify Vendors	Chaney		no	
15.5	Identify Part Details	Chaney		no	
15.6	Line Item Maturity	Albert		no	
15.7	Project Cost	Joseph		no	
15.8	Unit Cost	Mason		no	
15.9	Labor Cost	Albert		no	
15.10	Review Rubric/Grammar	Brad		no	
15.11	Submit Assignment	Chaney		no	
15.12	Revision After Grading	Chaney		no	
16	**Spring Project Plan**	Joseph	11/22/2024	no	
16.1	Determine Milestones and Deliverables from End to Beginning	Brad		no	
16.2	Develop Timeline	Mason		no	
16.3	Review Rubric/Grammar	Joseph		no	
16.4	Submit Assignment	Joseph		no	
16.5	Revision After Grading	Albert		no	
17	**VDR3 Prototype**	Joseph	12/3/2024	no	
17.1	Create Document	Mason		no	
17.2	Current State of Design	Joseph		no	
17.3	Forecast of Work Ahead	Albert		no	
17.4	Identify Problem Areas	Mason		no	
17.5	Complete Prototype	Chaney		no	
18	**Poster**	Brad	12/6/2024	no	
18.1	Create Poster File	Brad		no	
18.2	Review Rubric/Grammar	Mason		no	
18.3	Order Printed Poster	Brad		no	
18.4	Submit Poster	Joseph		no	

Appendix C: Functional Decomposition



Appendix D: Target Catalog

Target Catalog		
Function	Metric	Target
Activate motor upon test initiation	Voltage	12 V
Deactivate motor upon failure	Voltage	0 V
Track cycles/rotations (desired)	Rotations (Percentage)	Calculated within 99% Accuracy based on PPS
Track cycles/rotations (actual)	Rotations (Percentage)	98%
Track run time	Seconds	1 second

Detect failure	Seconds/Cycle	Actual Rotation Time > Expected Rotation Time * FOS
Switch type of test	Visual	P/F
Adjust speed	PPS	0-1000
Adjust cycle time	Time (seconds)	0-300 s
Input resistance load	Torque	0.03 - 0.45(N-m)
Initiate test	Voltage	5V
Cancel Test	Voltage	5V
Display test parameters	Visual	P/F
Display test results	Visual	>2
Secure stepper motor	Torque	>0.45 N-m
Secure Perma-Tork	Torque	>0.45 N-m
Secure coupler	Torque	>0.45 N-m
Allow for six motors	Number of Motors	6 Motors
Allow for manual setting of Perma-Tork	Area	>4620 mm^2
Allow for verification of Perma-Tork resistance torque	Torque	0.03-0.45 N-m
Allow for coupler fastening	Area	>1800 mm^2
Allow for motor replacement clearance	Area	>4000 mm^2

Appendix E: 100 Design Concepts

Brainstorming Concepts:

1. Structure is a rectangular prism, with the stepper motor being dropped into the top plate and secured using pins that are held in place by a plate secured over the stepper motor. The stepper motor shaft fits into a keyed coupler that is already attached to the Perma-Tork.
2. User interface includes an OLED screen with a knob and arrow keys. The knob is to adjust and set values, and the arrow keys are to navigate between test parameters
3. The entire setup is modular, with high-strength latches that can secure and stack each rectangular prism to each other
4. Electronics are housed in a rectangular box behind the main structure and have only a power cord sticking out behind it.
5. User interface includes a screen that runs during the test, showing run-time, torque, pps, etc. with a graph or just a few lines of output
6. The fixture will have an auto loader that the user can fit up to 3 stepper motors in. Once one motor stops spinning, the auto loader rotates like a pistol and fits another stepper motor into the slot.
7. Each motor is attached to the braking system of a car, where the brake pads are rated at different torques. The employee replaces the brake pads to start a different test and the resistance is constant.

