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Team 510: Danfoss IGV Test Fixture

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Abstract

The abstract is a concise statement of the significant contents of your project. The abstract should be one paragraph of between 150 and 500 words. The abstract is not indents.

Keywords: IGV Test Fixture

Abstract

Team 510 is creating a testing fixture for an inlet guide vane (IGV). An inlet guide vane is a mechanism that contains seven blades that open and close to regulate the flow of a fluid through a compressor.

Danfoss Turbocor® is a company that manufactures compressors which contain IGVs. In some cases, during manufacturing the IGVs can present failures as the blades are not able to fully open or close. The job of team 510 is to create a testing fixture to track two of the seven blades contained within the IGV to make sure it is fully functional. The testing system includes four lasers and four receivers split equally between two blades from the IGV. The lasers and receivers are placed in the center of the blade and the edge to accurately indicate whether the blade is fully open or fully closed.

In addition to tracking the movement of the blades, Team 510 is required to track the movement of a steel ball that indicates whether the blades fully open and close. The team will utilize the existing way of sensing this, two screws are supplied with a current and the electromagnetic flux of the steel ball can be measured as it moves. Lastly, the fixture will track the color of each IGV tested and track this data.

The testing fixture will utilize the existing baseplate which will be bolted down to the testing table. An L-shaped stand will be offset from the baseplate and will also be bolted down to the testing table. This stand will hold the laser array at the top looking down over the IGV, and the receivers will be set in the baseplate looking up through the opening. A piece of ultra scratch resistant acrylic will cover the top of the receivers to protect them. The IGV assembly failures will be caught before the compressor units are assembled.

Disclaimer

Your sponsor may require a disclaimer on the report. Especially if it is a government sponsored project or confidential project. If a disclaimer is not required delete this section.

Acknowledgement

These remarks thank 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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IGV	Inlet Guide Vane
OEM	Original Equipment Manufacturer
IR	Infrared
BOM	Bill of Materials

Chapter One: EML 4552C

1.1 Project Scope

Project Description

The objective of this project is to develop an apparatus that tests the functionality of eight different types of Danfoss Inlet Guide Vanes (IGVs), giving relevant data and prompting the operator with a pass or fail message. This will allow operators to ensure that defective IGVs are detected prior to installation into their associated compressor units and prevent the need for late-stage defect correction.

Key Goals

The key goals of this project are to produce a design and functional prototype capable of testing the functionality of Danfoss IGVs while reducing test operation times, production defect statistics, and the effort required from operators to perform the test. The test fixture will be able to return relevant data such as relative motor output, blade angle, and specific model of IGV being tested. This data indicated to the user will be sensed and processed autonomously, reducing the amount of time spent on testing the functionality. Initially, the test fixture will be used at Danfoss, but variations can be made to later iterations to be used in other facilities.

Markets

The project's primary market consists of our sponsoring company, Danfoss Turbocor® Compressors and other companies that manufacture flow control systems such as inlet vanes or chokes. The secondary market consists of compressor servicing and maintenance companies that may need to disassemble units and test for functionality. This criterion includes Danfoss as a secondary market, due to the service options that they provide to their customers. Other secondary markets can include third party companies that refurbish used compressors. The fourth market will be another inlet guide vane manufacturer such as General Electric (GE). GE can use the testing system to verify the functionality of their own IGV products which will need adjusted for the different products.

Assumptions

To define the responsibilities of the project, it will be assumed that the test fixture is to be installed to a pre-existing industrial workstation that will not be changed due for the testing system dimensioning purposes, and that production ready IGVs are provided. Meaning, each IGV will consist of a housing, guide fins, motor, and operating mechanism.

Additional assumptions include that the operators will be able to lift 50 pounds and are trained to use the system properly. Necessary power is assumed to be accessible at the workstation in which the test fixture will be operating.

Stakeholders

The project stakeholders are shown in the figure below.

Table 1

Stakeholders

	Investors	Decision-Makers	Advisors	Receivers
Sponsor *Bruce Barnett & William Bilbow*	X	X	X	X
Manager *Dr. McConomy*			X	
Experts *Manufacturing & test companies*				X
Operators *Danfoss, Compressor manufacturers*			X	X
General Readers *Compressor servicing, Danfoss*				X

1.2 Customer Needs

Danfoss has partnered with the FAMU-FSU College of Engineering to develop a device capable of testing Inlet Guide Vanes (IGVs). The team has been in contact with Bruce W. Barnett, who is the team's advisor and point of contact. During two separate meetings with Danfoss, one held on September 20th at 11:00am EST and September 27th at 11:00am EST, team 510 conducted a customer interview with Bruce W. Barnett in person. An operator was present and performed the current testing process for the team. She was also able to answer questions regarding the current testing process. The questions the team performed were open-ended. The responses to the set of questions, along with the interpreted needs are displayed in Table 2.

The responses to the questions helped the team determine what aspects our efforts will focus on. Our questions focused mainly on the type of test to be performed on the IGV. From the customer statements, an interpreted need for each statement was formulated. The interpreted needs describe the requirements needed to transition into the next phases of the project and understand device requirements.

Table 2

Customer Interaction

	Question	**Answer**	**Interpretation**
1	"Why do you think that a new IGV test fixture is required?"	"The old one is not working, and the tests are being done manually.... the old one only gave a pass or fail response."	The old test fixture is inoperable beyond the point at which Danfoss would have it repaired. This also gives us an opportunity to improve upon the old system.
2	"What was a common request to be added to the old system?"	"Having a user interface would be nice. Checking to ensure PNs match IGV PNs"	The device can be designed to provide feedback to the operator.

	Question	Answer	Interpretation
3	"How many variants of IGVs are needed to be tested by the same fixture?"	"There are four types of IGV that will go into any of eight different types of compressors"	The test station used for the device can be compatible with different types of IGVs while determining the IGV being tested.
4	What do you consider your biggest obstacles to be when performing the current IGV operation test?	"I have to pick up the IGV to place it into the current fixture and the IGV is heavy."	The IGV test fixture could require less effort for transportation.
5	What issues do you see with the current system in place?	"The fixture block is heavy and pinches wires when moved."	Loose wires can cause safety concerns and device failures. Ergonomics could be a point of focus.
6	"What would you like to see improved on from the current system?"	"The motor for the current system runs slow, running faster would save time."	The test can be done in less than 5 minutes to save time.
7	"What needs to be tested in order for a unit to pass?"	"The IGV must fully open and close. The magnetic indicator ball must be reading correctly"	The test device can fully open and close the IGV while reading the motion from the indicator ball.

	Question	Answer	Interpretation
8	"What would your idea of an ideal system include?"	"I would like the scan tool to be automatic and maybe even print out a current date label."	The device can read in the information from a scanner to start the test, and automatically produces real time part labels.
9	"What are the area constraints of the test apparatus?"	"The fixture will need to fit on the work bench in the same location and size restrictions as the old one."	The test system could ideally fit in the same location as the current system.
10	"If a unit fails, what does the current system do?"	"I will visually see an issue with the IGV while testing and fail the unit."	The microcontroller used can display the results of the test on a screen located above the testing station.
11	"What do you like about the previous IGV test system?"	"The previous system required no effort."	Users would benefit from an autonomous or 'hands-off' style system.
12	"What options do we have for power sources?"	"There is an outlet behind the workstation."	Power can be supplied from wall outlet if necessary.

From these interpretations, we determined the necessary areas of focus for our device as we transition into the next phases of the project. The design focuses on the test of an IGV to determine if it can go to the next step in the manufacturing process. The team will need to build a test station, that requires little to no maintenance, to make sure the IGV is fully functional and meets the quality set by Danfoss. The customer is concerned about the reliability of the testing device. The customer outlined a specified set of desired functions for the testing device; the testing device could be designed in a way that it can return a value representing relative power being consumed by the motor and if the IGV properly opens and closes. The final concept of the testing device is recommended to be automated with little user input. This will reduce testing times and improve the rate of the assembling of the compressors. Moreover, the testing device could have a visual feature to determine the IGV being tested by determining the color of the IGV and a display for the user. At the conclusion of the project, the customer desires to have a fully functional, production-ready, testing device.

The figure below shows the list of customer requirements in order of descending importance. It was agreed that the primary purpose of the system be given top priority with functions necessary to complete this customer need following suit. Safety being of the next most importance, followed by secondary customer needs and customer wants.

<u>Hierarchy of Customer Requirements</u>

1) Consistently sense/test IGV blade function with accuracy
2) System does not violate safety regulations within the facility
3) The system is reliable, durable, and structurally stable.
4) System documentation is clear & complete
5) System reliably determines IGV type and relative motor output

Our team will be responsible for generating documentation such as a maintenance manual, operations manual, mechanical drawings, electrical drawings, BOM and electronic copies of them all.

The figure below shows a Kano diagram. This is a tool used to weigh product feature impacts on customer satisfaction verse product functionality. Functions that are exciting to users are placed above the x-axis and functions that increase the product performance will be placed to the right of the y-axis. When a function generates high customer satisfaction but does not actually increase the product's performance, this is called an “exciter”. In the case of our customer requirements, the part number tracking and barcode label printing functions would be included in this category. They do not actually directly impact the performance of the system’s ability to properly identify if an IGV is working properly, but they are desired by the customer.

Any function that would be expected in the product to perform its primary goal, would be considered an “Expecter” and would be placed in the threshold attributes area of the Kano diagram. Examples relating to our product would be the identification of the Vane’s ability to open and close, and the function sensing the resistance of the motor during the test.

The functions that are specifically asked for by the customer would be called “spokens”. Examples of this could be, an operation time under five minutes, required size conformance and the function that sends data as feedback to the user. These are some of the functions that were specifically asked for by our customer.

The functions that are not specifically asked for but are understood to be customer requirements are called “unspokens”. This category would include necessary safety features, a long product lifecycle and durability appropriate for an industrial work environment.

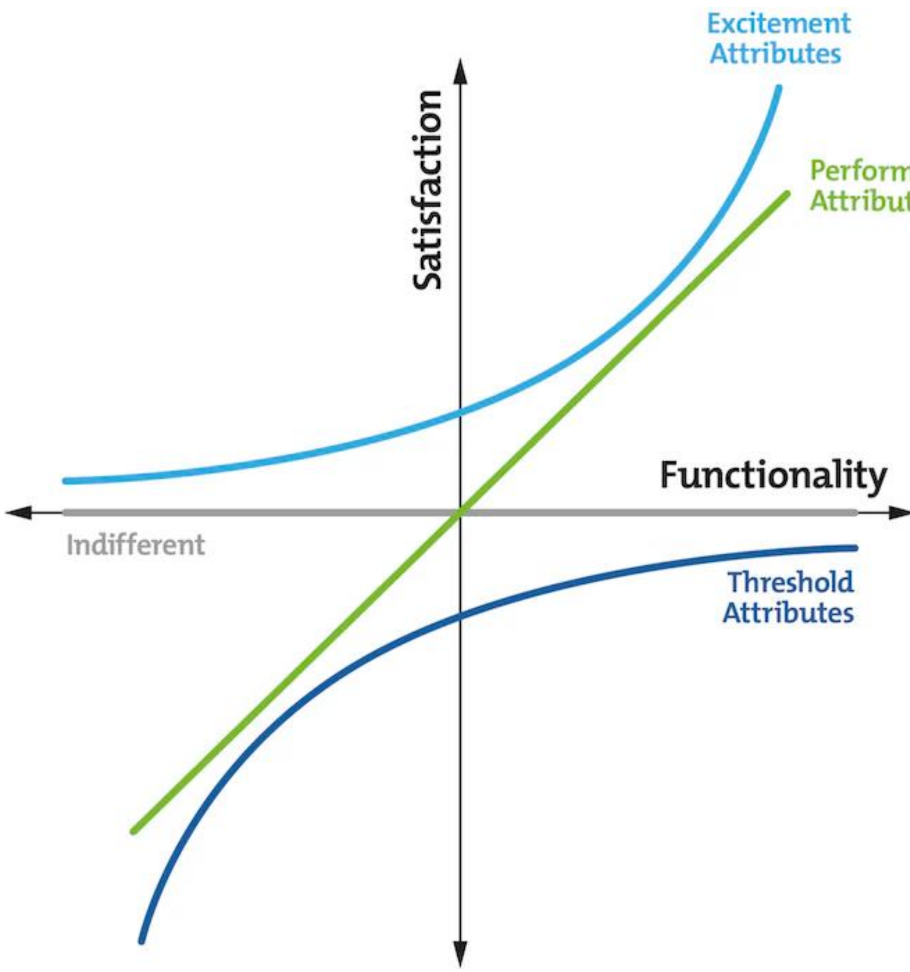


Figure 1 Image of Kano diagram.

1.3 Functional Decomposition

The functional decomposition for the project consists of major functions and their associated functions that perform based on the customer needs. Our system requires a test operation to be performed. To perform this test, controls are necessary, an example being that power needs to be supplied to the IGV. The system also requires signal capabilities and a method of controlling these functions.

In the functional decomposition performed by team 510, the testing procedure for the IGV, was analyzed and broken down into its simplest functions as shown in Figure 1. The testing procedure was broken down into four systems proceeding into 18 subsystems. The representation of the functional decomposition shows that the four main functions are structure, communication, controls, and sense.

To complete the functional decomposition, the team looked at the key goals and customer needs to determine the functions needed for the project. The functions were derived from requirements, timelines, and main goals to achieve. It was taken into consideration the human component which can be unpredictable. The previous thought process was implemented while creating the flowchart of the function decomposition.

The figures below show the function decomposition hierarchy and the cross-reference table.

Figure 2 Functional hierarchy denoting the flow of the functions.

Considering the key goals and customer needs, the team came up with four main factors impacting the complexity of subsystems. The four major functional groups for the design are structure, communication, controls, and sense.

Structure is of concern considering the placement of the compressor casing and the components needed to perform the test. With respect to this category, the team wants to find a way to secure the casing where the IGV is placed. This would improve the quality of the test and secure the IGV so that no damage is made to it during the test. Finally, all the electrical components used for the test are to be secured so that little maintenance is needed to run the test.

The communication function is essential as it will meet the customer's need to give information to the operator during the test procedure. The focus of communication is letting the user know the time the test procedure is over and relevant information about the test.

The controls function serves as the bridge between communication and sensing of the system. This is the part of the system that the operator interacts with to start and stop the testing procedure. Once the test is started, the power supplied by the system will open and close the IGV blades while restricting its motion to the range requested by the customer.

The sensing part of the test procedure is the most important part of the system and was broken down into 5 sub-functions: measure resistance from motor, track movement of IGV blades, determine IGV model, , and monitor testing state. The sensed information is essential to determine whether the test is successful or not.

1.3.1 Connection to Systems

The IGV Test Fixture has four main functions: structure, communication, controls, and sense. Team 510 decided that *control* is a key component and the most important part of the system. *Controls* will allow the operator to start and stop the test after its completion. If the test for the system is started, the system will be able to *sense* the resistance from the motor, track the movement of IGV blades, determine IGV model, , and monitor testing state. The tracking of the

IGV blades, and reading the resistance from the motorwill be a key component to determining whether the test passed or failed. The monitoring of the testing state will help the operator determine the progress of the test. The sensed information is going to be *communicated* to the operator. The indication will notify the operator once the test is completed and the details about the test.

To ensure optimal results, the system will incorporate a stable *structure* to maintain the stability of the unit that contains the IGV and a separate unit to protect the electrical components to minimize system maintenance requirements.

Table 3

Functional Cross Reference

	Structure	Communication	Controls	Sense
Maintain Integrity	x			
Protect Components	x			
Indicate Results		x	x	
Receive Inputs		x	x	x
Start and Stop Test		x	x	x
Measure Resistance			x	x
Track Blade Movements			x	x
Determine Model			x	x
Ball Indicator Location			x	x
Determine Testing State			x	x

	Structure	Communication	Controls	Sense
Move IGV Blades			x	

1.3.2 Smart Integration

The functional cross reference shows that the system will be requiring lots of control and sensing related functions. The sub-function within the controls major function, of opening and closing the IGV fins is connected to the sub-function of sensing the resistance of the motor being controlled. This sort of relationship can be seen for tracking the blade movements, and determining the model of IGV. These functions require control methods to be performed, and in doing so they are sensing whether the tasks are being done to a passable extent.

A similar relationship arises between the user indication sub-functions within the communication major function and the outputs control sub-function. Additionally, for a user to control the test fixture, their inputs must be sensed with control. This ties the user inputs sub-function in the sense major function with the input/output management and receive inputs functions from the control and communication major functions respectively.

The sub-function "Contain IGV" and "Protect Components" are both used to ensure that components of the system, including the IGV within the system, are less prone to damage or instability in the operating environment.

1.3.3 Action and Outcome

This project will utilize both hardware and software to test the IGV. Software will be utilized to analyze the output from the sensors to determine whether the IGV passed or failed testing. Hardware will contain and protect the electronics as well as maintain a safe operating area for the IGV. The testing fixture will be able to sense if the IGV has fully opened and fully closed and provide the user with supporting data and describe the IGV unit in test. Sensors will be able to: detect the unit being tested and store the information, measure the resistance to the motor. There will be a large amount of electronics involved in this device, the hardware must be able to safely contain these components while being sturdy enough to support the IGV.