8. The motor is used to spin rotor blades that turn to provide a different resistance against the air as the requested torque increases. The enclosure will house a fan that blows in the opposite direction.
9. The motor is fastened using glue to the top plate. As the motor increases in heat, the glue loosens. Once the motor fails, the heat is hot enough to take the motor out from the hold of the glue.
10. Under a certain PPS, two motors are attached to each other and work against each other until one of them fails.
11. The main modular structure is a triangular prism each with screws on the top and bottom of the structure to mount to each other creating a hexagon providing around 90 degrees of entrance at each face and additional space in the center
12. The structure is a set of 3 modular rectangular prisms housing two motor fixtures each separated to allow space for the PLC and a motor driver for each motor
13. The structure is a rectangular prism housing all 6 motor lifecycle fixtures. The Perma-Torks are mounted to the bottom plate permanently but leaving space for set screw adjustment. The coupler is operating in free space mounted to the Perma-Tork. The 910089 stepper motor slides into a housing that is enclosed by a plate that slides across the top of the housing.
14. The fixture is a separate structure for each motor life cycle structure. The bottom plate provides a hole for the Perma-Tork to securely sit in and has counter bore to allow clearance for mounting screws. 4 cylindrical extrusions to the top plate for the motor

housing provide the main rigidity of the structure to provide ample space for user friendliness.

15. User interface is an Arduino LED with a single knob that allows for transition between the different life cycle test and a button to select the variables (speed, PPS, torque) and sends a matrix of information to a computer that creates a MATLAB graph of the life cycle test
16. The fixture connects all 6 motors to a single gear box that has a gear ratio of 6:1 that connects to a single Perma-Torque if all stepper motors are being tested at the same resistance.
17. The structure is a rectangular caterpillar tread that allows for a flexible layout with a rubber bottom to prevent slip and vibration. The design can also be separated into individual tread segments.
18. The stepper motor life cycle structure motor is attached to a coupler that spins the blades within a contained structure housing a fluid with a certain viscosity and density matching the torque resistance.
19. The Perma-Tork is replaced with a hysteresis break where torque is adjusted by the input current rather than manual adjustment.
20. The top plate which contains the motor housing is a press fit mold made of a polymer that allows the motor to be inserted and constrained without set screws.
21. The main structure of this fixture has a triangular shape fastening 3 individual motors on one level. Each motor is in a vertical orientation and attached to a second level that incorporates another set of 3 motors to test.

22. The structure includes a rotating turntable that has 6 motor testing assemblies oriented in a circular area with power and driving components at the center of the fixture.
23. The fixture will have a structure that two rows of 3 motors to be tested with 6 in total on one baseplate. Then Perma-Tork resistance loaders will be in parallel to the shaft and orientation of each of the motors. Displays for each motor assembly will output results from each test and a PLC will be used to adjust speed and direction for each assembly.
24. The fixture will have a gear box enabling resistance to each stepper motor at certain levels giving different torque values. It will test 6 motors at once with a main HMI display of data received as well as control over the speed and direction the motors are ran at.
25. The structure of the fixture will have a pivot like motion for each motor assembly with the resistance loader, The orientation will change at certain angles allowing effects of differing angles the motor will run at.
26. The fixture will include a worm gear that is attached to a resistance loader. This worm gear will connect to each rotating shaft of the motors being tested giving resistance to all motors.
27. Each motor will have a hydraulic piston that is attached to the rotating shaft of the motor, the linkage made will allow rotation as well as an in and out motion for the piston mimicking a resistance for each motor tested.
28. The structure models the look of a vertical conveyer that puts each motor assembly in a vertical orientation including a main display for all data results.

29. The structure of the fixture will model a circular tower that orients each motor vertically allowing the shafts to connect with a rotating spur gear in the center of the tower that is connected to resistance loader. Individual displays will be installed at each motor.
30. The fixture incorporates an assembly line motion of auto installing a motor, conducting the test then removing and installing the next motor to run an individual test on it. One display will be used to output results for the tested motor and save results to plot and compare between each motor result. One PLC and driver are used to power the motor component during testing.
31. Individual half open structures for each motor with wires running to a central PLC with a user interface. Perma-Tork bottom mounted.
32. A two-motor, open face structure with one PLC and HMI for the two motors. Perma-Tork bottom mounted.
33. A one-motor, open structure with one PLC and HMI. Perma-Tork bottom mounted.
34. A fixture holding all Perma-Torks from their top face with a small area in between the motor and Perma-Tork mounts for the couplers. Spaces for all motors to be attached to their corresponding couplers.
35. Cylindrical open-face structure with a top mount for the motor that lifts up and swivels for easy access to adjust and verify the Perma-Tork.
36. The fixture is made of a bottom plate for the Perma-Tork and a top mount for the motor that can be fixed to the bottom plate with screws. The top mount has one open face. Acts as a shell.