1.3.4 Functional Resolution

At the basic level, the device has four different functions. The structure of the device would be protecting the electronics and sensors of the device, so that the device would still for work and maintain its structure if it were to be dropped or hit with metal parts, since it would be in a manufacturing warehouse floor environment. For Communication, the device would need a way to show the results of the tested part for the operator and provide a way for the operator to start and stop the test whenever desired. For sense, our device will have different sensors to read the parameters while the test occurs. Controls would be the part that integrates the sensing and communication together, which is basically the electronics which processes the data recorded by the sensors and determine the outcome of the tested part as a pass or fail, which is provided to the end user through the communication.

1.4 Targets and Metrics

Targets for the project were established to evaluate its functionality, also metrics were implemented to quantify the targets in the design process. To simplify the device, five main systems were created: Structure, Controls, Sense, Communication and Provision. The main functions are further broken down into subsystems for greater detailing for each respective system. Each function has its own targets and metrics associated with each of them, which helps the team to verify if each design component fulfilling its function.

While some targets are essential for the core functionality of the system, others are considered key goals, which are not critical systems for the functionality of the system, but they add value to the final prototype.

The team will use the iterative design process and prototype to constantly evaluate the targets through the development process of the project, which will help with adjustments on design if targets are not met during the process.

1.4.1 Sensing Targets

The main objective of the IGV functionality test fixture is to determine if an IGV assembly is functioning properly. To do this, the system must sense all functions necessary to pass the specifications of the design while performing their functions. The following explanations below cover the required functions to be sensed, their target values and the associated metrics.

Measuring Motor Effort

Within the IGV assembly, there are blades which are moved by a stepper motor. When in use, there is a range of acceptable effort that the stepper motor must provide to move the blades. The stepper motor must provide a torque 0.45 Nm (64 oz-in) to move the blades. If more than this is required, then something is wrong with the unit. If the stepper motor only requires considerably less torque, then it can be assumed that something is wrong with the unit. Our system will need to successfully identify the effort of the motor as torque output, in order to pass or fail the unit.

Tracking Test State

The state of the test refers to the orientation of the IGV blades. During testing, the blades can be closed, closing, opening or open. If the blades are partially open, but not closing or opening, then they are in the partially open state. Our system will need to be able to display what it is attempting to do with the blades, such as the states listed previously.

Tracking Movement of IGV Blades

The blades within the IGV must be tested to ensure that they move in the correct direction or at all when prompted to. To determine if this is the case, the system will need to produce a binary signal prompting the user to know that the IGV is open or closed. If the system attempts to open or close the IGV and the sensed data does not match the intended state, the system will fail the unit. The table below shows an example of the logic behind the IGV blade tracking test. An IGV passing this test will not guarantee the unit to pass overall. The IGV will have to pass all tests in order to be passed.

Test Fixture Intent	**Sensed Data**	**Pass/Fail**
Open IGV blades	Blades are open	PASS (Open function)
Open IGV blades	Blades are closed	FAIL
Close IGV blades	Blades are open	FAIL
Close IGV blades	Blades are closed	PASS (Close function)

Determining IGV Model

The table below shows each of the different IGV models that our system will be required to test for functionality.

Description	IGV PN	Throat Color
TT400 IGV Assembly	200232	Gold
TT700 IGV Assembly	255006	Steel
TT300 IGV Assembly	200144	Black
TT350 IGV Assembly	290005	Blue

Each IVG varies in throat height and color. Our system will need to be able to track which IGV it is testing and display that to the user for verification. This can be done within the software of the fixture as binary or true/false.

1.4.2 Structure Targets

The structure of the system will be necessary to ensure that the volume and weight of the system, including the IGV, can fit into the workstation without risk of the table buckling, tipping, or lacking space. The final design will take into consideration the current workstation provided by Danfoss. Moreover, the structure of the testing system will implement a physical boundary to protect the hardware from the manufacturing environment. The specific shape of the physical boundary volume is a rectangle. The base area of the rectangular boundary being a square that is 0.185 m^2, and the volume being 0.2 m^3. This physical boundary of the test fixture will be bigger than the IGV to account for the space taken by the hardware used to perform the test. The workstation where the test is going to be performed is assumed to be able to support a load of 230 kg.

Once the IGV is placed in the support block provided by Danfoss, the IGV assemblies will be restricted from moving as long as they are placed in the same orientation every time they are tested. The team will design a system within the testing volume target, to test each IGV assembly for functionality and ensure they can proceed to the next step in the manufacturing process if they are functionally sound. The motivation for this target is that the testing mechanism provided by team 510 will not be responsible for giving an accurate test if the IGV is placed in the wrong orientation.

Team 510 will design a physical boundary within the volumetric boundary provided, to protect the hardware from the manufacturing environment. This is essential as it will prevent the hardware from getting damaged and stopping the manufacturing line. For that reason, the boundary that oversees the protection of the hardware should withstand an impact force of 15 newtons evenly distributed across the boundary. Moreover, the boundary should not have sharp edges or protrusions to avoid the risk of injuries. Finally, the boundary should be closed to avoid the exposure of the electronics which can be dangerous to the technician.

To avoid the tipping of the testing system, the center of gravity must be low. The center of gravity must be located on the bottom half of the total height of the testing system. This will prevent the testing system from getting tipped if a force of 10 newtons is applied evenly distributed in the uppermost section of the testing structure.

1.4.3 Controls Targets

The controls of the testing system will be responsible for data acquisition, data processing and responsible for operating the testing system. The controls will work upon receiving input (start/stop) from the user. The system is to compute the essential information collected from the test and store it from triggered from a start action from the user.

Start Test

The operator inserts the IGV into the testing system and starts the test manually once the check list of steps to start is done. The controls of the systems will handle all the procedures that will collect and process the data.

Restricts IGV Blades

The IGV assemblies have a built-in restrictor for the blade opening range. The testing system should not force the blades beyond the range at which the blades are supposed to operate. Forcing the blades beyond the design specified angles can damage the IGV and the electric motor. The fatigue over time that occurs from the motor being operated to stall torque constantly, would require maintenance and replacement at an increased rate. Therefore, restricting the blade range using controls will be a useful way to prevent premature wear of the components. The target is to not to bring the motor to stall torque when testing under normal procedure of use, so the test outcome will be dependent whether stall torque is reached.

Open and Close IGV

During the duration of the test, the test system will fully open and close the IGV blades, to ensure that the IGV will be able to operate as required while in service. If the IGV is not able to fully open and fully close, the unit will fail. The target is to determine if the blades are fully open and fully closed, both of these conditions need to be at the extremes of the opening range, since with longer ranges above fully open and fully close damage of components can occur.

Stop Test

Once all the tests are completed and data acquired, the testing system is to notify the operator of the test completion to start the next step. The test is to be completed in under 5 minutes, if the test were to take longer, the controls need to notify the operator that the test has failed. In the case that something has gone wrong, the operator will be able to stop the test manually with an input that will override the testing operations.

Store Information

After collecting the data and valuable information about the test, the controls will be responsible for storing the data in an accessible way for Danfoss if they wish to consult it later. The required parameters stored in the systems are the required motor torque, the available range of the IGV blades and the time required to perform the test.

Read and Process Angle of IGV Blades

The controls will read in the data sensed for the IGV's blade angle and decide if the opening is within design specification. The IGV blade range is important because the amount of air processed by the compressor is a function of the opening of the IGV and the blade angle regulates the amount of air available for the compressor.

Monitor Torque output of the Electric Motor

The controls are responsible for monitoring the relative torque output from the electric motor used on the IGV assembly. From this, the system will determine if the motor is either exceeding or underperforming or matching design specified torque required. From these measurements, the system can determine if the motor is forcing the blades beyond the angle limit of the open state, or if there is a manufacturing defect such as a part causing higher friction between the moving parts. If the power is not in the range that we specify the test will fail.

1.4.4 Communications Targets

Communication is important to ensure the system can understand the operator and display the results of a test to the operator. This function is heavily related to the controls of the testing system as the user must communicate to the system to start or stop the test. These aspects must be communicated to the system to allow for the control of the system. The main function of communication is to indicate the results of the test to the user, via visual and audio indicators.

Indicate Results to User

Visual and audio indicators will be utilized to demonstrate the results of the test and stimulate a response from the operator when testing is finished or if something went wrong. Several metrics need to be met to ensure the system prompts the user to respond accurately. Regarding visual indication, the LCD screen must be of an appropriate size to allow the operator to accurately denote the output on the screen. This will be determined when purchasing an LCD screen based off dimensions of outputs and screen. The operator should be able to read the LCD screen from one meter away.

Audio indication will be utilized to alert the operator if the test has gone awry and to alert upon completion of testing. Two different sounds will be utilized to indicate the difference between a problem or a successful completion. To ensure the noise is loud enough for the user to understand that something has occurred during testing a noise level of 85 decibels is required. This allows the user to become alerted to a problem or completion of the test.

Receive Inputs from User

Receiving inputs from the user relies on the operator initializing or aborting the test and this getting communicated to the system. This is related to the controls function which processes the start and stop commands. Both will take in a binary metric, either a one or a zero, to determine if the user wants to start or stop the test. The input is received and communicated to controls to allow the testing to commence or to abort testing. Each input from the user must be recognized and denoted as a start or stop to the testing.

1.4.5 Provision Targets

The provision function is responsible for supplying power to the whole of the system. Both the IGV and the testing apparatus will need different power sources as they both require a different amount of power.

Supplies Power to the IGV

The IGV is powered by a four-prong connector that supplies power to a stepper motor. This motor is utilized to move the worm gear connected to the IGV Drive Assembly which in turn opens and closes the blades. This motor requires 12 volts to be supplied at ~0.4 amps for the motor to output 5.5 watts of power. To determine these values a multimeter will be utilized to ensure the power source will output the appropriate number of volts and amps to allow the motor to run at the proper strength. If the motor is supplied with too much power that could lead to damage of the assembly. If too little power is supplied the motor will not have enough torque to open and close the blades at a level congruent with Danfoss.

Supplies Power to the Test System

The test system requires its own separate power source to power the electronics that run the testing software and hardware. Each sensor will take a fraction of the power supplied to the system and therefore 9 volts and 0.5-2 amps are required to power the whole test system. Power will be measured via a multimeter to ensure proper voltage and ampere is supplied. If the testing system is provided with too little power not all sensors will run as necessary. In the case of the testing system, if too much power is supplied, the system could cause a short and break, meaning the hardware and software will not run as required.

1.4.6 Target Summary

The targets and metrics discussed have been generated from functions within our functional decomposition, or requirements surrounding the functions. Many of the critical targets share a goal, such as those produced by the sense, control and communication functions. Some targets produced by these functions are to sense data, control the sensing of the data, process the sensing of the data and communication of the sensed data. Since many of these functions are similar, some can be integrated into one function in concept generation, however the targets are going to be verified separately to ensure that they all match their respective requirements. The table below shows the critical targets and metrics as outlined by our team and sponsor.

System	***Function***	***Target***	***Metric***
Sense	Collects test data	1/0	Binary
Sense	Measures motor torque	±15%	Margin of Error
Sense	Determines IGV model	1/0	Binary
Sense	Tracks movement of indicator ball	±15%	Margin of Error
Sense	Determines IGV state	1/0	Binary
Control	Processes start & stop commands	1/0	Binary
Control	Stores test data related to torque failure	1/0	Binary
Control	Stores test data related to open/close failure	1/0	Binary
Control	Stores test data related to indicator ball	1/0	Binary
Control	Restrict IGV blade	1/0	Binary
Control	Open/close IGV	1/0	Binary
Control	Stores test data related to failure	1/0	Binary
Control	Time to completion	5 minutes	Time
Control	Read and Process Ball Indicator location	1/0	Binary
Provisions	Supplies power to IGV	12 Volts	Voltage
Provisions	Supplies power to IGV	~0.4 Amps	Current
Provisions	Supplies power to IGV	5.5 Watts	Power
Provisions	Supplies power to test system	9 Volts	Voltage
Provisions	Supplies power to test system	0.5 - 2 Amps	Current
Structure	Can be supported by the workstation provided	< 230 kg	Mass
Structure	Fits within the workspace volume provided	0.2 m^3	Volume
Structure	Fits within the square workspace area provided	0.185 m^2	Area

System	Function	Target	Metric
Structure	Fixture does not tip over when an environmentally reasonable force is applied to its highest point	10 N	Force
System	***Function***	***Target***	***Metric***
Communications	Provide visual indication	1 meter	Distance
Communications	Provide audio indication	85 dB	Noise level
Communications	Receive inputs from user	1/0	Binary

1.5 Concept Generation

Introduction

Concept generation is useful to address a concept solution for the project's objective. To achieve this, team 510 performed several concept generation sessions to generate at least one hundred ideas. In order to do this, many different generation tools were used by the team such as brainstorming, biomimicry, anti-problem, crap shoot, and forced analogy.

Concept Generation Tools

Brainstorming

Brainstorming is the process of thinking about the problem and then thinking of the first concepts that come to mind to solve that problem. These are typically the first concepts generated before more clever techniques are used. An example of a solution produced through this method is concept #1. While watching the operators at Danfoss struggle through their current process in place, our team members thought of user centric methods to make the testing process easier. The resulting concept is a hood like structure that the user can easily open and close onto IGV units to be tested. This concept would use struts to ensure that minimal effort is required from users to operate. On this hood there could be many types of sensors compatible with an Arduino that would conduct functionality tests once the hood is closed onto the IGV assembly.

Biomimicry

Biomimicry is the use of biological inspiration to generate concepts for a potential system using concepts already used by nature. An example of a concept generated by biomimicry would be concept #92, which uses acoustic signature mapping to determine the angle of the IGV blades while they are being tested for functionality. This concept is similar to the way that bats navigate their surroundings, which was the motivation behind the concept.

Anti-Problem

The anti-problem concept generation tool requires teams to try to think of ideas that prevent the problem from being solved. From this, the function required to do so is exposed as critical. For example, our desire is to test the functionality of the IGV blades. So, some concepts generated from the anti-problem tool were to cover the blades so that they cannot be seen and place objects that obstruct the movement of the blades. This showed the team important elements of conducting the functionality test as shown in the table below.

Anti-Problem Response	Take-away
Cover IGV blades up	Visibility of Blades
Obstruct movement of the IGV blades	Blade Clearance

Introduce water into the IGV assembly's electronics	Environment (Electronics Protection)

Forced Analogy

The forced analogy concept generation tool is a process of creating lists of random objects, activities, living things, etc. and shuffling them in a way that they cannot be seen. The team then must randomly select an item from a list one at a time and force solutions to the problem using the few items chosen at that time. This process is then iterated to generate multiple concepts. An example of a concept generated using this tool would be concept #95, the capacitive touch sensor system. This system would use capacitive touch sensors temporarily placed on the IGV blades to determine if the blades were closing when they were supposed to, during the functionality test. This forced analogy was produced from a combination of the following randomized items 'capacitor', 'attach to blades' and 'microcontroller'.

Crap Shoot

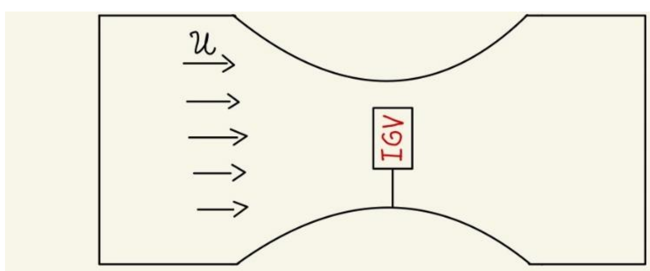
The crap shoot concept generation tool uses word banks (categories) filled with words (items) that are then randomly selected using dice or cards. The team must then propose a concept using three of the randomly picked items. For example, our group created the table below and used a number generator to create concept #108. In this concept, the IGV is placed into the base plate, a rack and pinion mechanism move lasers down into the blade housing to sense blade movement. The associated numbers generated to reach this concept were (1,3,4).

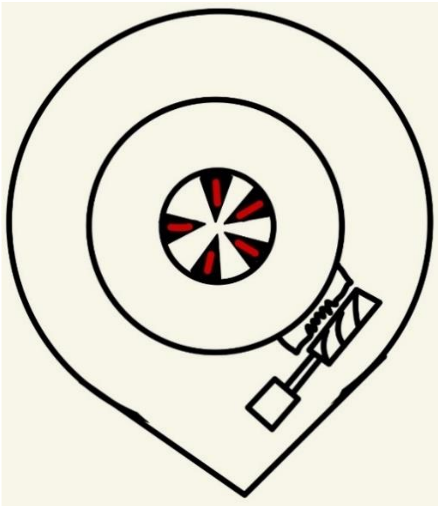
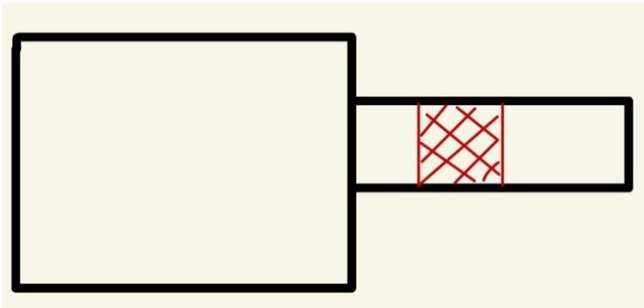
#	Control/Processing	Sense	Mechanism
1	Arduino	IR Sensor	4 bar mechanism