37. The motor, coupler, and Perma-Tork fixtures are built into a Lazy Susan that can be rotated to bring the motor the user wants to see forward. All in one design with a central User Interface.
38. Fixture with motorized Perma-Tork adjustment using a large gear attached to the top face of the Perma-Tork. Uses open air structure.
39. With a press fit coupler, there is a motor that automatically lifts up the motor from the coupler and Perma-Tork upon failure.
40. The fixture has 6 mount assemblies attached to each other with hinges that can be folded together to conserve space but opened to allow for easy access.
41. **Biomimicry:** Use a hollow cylindrical frame, similar to bamboo, which is the best cross section shape for resisting torsion.
42. **Biomimicry:** Use a glue-like substance, similar to tree resin, to hold the stepper motor and Perma-Tork in place during the test procedure.
43. **Biomimicry:** Microcontroller and other exposed electronics susceptible to water damage are coated in a water proofing material similar to beeswax protecting the hive from water damage.
44. The frame is made from retractable, telescoping, supports which adjust to varying motor shaft and coupler lengths and also aid the process of setting the motor in correct vertical position.
45. The underside of the frame to be equipped with hooks that latch onto the supports of the fixture stand preventing the frame from rotating unintentionally.

46. Use a Hoeken straight-line linkage to vertically displace the motor in and out of the frame while also ensuring the motor shaft is aligned with the coupler axis.
47. Motor mount and Perma-Tork mount incorporate inflatable rubber bladders which inflate to the corresponding diameters creating a press fit and preventing unwanted slipping.
48. **Forced Analogy:** A spool, similar to a fishing reel, is used to retract or extend the vertical position of the top motor mount into desired position.
49. **Forced Analogy:** The coupler connecting the motor shaft to the Perma-Tork uses a circular clamp that tightens around both shafts, drawing the clamp pieces together like a drywall screw anchor.
50. **Forced Analogy:** The test outputs are transmitted from the microcontroller to the user's phone in a file via an internet connection.

Morphological Chart

51. Box with Hatch, Pinned Plate with Motor Cover, Bottom Face Mount, Jointed/Flexible Coupler, Hand Adjustment, Arduino, Modular Layout
52. Skeletal Frame, Screw Hole Plate, Bottom Face Mount, Spline Coupler, Lever Arm Adjustment, PLC, Modular Layout
53. Skeletal Frame, Screw Hole Plate, Bottom Face Mount, Jointed/Flexible Coupler, Pinned Lever Arm Adjustment, PLC, Modular Layout
54. Box with Hatch, Pinned Plate with Motor Cover, Top Face Mount, Spline Coupler, Lever Arm Adjustment, Arduino, Modular Layout
55. Open Face Box, Screw Hole Plate, Bottom Face Mount, Press Fit Coupler, Hand Adjustment, PLC, Modular Layout