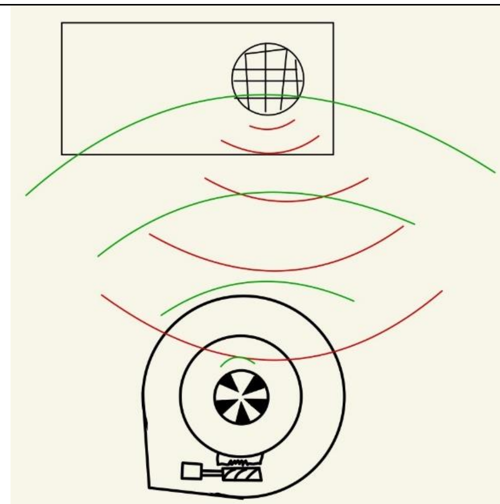
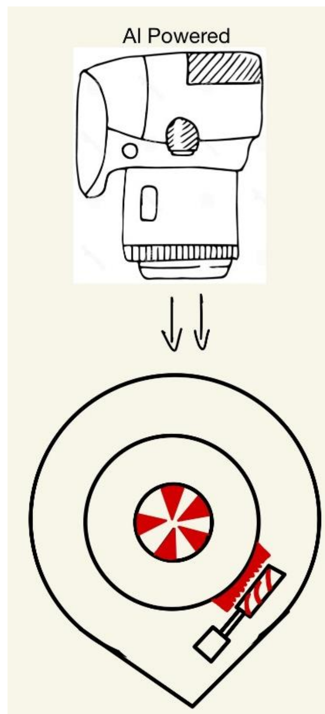
2	Raspberry Pi	Fan	6 bar mechanism
3	iPad	Laser	Struts
4	Laptop	Push Button	Rack & Pinion
5	Card input to mechanical processor	Sonic Sensor	Slot Mechanism
6	Lights to indicate manual functions to user	Stepper Motor	Slider mechanism

Medium Fidelity Concepts

Five medium fidelity concepts were selected, these concepts contain features that are favorable for many functions of the design but not every function. Medium fidelity concepts are utilized to determine how well the different features of each design will help meet the needs of the project. While these concepts do not fully encompass the entirety of the customer's needs, they are useful to determine which characteristics are most important for the final design.

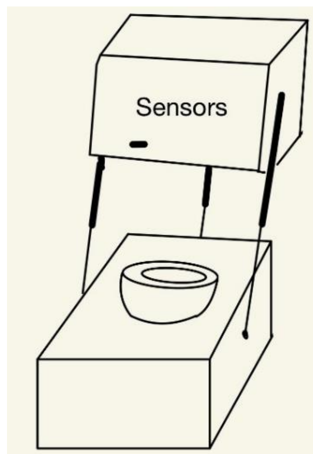
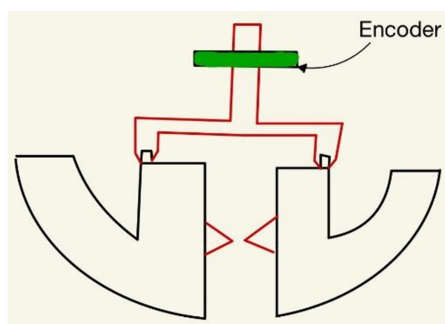
Concept Number	Description	Figures
11	[**El Niño**] Utilizing an air blower, the air would pass through the IGV on one end. The other end will have a sensor such as a pressure transducer that will be able to detect the minimal changes in pressure from the blower. When the blades are fully open flow will be nearly unrestricted through the blades, providing a high reading from the sensor. When the blades are fully	

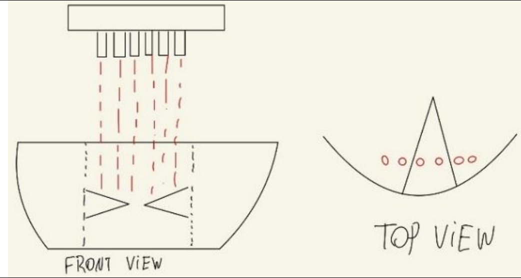
	closed the opposite will occur.	
50	[**Blade Runner**] Have the operator add a removable piece of reflective tape to the IGV drive assembly. Using an angular position sensor, the position of the drive assembly can be tracked as the IGV blades open and close.	
58	[**Nano Tensioner**] A strain gauge torque sensor would be utilized on the shaft of the stepper motor, this sensor would be capable of determining how much torque is being applied to the drive assembly as the blades open and close.	
65	[**Dare Devil**] Utilize an ultrasonic sensor that can detect the change in distance of the blade tip as it rotates from the open to closed position.	

		
105	[**SocialCredit**] Cameras installed above the IGV blades and drive assembly would be capable of tracking the position of the blades and drive assembly. Image recognition software would be required to read the images the cameras produce and convert to necessary data.	

High Fidelity Concepts

Three high fidelity concepts were chosen to fully encompass the scope of the project. Each concept includes characteristics which satisfy the needs of the customer. The high-fidelity concepts contain the majority of the functions necessary for the test system to successfully operate. High fidelity concepts are useful during concept selection to compare designs and determine which will fit best with the needs of the project and which will represent the most functions.

Concept Number	Description	Figures
1	[**Mystery Box**] The IGV assembly is placed onto the test block. A lid block with infrared sensors mounted on it is brought down to the IGV assembly once firmly in place. The IR sensors determine via binary if the blades are open or closed. The slider mechanism supported by car hood struts control the travel of the lid block. The lid block also acts as housing for almost all electronics, including user displays. The bottom of the base block can be painted white to increase accuracy of the IR sensors.	
3	[**Butter Cookie**] An electric motor is attached to a mechanism that clicks into the blade housing that rotates as the blades change angle. The rotation can be read into a microcontroller as the motor is spun and generates an induced current or via rotary encoder. Using this data, the angle of the IGV blades can be determined with the microcontroller software.	
108	[**Mega Maid**] A polar array of lasers on a lid block is brought down onto the IGV assembly with a rack and pinion mechanism. The lid mechanism houses the electronics of the sensing,	

	communication and control components. The lasers would be able to give an accuracy of how open or closed the IGV blades are, proportional to the amount included in the array.	

1.6 Concept Selection

During concept generation, one hundred ideas were generated and placed in Appendix D of this document. To evaluate these ideas, the customer requirements and engineering characteristics of the design were first decided.

Number	Customer Requirements	Engineering Characteristics
1	Accurately test IGV functions	Collects test data
2	Notifies test results	Provides indication (volume and audio)
3	Meets safety regulations	Keeps technician safe (1910.212 OSHA Standard)
4	System is reliable	14500 cycles with no defects
5	System is stable	Fixture does not tip over
6	Completes the assembly of 26 IGVs per shift	Test completion under 5 minutes
7	Tracks IGV model	Determines IGV model

Number	Customer Requirements	Engineering Characteristics
8	-	Stores data related to torque failure
9	-	Supplies power to test system
10	-	Can be supported by workstation
11	-	Fits within the workspace volume provided
12	-	Fits within the workspace area provided

Binary Pairwise Comparison

A binary pairwise comparison matrix was created by comparing the customer needs against one another using the table below. Next, we compared, if the customer need of the row was considered more important than the one of the columns, a '1' was input into the intersecting cell. If otherwise, a '0' was input into the placeholder, which meant that the customer need of the row was more important than the one in the column. After comparing all the customer needs to one another, the '1's of each row were summed into a column. This value represents the weight factor of the customer's needs. In the table below, it was determined that 'accurately testing the IGV's functions' is the most important engineering characteristic.

Binary Pairwise Comparison Chart								
Customer Needs	1	2	3	4	5	6	7	Total
1. Accurately Test IGV Functions	-	1	1	1	1	1	1	6
2. Notifies Test Results	0	-	1	1	0	1	1	4
3. Meets Safety Regulations	0	0	-	0	0	1	1	2
4. System is Reliable	0	0	1	-	0	1	1	3
5. System is Stable	0	1	1	1	-	1	1	5
6. Completes the Assembly of 26 IGV's per Shift	0	0	0	0	0	-	1	1
7. Tracks IGV Model	0	0	0	0	0	0	-	0
Total	0	2	4	3	1	5	6	n-1 = 6

House of Quality

The House of Quality (HoQ) includes the list of customer requirements in the rows and the list of engineering characteristics in the columns. The main goal of the HoQ is to determine which engineering characteristics are most important to the design based on the customer requirements. When comparing customer needs and engineering characteristics a ranking of 0, 1, 3, 5, 7 and 9 were used to assign values from least (0) to most (9) significance to the project. After comparing all the engineering characteristics, customer requirements and assigning the values for each comparison, the value assigned was multiplied by the importance weight factor found using the binary pairwise comparison matrix. Then all the values of each column were added into a new row titled raw score. After that, each raw score of the respective engineering characteristic was divided by the total sum of the raw scores. This value represents the relative weight percent of each of the engineering characteristics. The value calculated for the relative weight is used to determine the rank order with the highest relative weight ranking first, and others following in descending order.