56. Skeletal Frame, Pinned Plate with Motor Cover, Top Face Mount, Spline Coupler, Lever Arm Adjustment, Arduino, Modular Layout
57. Box with Hatch, Pinned Plate with Motor Cover, Bottom Face Mount, Jointed/Flexible Coupler, Hand Adjustment, PLC, Modular Layout
58. Open Face Box, Screw Hole Plate, Top Face Mount, Jointed/Flexible Coupler, Pinned Lever Arm Adjustment, PLC, Modular Layout
59. Box with Hatch, Pinned Plate with Motor Cover, Top Face Mount, Press Fit Coupler, Hand Adjustment, Arduino, One Structure
60. Open Face Box, Screw Hole Plate, Bottom Face Mount, Spline Coupler, Pinned Lever Arm Adjustment, Arduino, Modular Layout
61. Skeletal Frame, Screw Hole Plate, Bottom Face Mount, Press Fit Coupler, Hand Adjustment, PLC, Modular Layout
62. Box with Hatch, Pinned Plate with Motor Cover, Bottom Face Mount, Spline Coupler, Lever Arm Adjustment, PLC, Modular Layout
63. Open Face Box, Screw Hole Plate, Top Face Mount, Spline Coupler, Hand Adjustment, Arduino, Modular Layout
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65. Open Face Box, Screw Hole Plate, Bottom Face Mount, Jointed/Flexible Coupler, Lever Arm Adjustment, PLC, Modular Layout
66. Skeletal Frame, Pinned Plate with Motor Cover, Top Face Mount, Spline Coupler, Pinned Lever Arm Adjustment, PLC, Modular Layout

67. Box with Hatch, Pinned Plate with Motor Cover, Bottom Face Mount, Press Fit Coupler, Hand Adjustment, Arduino, Modular Layout
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89. Box with Hatch, Pinned Plate with Motor Cover, Top Face Mount, Press Fit Coupler, Lever Arm Adjustment, PLC, Modular Layout
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98. Open Face Box, Screw Hole Plate, Bottom Face Mount, Jointed/Flexible Coupler, Pinned Lever Arm Adjustment, PLC, Modular Layout
99. Box with Hatch, Pinned Plate with Motor Cover, Top Face Mount, Press Fit Coupler, Lever Arm Adjustment, Arduino, Modular Layout

100. Open Face Box, Screw Hole Plate, Top Face Mount, Spline Coupler, Lever Arm Adjustment, PLC, Modular Layout

Appendix F: Concept Selection Charts

Customer Requirements	User Interface	Failure Detection	Allow Manual Resistance Load Adjustment	User Friendliness	Reliability	Total
User Interface	-	0	1	0	0	1
Failure Detection	1	-	1	1	0	3
Allow Manual Resistance Load Adjustment	0	0	-	0	0	0
User Friendliness	1	0	1	-	0	2
Reliability	1	1	1	1	-	4
Total	3	1	4	2	0	

Table 1: Binary Pairwise Comparison

		Engineering Characteristic													
Improvement Direction		↑	↓	↑	↓	↑	↑	↑	-	-	-	↑	↑	↑	↓
Units		Pa	# Steps	in^2	lb	oz-in	oz-in	oz-in	Total #	P/F	P/F	in^2	in^2	in^2	in^3
Customer Requirements	**Importance Weight Factor**	**Rigidity**	**Test Prep Steps**	**Allowing Resistance Load Adjustment**	**Weight**	**Secure Stepper Motor**	**Secure Resistance Torque Device**	**Secure Coupler**	**Track Cycles and Rotations (Actual)**	**Display Test Parameters**	**Display Test Results**	**Allow for Resistance Torque Verification**	**Coupler Clearance**	**Allow for Motor Replacement Clearance**	**Size**
User Interface	1	0	5	0	0	0	0	0	3	5	5	0	0	0	3
Failure Detection	3	1	1	0	0	3	3	3	5	1	1	0	0	0	0
Resistance Load	0	5	3	5	1	1	5	1	0	0	0	3	3	1	3
User Friendliness	2	0	5	3	5	3	5	5	1	3	3	5	5	5	5
Reliability	4	5	0	1	3	5	5	5	5	0	1	1	1	1	1
Raw Data		23	18	10	22	35	39	39	40	14	18	14	14	14	17
Relative Weight %		7.26	5.68	3.15	6.94	11.04	12.30	12.30	12.62	4.42	5.68	4.42	4.42	4.42	5.36
Rank Order		5	7	14	6	4	2	2	1	10	7	10	10	10	9