Engineering Characteristic													
Improvement Direction		-	↑	-	↑	↑	↓	↓	-	↑	-	↑	-
Units		N/A	dB - m	N/A	N/A	Nm	N/A	N/A	N/A	V	kg	m^3	m^2
Customer Requirements	**Importance Weight Factor**	Collects test data	Provides indication (visual and audio)	Keeps technician safe (1910.212 OSHA standard)	14500 cycles with no defects	Fixture does not tip over	Test completion under 5 minutes	Determines IGV model	Stores data related to open/close failure	Supplies power to test system	Can be supported by workstation	Fits within the workspace volume provided	Fits within the workspace area provided
Accurately test IGV functions	**5**	9	3	1	3	3	0	0	9	9	3	1	1
Notifies test results	**4**	9	9	0	0	1	3	1	9	3	3	1	1
System is reliable	**4**	3	3	0	9	3	0	1	1	9	3	0	0
System is stable	**3**	3	1	9	0	9	0	0	0	0	9	3	3
Completes the assembly of 26 IGVs per shift	**2**	0	3	1	3	9	9	0	3	3	3	1	1
Tracks IGV model	**1**	9	0	0	0	0	0	9	3	1	1	0	0
Raw Score (628)		111	72	34	57	76	30	17	94	100	73	20	20
Relative Weight %		17.68	11.46	5.41	9.08	12.10	4.78	2.71	14.97	15.92	11.62	3.18	3.18
Rank Order		9	8	5	1	4	7	6	11	3	2	11	13

The most important characteristic determined using the House of Quality is that the system ‘Collects test data’, the second being ‘supplies power to test system’ and third being ‘stores data related to open/close failure’.

Pugh Charts

The Pugh Chart is a relative comparison technique. It compares engineering characteristics of each concept to a datum concept. The concepts are graded using (+) for better, (-) for worse and (S) for satisfactory. The number of better, satisfactory and worse were counted and concepts were eliminated based off their respective rankings. The datum chosen for the first iteration of the Pugh Chart was concept 96 (Ruby).

Concepts									
Engineering Characteristics	Ruby (96)	ElNiño (11)	BladeRunner (50)	NanoTension (58)	Dare Devil (65)	SocialCredit (105)	MysteryBox (1)	ButterCookie (3)	MegaMaid (108)
Collects Test Data	**- DATUM -**	S	-	-	S	S	S	S	S
Provides Indication		S	-	-	S	-	+	+	+
Fixture Does Not Tip Over		-	-	-	S	-	-	S	S
Stores Data Related to Open/Close Failure		+	-	+	+	S	+	+	+
Supplies Power to Test System		S	S	S	S	S	S	S	S
Can be Supported by Workstation		+	+	+	+	+	+	+	+
Total Pluses		2	1	2	2	1	3	3	3
Total Satisfactory		3	1	1	4	3	2	3	3
Total Minuses		1	4	3	0	2	1	0	0
		Yes	No	No	Yes	No	Yes	Yes	Yes

After the first iteration of the Pugh Chart, the four highest scoring designs were evaluated a second time using the Pugh Chart. The designs were Butter Cookie, Mystery box, El Niño, and Mega Maid. The new datum selected for the comparison was Dare Devil.

Concepts					
Engineering Characteristics	Dare Devil (65)	ButterCookie (3)	MysteryBox (1)	ElNiño (11)	MegaMaid (108)
Collects Test Data	**- DATUM -**	S	+	-	+
Provides Indication		S	S	-	+
Fixture Does Not Tip Over		+	S	S	S
Stores Data Related to Open/Close Failure		+	+	-	+
Supplies Power to Test System		S	S	S	S
Can be Supported by Workstation		S	S	-	S
Total Pluses		2	2	0	3
Total Satisfactory		4	4	2	3
Total Minuses		0	0	4	0
		Yes	Yes	No	Yes

After the second iteration of the Pugh Chart, Mystery Box ranked the highest with 2 pluses and 3 satisfactory and no minuses in comparison to Mega Maid with 1 plus, 3 satisfactory and 1 minus.

Analytical Hierarchy Process

The Analytical Hierarchy process (AHP) is used when determining the importance of each engineering characteristic. The method consists of evaluating each engineering characteristic against the other to determine which characteristics are most important to the goals of the project. AHP validates concept selection based on the Pugh Charts and ensures no bias towards a specific concept. An AHP table was made for each engineering characteristic and the final measured values are shown in the table below.

	norm[C] Matrix							
	Analytical Hierarchy Process	A	A	A	A	A	A	
B	**Engineering Charactersitic**	Collects Test Data	Provides Indication	Fixture Does Not Tip Over	Stores Data Related to Open/Close	Supplies Power to Test System	Can be Supported by Workstation	**Critical Weight {W}**
B	Collects Test Data	0.127	0.088	0.384	0.081	0.260	0.136	0.179
B	Provides Indication	0.636	0.441	0.384	0.242	0.260	0.227	0.365
B	Fixture Does Not Tip Over	0.042	0.147	0.128	0.565	0.156	0.136	0.196
B	Stores Data Related to Open/Close Failure	0.127	0.147	0.018	0.081	0.260	0.227	0.143
B	Supplies Power to Test System	0.025	0.088	0.043	0.016	0.052	0.227	0.075
B	Can be Supported by Workstation	0.042	0.088	0.043	0.016	0.010	0.045	0.041
	Total	1.000	1.000	1.000	1.000	1.000	1.000	1.000

AHP Results

[C] Matrix								
	Analytical Hierarchy Process	A	A	A	A	A	A	
B	**Engineering Charactersitic**	Collects Test Data	Provides Indication	Fixture Does Not Tip Over	Stores Data Related to Open/Close	Supplies Power to Test System	Can be Supported by Workstation	**Average**
B	Collects Test Data	1	0.200	3.000	1.000	5.000	3	2.040
B	Provides Indication	5.000	1	3.000	3.000	5.000	5.000	3.400
B	Fixture Does Not Tip Over	0.333	0.333	1	7.000	3.000	3.000	2.333
B	Stores Data Related to Open/Close Failure	1.000	0.333	0.143	1	5.000	5.000	1.495
B	Supplies Power to Test System	0.200	0.200	0.333	0.200	1	5	0.387
B	Can be Supported by Workstation	0.333	0.200	0.333	0.200	0.200	1	0.378
	Total	7.867	2.267	7.810	12.400	19.200	22.000	11.924
	Average	1.311	0.378	1.302	2.067	3.200	3.667	

[Pi] Matrix				
	Analytical Hierarchy Process	A	A	A
B	**Engineering Charactersitic**	ButterCookie	MysteryBox	MegaMaid
B	Collects Test Data	0.074	0.283	0.643
B	Provides Indication	0.333	0.333	0.333
B	Fixture Does Not Tip Over	0.260	0.106	0.633
B	Stores Data Related to Open/Close Failure	0.239	0.623	0.138
B	Supplies Power to Test System	0.106	0.633	0.260
B	Can be Supported by Workstation	0.155	0.069	0.777

Concept	**Alternative Value**
Butter Cookie	0.235
Mystery Box	0.333
Mega Maid	0.432

After using the AHP tables which demonstrated which engineering characteristics were most important, the highest scoring designs were compared to each selection criteria, the table below shows the final calculated results (highest is best).

In the results from the AHP, the concept named Mega Maid scored the highest, the concept also scored the highest on the Pugh Chart, the Mystery Box concept scores close second which is understandable since the architecture is similar between the concepts. The main feature of the Mega Maid uses lasers to determine the state of opening or closing of the IGV blades, the lasers would be accommodated in a lid which would be located normal to the IGV assembly, multiple lasers would be used to focus on one blade of the IGV and depending on how many lasers pass the IGV without touching the blade, it would determine at what point of opening/closing the blades are.

Visualizing Concept Selection via Mimuro Plot

The figure below uses an adjusted concept of the Mimuro plot to give a visual comparison of how well our top concepts satisfy the AHP, feasibility and creativity requirements of our project. To do produce this graphic, we utilized the CSM and TASC processes to determine the values of each concept relative to each other. We decided to create this graphic to give a simple visualization supporting why we chose our 'top' concept.