Table 2: House of Quality

Engineering Characteristics	Relative Weight (%)	Rank	Criteria (Average)
Rigidity	7.26	5	7.28
Test Prep Steps	5.68	7	
Allowing Resistance Load Adjustment	3.15	14	
Weight	6.94	6	
Secure Stepper Motor	11.04	4	
Secure Resistance Torque Device	12.30	2	
Secure Coupler	12.30	2	
Track Cycles and Rotations (Actual)	12.62	1	
Display Test Parameters	4.42	10	
Display Test Results	5.68	7	
Allow for Resistance Torque Verification	4.42	10	
Coupler Clearance	4.42	10	
Allow for Motor Replacement Clearance	4.42	10	
Size	5.36	9	

Table 3: House of Quality Outputs

		Concepts							
Engineering Characteristics	IGV Assembly	Swivel Frame	Hysteresis Break	Tower Tester	StepperLife Pro	Torque Master	H-Frame	Modular Skeleton	Solo C-Frame
Track Cycles and Rotations (Actual)	- DATUM -	+	+	+	+	+	+	+	+
Secure Coupler		S	S	+	S	S	+	+	+
Secure Resistance Torque Device		+	+	S	+	S	+	+	+
Secure Stepper Motor		S	S	S	S	S	S	+	S
Rigidity		-	-	-	+	+	+	S	+
Total Pluses		2	2	2	3	2	4	4	4
Total Satisfactory		2	2	2	2	3	1	1	1
Total Minuses		1	1	1	0	0	0	0	0
Keep?	No	Yes	No	No	Yes	No	Yes	Yes	Yes

Table 4: Initial Pugh Chart

		Concepts			
Engineering Characteristics	H-Frame	Modular Skeleton	Solo C-Frame	StepperLife Pro	Swivel Frame
Track Cycles and Rotations (Actual)	- DATUM -	S	S	S	S
Secure Coupler		S	-	-	-
Secure Resistance Torque Device		-	-	S	-
Secure Stepper Motor		S	-	-	-
Rigidity		-	S	S	-
Total Pluses		0	0	0	0
Total Satisfactory		3	2	3	1
Total Minuses		2	3	2	4
Keep?	Yes	Yes	No	Yes	No

Table 5: Final Pugh Chart

[C] Matrix							
	Analytical Hierarchy Process	A	A	A	A	A	
B	**Engineering Charactersitic**	Track Cycles and Rotations (Actual)	Secure Coupler	Secure Resistance Torque Device	Secure Stepper Motor	Rigidity	Average
B	Track Cycles and Rotations (Actual)	1	3.000	3.000	3.000	5.000	3.000
B	Secure Coupler	0.333	1	1.000	1.000	5.000	1.667
B	Secure Resistance Torque Device	0.333	1.000	1	1.000	5.000	1.667
B	Secure Stepper Motor	0.333	1.000	1.000	1	5.000	1.667
B	Rigidity	0.200	0.200	0.200	0.200	1	0.360
	Total	2.200	6.200	6.200	6.200	21.000	8.360
	Average	0.440	1.240	1.240	1.240	4.200	

Table 6: Analytical Hierarchy ([C] Matrix)

norm[C] Matrix							
	Analytical Hierarchy Process	A	A	A	A	A	
B	**Engineering Charactersitic**	Track Cycles and Rotations (Actual)	Secure Coupler	Secure Resistance Torque Device	Secure Stepper Motor	Rigidity	Critical Weight {W}
B	Track Cycles and Rotations (Actual)	0.455	0.484	0.484	0.484	0.238	0.429
B	Secure Coupler	0.152	0.161	0.161	0.161	0.238	0.175
B	Secure Resistance Torque Device	0.152	0.161	0.161	0.161	0.238	0.175
B	Secure Stepper Motor	0.152	0.161	0.161	0.161	0.238	0.175
B	Rigidity	0.091	0.032	0.032	0.032	0.048	0.047
	Total	1.000	1.000	1.000	1.000	1.000	1.000

Table 7: Analytical Hierarchy (Normalized [C] Matrix)

Consistency Check					
Weighed Sum Vector {Ws} = [C]{W}	{W}	Cons = {Ws}./{W}	Average Consistency (λ)	Consistency Index (CI)	Consistency Ratio (CR)
2.236	0.429	5.215	5.152	0.038	0.034
0.902	0.175	5.165			
0.902	0.175	5.165			
0.902	0.175	5.165			
0.238	0.047	5.050			

Table 8: Analytical Hierarchy (Consistency Check)

	[Pi] Matrix			
	Analytical Hierarchy Process	A	A	A
B	**Engineering Charactersitic**	H-Frame	Modular Skeleton	StepperLife Pro
B	Track Cycles and Rotations (Actual)	0.333	0.333	0.333
B	Secure Coupler	0.455	0.455	0.091
B	Secure Resistance Torque Device	0.333	0.333	0.333
B	Secure Stepper Motor	0.455	0.455	0.091
B	Rigidity	0.714	0.143	0.143

Table 9: Analytical Hierarchy ([Pi] Matrix)

	[C] Matrix for Track Cycles and Rotations (Actual)				
	Analytical Hierarchy Process	A	A	A	
B		H-Frame	Modular Skeleton	StepperLife Pro	Average
B	H-Frame	1	1.000	1.000	1.000
B	Modular Skeleton	1.000	1	1.000	1.000
B	StepperLife Pro	1.000	1.000	1	1.000
	Total	3.000	3.000	3.000	3.000
	Average	1.000	1.000	1.000	

Table 10: Analytical Hierarchy (Concept Performance of Engineering Characteristic)

	[C] Matrix for Secure Coupler				
	Analytical Hierarchy Process	A	A	A	
B		H-Frame	Modular Skeleton	StepperLife Pro	Average
B	H-Frame	1	1.000	5.000	2.333
B	Modular Skeleton	1.000	1	5.000	2.333
B	StepperLife Pro	0.200	0.200	1	0.467
	Total	2.200	2.200	11.000	5.133
	Average	0.733	0.733	3.667	

Table 11: Analytical Hierarchy (Concept Performance of Engineering Characteristic)

[C] Matrix for Secure Resistance Torque Device					
	Analytical Hierarchy Process	A	A	A	
B		H-Frame	Modular Skeleton	StepperLife Pro	Average
B	H-Frame	1	1.000	1.000	1.000
B	Modular Skeleton	1.000	1	1.000	1.000
B	StepperLife Pro	1.000	1.000	1	1.000
	Total	3.000	3.000	3.000	3.000
	Average	1.000	1.000	1.000	

Table 12: Analytical Hierarchy (Concept Performance of Engineering Characteristic)

[C] Matrix for Secure Stepper Motor					
	Analytical Hierarchy Process	A	A	A	
B		H-Frame	Modular Skeleton	StepperLife Pro	Average
B	H-Frame	1	1.000	5.000	2.333
B	Modular Skeleton	1.000	1	5.000	2.333
B	StepperLife Pro	0.200	0.200	1	0.467
	Total	2.200	2.200	11.000	5.133
	Average	0.733	0.733	3.667	

Table 13: Analytical Hierarchy (Concept Performance of Engineering Characteristic)

[C] Matrix for Rigidity					
	Analytical Hierarchy Process	A	A	A	
B		H-Frame	Modular Skeleton	StepperLife Pro	Average
B	H-Frame	1	5.000	5.000	3.667
B	Modular Skeleton	0.200	1	1.000	0.733
B	StepperLife Pro	0.200	1.000	1	0.733
	Total	1.400	7.000	7.000	5.133
	Average	0.467	2.333	2.333	

Table 14: Analytical Hierarchy (Concept Performance of Engineering Characteristic)

norm[C] Matrix for Track Cycles and Rotations (Actual)					
	Analytical Hierarchy Process	A	A	A	
B		H-Frame	Modular Skeleton	StepperLife Pro	Design Alternative Priorities {Pi}
B	H-Frame	0.333	0.333	0.333	0.333
B	Modular Skeleton	0.333	0.333	0.333	0.333
B	StepperLife Pro	0.333	0.333	0.333	0.333
	Total	1.000	1.000	1.000	1.000