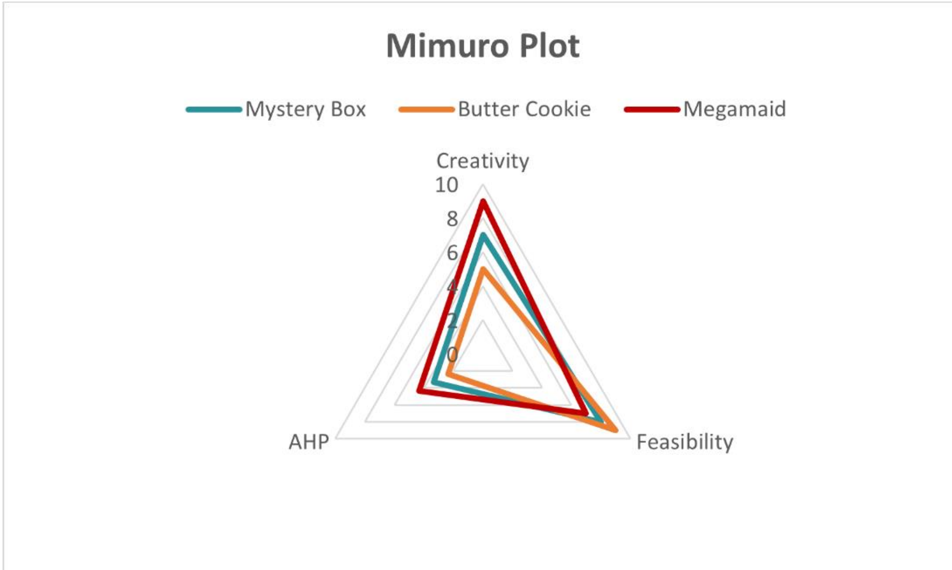


Figure 3: Mimuro Plot

The data for the Mimuro plot above is shown in the table below. The AHP column uses data produced by our Analytical Hierarchy Process charts, which has been multiplied by a factor of ten to fit the range of the plot. The creativity and feasibility columns use data produced by the team's understanding of the concepts relative to each other. A more creative, or more feasible concept will score relatively higher (out of ten) than concepts that are less respectively.

	Creativity	Feasibility	AHP (*10)
Mystery Box	7	8	3.33
Butter Cookie	5	9	2.35
Mega Maid	9	7	4.32

Final Selection

After considering the results of the data provided by the HoQ, AHP, Pugh charts and adjusted Mimuro plot, our team came together and held a vote for which of the concepts we would select as our final concept. It was a unanimous decision to use the Mega Maid concept, which utilizes a polar array of lasers and receivers to satisfy our primary function of determining the angle of the IGV assembly blades during the functionality test.

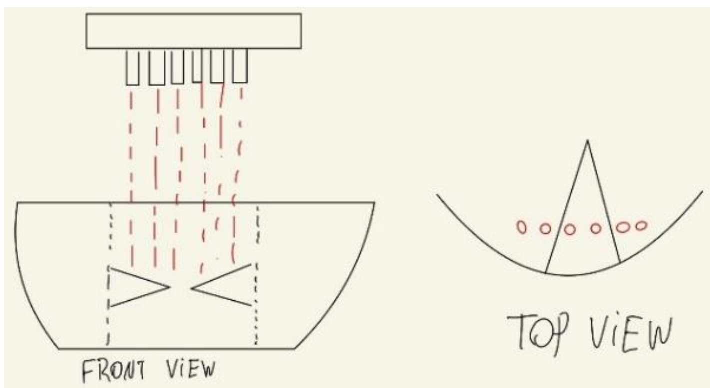


Figure 4: Mega Maid Concept

1.8 Spring Project Plan

Chapter Two: EML 4552C

2.1 Spring Plan

Project Plan.

Build Plan.

Appendices

Appendix A: Code of Conduct

Appendix B: Functional Decomposition

Appendix C: Target Catalog

System	***Function***	***Target***	***Metric***
Sense	Collects test data	1/0	Binary
Sense	Measures motor torque	±15%	Margin of Error
Sense	Determines IGV model	1/0	Binary
Sense	Tracks movement of indicator ball	±15%	Margin of Error
Sense	Determines IGV state	1/0	Binary
Control	Processes start & stop commands	1/0	Binary
Control	Stores test data related to torque failure	1/0	Binary
Control	Stores test data related to open/close failure	1/0	Binary
Control	Stores test data related to failure	1/0	Binary
Control	Time to completion	5 minutes	Time
Provisions	Supplies power to IGV	12 Volts	Voltage
Provisions	Supplies power to IGV	~0.4 Amps	Current
Provisions	Supplies power to IGV	5.5 Watts	Power
Provisions	Supplies power to test system	9 Volts	Voltage
Provisions	Supplies power to test system	0.5 - 2 Amps	Current
Structure	Can be supported by the workstation provided	< 230 kg	Mass
Structure	Fits within the workspace volume provided	0.2 m^3	Volume
Structure	Fits within the square workspace area provided	0.185 m^2	Area
Structure	Fixture does not tip over when an environmentally reasonable force is applied to its highest point	10 N	Force

System	***Function***	***Target***	***Metric***
Communications	Provide visual indication	1 meter	Distance
Communications	Provide audio indication	85 dB	Noise level
Communications	Receive inputs from user	1/0	Binary

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 5 below the caption has a period after the figure number and is left justified whereas the figure itself is centered.

Figure 5. 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 2

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.*

Appendix D: Raw Concept Ideas

Brainstorm Concepts

1. Slider mechanism with sensors mounted on hood block and car hood struts allowing ease of use
2. Force sensing bumper piston to feel if IGV is open or closed
3. Stepper motor/servo mechanism clicks into brown housing to read angle of travel
4. Pixy-cam with algorithm to determine blade angles
5. IR sensors placed with while backdrop to determine via infrared
6. IR receiver on one side, IR emitter on the other, open or closed blades would be read by signal received or not
7. Gyroscopic Sensor to be placed on IGV to sense blade motion/orientation
8. Laser pulses to determine the time it takes for the laser to return, more time = open, less time = closed
9. Tilt switch to be placed onto blades and activate lights for open/closed conditions
10. Magnetic Hall Effect sensor to determine orientation of IGV magnet which is paired with blades
11. Flow sensor and blower, air is fanned into IVG on one end, the other end senses air speed for how open the IGV is
12. Accelerometer attached to the blades for angle/orientation determination
13. Magnetometer to sense magnetic field changes caused by IGV
14. Inductance driven system to read magnetic flux of IGV blade movement
15. A light could flash on one end of the IGV and a sensor on the other end could
16. Microwave motion radar pointed to blades
17. Place displacement sensor between IGV stopper and brown rotator so that angle can be determined
18. Flow circulation sensor determines how far between open and closed the IGV is with air incoming
19. Sound magnitude sensor to determine how much sound passes through the IGV
20. Drop beads into IGV area continuously and count how many come out the bottom
21. Pressure sensor on each side of the blades
22. Displacement of worm gear threads sensor
23. Cam mechanism to determine displacement of brown bearing housing
24. e COGNEX AI trained cameras to detect movement of IGVs (BoP)
25. Use drone with cameras to detect motion of IGVs
26. Use cameras from the manufacturing floor to detect motion of IGVs (FA)
27. Introduce a camera inside IGV to detect motion of IGV
28. Use a force sensor to detect the force created while closing the IGV
29. Use Tilt Sensor to detect change in motion of IGV blades
30. Use Strain Gauge Sensor
31. Use Fiber Optic Motion Sensor (FA)

32. Use Hall Effect Sensor to detect motion of track indicator ball
33. Use Laser Motion Sensor
34. Drop water into the blades.
35. Do visual inspection
36. Place a sensor and introduce a fluid. If the sensor detects fluid motion, the IGV blades are open
37. Monitor the weight distribution in the system
38. Apply a thin layer of conductive material to the IGV blades. Use electrostatic charge sensors to detect changes in the charge distribution of the blades
39. Torque Sensor to measure the torque applied to the IGV mechanism.
40. Use MRI technology to create multiple images of the IGV (FA)
41. Use drag sensors to detect the drag of the fluid as the IGV opens and closes
42. Use a string attached to one IGV blade.
43. Use a camera at the bottom of the IGV and a light source on top
44. Shadow detection
45. Test the movement of the gears connected to the motor
46. Place a weight on top of the blades. If the weight moves, the IGV is either closing or opening
47. Place a small smoke machine below the IGV. If smoke goes through, the IGV is open. Otherwise, it is closed
48. Have a faucet with a tank located below. The faucet is to be connected to an Arduino that will regulate the flow and monitor the motor from the IGV. The tank has a weight sensor.
49. Paint a white dot on the IGV Drive Assembly, utilize this white dot to track the angular position of the Drive Assembly and determine if it has fully opened or closed.
50. Instead of painting a dot, utilize reflective tape to track the Drive assembly's angular position.
51. Utilize a camera with software capable of tracking the blades themselves, image tracking to show how much the blades defer when the system is activated.
52. Make a system that is planted via two legs but the other two can be moved to allow for easy access to the platform where the IGV will be placed.
53. Mount a potentiometer to the IGV blades and track the position of the potentiometer as the IGV blades open and close.
54. Use a rotary encoder that is placed in the IGV Drive Assembly, the rotary encoder will be able to track the angular position of the IGV blades.
55. Use an electromagnetic sensor, such as a resolver, that can track the angular position of the blades with high precision and accuracy.
56. Implement a Hall Effect sensor that can measure the difference in the magnetic field as the IGV blades open and close.
57. Install an optical encoder above the IGV Drive Assembly, this will be able to track the position of the blades and convert the angular position into electrical sensors.