Table 15: Analytical Hierarchy (Normalized Concept Performance of Engineering Characteristic)

norm[C] Matrix for Secure Coupler					
	Analytical Hierarchy Process	A	A	A	
B		H-Frame	Modular Skeleton	StepperLife Pro	Design Alternative Priorities {Pi}
B	H-Frame	0.455	0.455	0.455	0.455
B	Modular Skeleton	0.455	0.455	0.455	0.455
B	StepperLife Pro	0.091	0.091	0.091	0.091
	Total	1.000	1.000	1.000	1.000

Table 16: Analytical Hierarchy (Normalized Concept Performance of Engineering Characteristic)

norm[C] Matrix for Secure Resistance Torque Device					
	Analytical Hierarchy Process	A	A	A	
B		H-Frame	Modular Skeleton	StepperLife Pro	Design Alternative Priorities {Pi}
B	H-Frame	0.333	0.333	0.333	0.333
B	Modular Skeleton	0.333	0.333	0.333	0.333
B	StepperLife Pro	0.333	0.333	0.333	0.333
	Total	1.000	1.000	1.000	1.000

Table 17: Analytical Hierarchy (Normalized Concept Performance of Engineering Characteristic)

norm[C] Matrix for Secure Stepper Motor					
	Analytical Hierarchy Process	A	A	A	
B		H-Frame	Modular Skeleton	StepperLife Pro	Design Alternative Priorities {Pi}
B	H-Frame	0.455	0.455	0.455	0.455
B	Modular Skeleton	0.455	0.455	0.455	0.455
B	StepperLife Pro	0.091	0.091	0.091	0.091
	Total	1.000	1.000	1.000	1.000

Table 18: Analytical Hierarchy (Normalized Concept Performance of Engineering Characteristic)

		norm[C] Matrix for Rigidity			
	Analytical Hierarchy Process	A	A	A	
B		H-Frame	Modular Skeleton	StepperLife Pro	Design Alternative Priorities {Pi}
B	H-Frame	0.714	0.714	0.714	0.714
B	Modular Skeleton	0.143	0.143	0.143	0.143
B	StepperLife Pro	0.143	0.143	0.143	0.143
	Total	1.000	1.000	1.000	1.000

Table 19: Analytical Hierarchy (Normalized Concept Performance of Engineering Characteristic)

Concept	Alternative Value
H-Frame	0.394
Modular Skeleton	0.367
StepperLife Pro	0.240

Table 20: Final Selection

Appendix A: APA Headings (delete)

Heading 1 is Centered, Boldface, Uppercase and Lowercase Heading

Heading 2 is Flush Left, Boldface, Uppercase and Lowercase Heading

Heading 3 is indented, boldface lowercase paragraph heading ending with a period.

Heading 4 is indented, boldface, italicized, lowercase paragraph heading ending with a period.

Heading 5 is indented, italicized, lowercase paragraph heading ending with a period.

See publication manual of the American Psychological Association page 62

Appendix B Figures and Tables (delete)

The text above the cation always introduces the reference material such as a figure or table. You should never show reference material then present the discussion. You can split the discussion around the reference material, but you should always introduce the reference material in your text first then show the information. If you look at the Figure 1 below the caption has a period after the figure number and is left justified whereas the figure itself is centered.

Figure 1. Flush left, normal font settings, sentence case, and ends with a period.

In addition, table captions are placed above the table and have a return after the table number. The second line of the caption provided the description. Note, there is a difference between a return and enter. A return is accomplished with the shortcut key shift + enter. Last, unlike the caption for a figure, a table caption does not end with a period, nor is there a period after the table number.

Table 1

The Word Table and the Table Number are Normal Font and Flush Left. The Caption is Flush Left, Italicized, Uppercase and Lowercase

Level of heading	Format
1	**Centered, Boldface, Uppercase and Lowercase Heading**
2	**Flush Left, Boldface, Uppercase and Lowercase**
3	***Indented, boldface lowercase paragraph heading ending with a period***
4	***Indented, boldface, italicized, lowercase paragraph heading ending with a period.***
5	*Indented, italicized, lowercase paragraph heading ending with a period.*

References

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