58. Use a strain gauge torque sensor that can show how much torque is being applied to the motor as the IGV blades open and close.
59. Install a rotary torque sensor in between the motor and the IGV, this allows for easy reading of how the torque changes when the blades open and close.
60. Place a reaction torque sensor over the entire IGV Drive Assembly, this will be able to track the torque of the Drive Assembly as it rotates open and closed.
61. Use an optical torque sensor that can measure torque in a non-contact way.
62. Use a telemetry system that is capable of wirelessly transmitting torque data from the IGV blades to a stationary receiver.
63. Implement limit switches to detect when the IGV blades are fully open and fully closed.
64. Use proximity sensors that can monitor the proximity of the blades via specific reference points (open position and closed position)
65. Use ultrasonic sensors to detect the distance between the IGV blades at the fully open and fully closed positions.
66. Use acoustic sensors and sounds to monitor how the sensor reading changes as the blades open and close.
67. Monitor the tilt of the blades via a tilt sensor.
68. Attach RFID tags to each IGV blade and use RFID readers to read the positioning of each blade. RFID □ Radio Frequency Identification
69. Simulate flow on the IGV and use pressure sensors to show the air pressure changes caused by the blade movement.
70. Use Fiber optic sensors to detect strain or movement of IGV blades.
71. Utilize a wireless angle sensor that communicates the IGV blade positions to a central control system.
72. Install Bluetooth Low Energy Beacons to the blades to use proximity-based position tracking (how close each blade is to each other)
73. Integrate wind tunnel and use flow analysis to determine how open or closed the IGV blades are
74. Radio measurement tool to determine blade orientation
75. Post installation testing
76. Infrared temperature scanning
77. Visual inspection
78. Pressure drop test
79. 3D scanner
80. X-ray scanning
81. Magnetic field sensing
82. 3D printed die
83. Robot that replaces the operators' functions
84. Car alignment tool used on blades
85. Spin test
86. Potentiometer attached to electric motor
87. Material to test blade functionality

88. Dials used to determine change in distance from blade movements
89. Machine learning
90. Feeler gauge testing
91. Smoke dissipation test for relative flow allowed through blades

Biomimicry Concepts

92. Acoustic signature mapping of IGV blades similar to how bats and dolphins navigate
93. Electroreception can be used to determine IGV motor effort the same way that Sharks use it to locate prey
94. Use polarized Lense on pixy Cam to determine blade angles, use Arduino for the rest

Forced Analogy

95. Capacitive touch sensor on each blade (or just some) that touch when closed, not when open
96. [Ruby] Use CMM Testing tool to determine blade angles and send data to processor for communication to user

Anti-Problem

97. Fatigue Testing
98. Fatigue harsh environment testing
99. IGV blade hanger, lift system
100. Explosive testing
101. Water exposure
102. Movement obstruction
103. Cover blades up
104. Height and drop test

Crap Shoot

105. Use image recognition software and digital image processing along with several cameras that can monitor the IGV and have the software calculate if the blades opened and closed successfully.
106. Sensed data is printed and placed into IGV unit folder for design specification confirmation
107. Arduino controlled stepper motor reads blade housing angle, prints it onto paper and place into folder, using 4 bar mechanism to house IGV
108. Raspberry Pi is used to control and process lasers & data, that roll down onto the IGV assembly with a rack and pinion mechanism

Appendix E: Concept Selection Tables

Table 3: Binary Pairwise Comparison

Binary Pairwise Comparison Chart									
Customer Requirements	1	2	3	4	5	6	7	8	Total
1. Alerts operator ASAP	-	1	1	1	1	0	1	0	5
2. Non-obstructive size	0	-	1	0	1	0	0	0	2
3. Noticeable color	0	0	-	0	1	0	0	0	1
4. Minimum Lifespan of 3 years	0	1	0	-	0	0	0	1	2
5. Used on Floor	0	0	1	1	-	1	0	1	4
6. Fully Autonomous	1	1	1	1	0	-	0	0	4
7. Communicates error to user	0	1	1	1	1	1	-	0	5
8. User can use emergency stop	1	1	1	0	0	1	1	-	5
Total	2	5	6	5	3	3	2	2	n - 1 = 7

Table 4: House of Quality (HoQ)

Engineering Characteristic													
Improvement Direction		-	↑	-	↑	↑	↓	↓	-	↑	-	↑	-
Units		N/A	dB - m	N/A	N/A	Nm	N/A	N/A	N/A	V	kg	m^3	m^2
Customer Requirements	**Importance Weight Factor**	Collects test data	Provides indication (visual and audio)	Keeps technician safe (1910.212 OSHA standard)	14500 cycles with no defects	Fixture does not tip over	Test completion under 5 minutes	Determines IGV model	Stores data related to open/close failure	Supplies power to test system	Can be supported by workstation	Fits within the workspace volume provided	Fits within the workspace area provided
Accurately test IGV functions	**5**	9	3	1	3	3	0	0	9	9	3	1	1
Notifies test results	**4**	9	9	0	0	1	3	1	9	3	3	1	1
System is reliable	**4**	3	3	0	9	3	0	1	1	9	3	0	0
System is stable	**3**	3	1	9	0	9	0	0	0	0	9	3	3
Completes the assembly of 26 IGVs per shift	**2**	0	3	1	3	9	9	0	3	3	3	1	1
Tracks IGV model	**1**	9	0	0	0	0	0	9	3	1	1	0	0
Raw Score (628)		111	72	34	57	76	30	17	94	100	73	20	20
Relative Weight %		17.68	11.46	5.41	9.08	12.10	4.78	2.71	14.97	15.92	11.62	3.18	3.18
Rank Order		9	8	5	1	4	7	6	11	3	2	11	13

Table 5: Pugh Chart (Iteration 1)

	Concepts								
Engineering Characteristics	Ruby (96)	ElNiño (11)	BladeRunner (50)	NanoTension (58)	Dare Devil (65)	SocialCredit (105)	MysteryBox (1)	ButterCookie (3)	MegaMaid (108)
Collects Test Data	- DATUM -	S	-	-	S	S	S	S	S
Provides Indication		S	-	-	S	-	+	+	+
Fixture Does Not Tip Over		-	-	-	S	-	-	S	S
Stores Data Related to Open/Close Failure		+	-	+	+	S	+	+	+
Supplies Power to Test System		S	S	S	S	S	S	S	S
Can be Supported by Workstation		+	+	+	+	+	+	+	+
Total Pluses		2	1	2	2	1	3	3	3
Total Satisfactory		3	1	1	4	3	2	3	3
Total Minuses		1	4	3	0	2	1	0	0

Table 6: Pugh Chart (Iteration 2)

	Concepts				
Engineering Characteristics	Dare Devil (65)	ButterCookie (3)	MysteryBox (1)	ElNiño (11)	MegaMaid (108)
Collects Test Data	- DATUM -	S	+	-	+
Provides Indication		S	S	-	+
Fixture Does Not Tip Over		+	S	S	S
Stores Data Related to Open/Close Failure		+	+	-	+
Supplies Power to Test System		S	S	S	S
Can be Supported by Workstation		S	S	-	S
Total Pluses		2	2	0	3
Total Satisfactory		4	4	2	3
Total Minuses		0	0	4	0

Table 8: Analytical Hierarchy Process Criteria Comparison

	[C] Matrix							
	Analytical Hierarchy Process	A	A	A	A	A	A	
B	**Engineering Charactersitic**	Collects Test Data	Provides Indication	Fixture Does Not Tip Over	Related to Open/Close Failure	Supplies Power to Test System	Can be Supported by Workstation	**Average**
B	Collects Test Data	1	0.200	3.000	1.000	5.000	3	2.040
B	Provides Indication	5.000	1	3.000	3.000	5.000	5.000	3.400
B	Fixture Does Not Tip Over	0.333	0.333	1	7.000	3.000	3.000	2.333
B	Stores Data Related to Open/Close Failure	1.000	0.333	0.143	1	5.000	5.000	1.495
B	Supplies Power to Test System	0.200	0.200	0.333	0.200	1	5	0.387
B	Can be Supported by Workstation	0.333	0.200	0.333	0.200	0.200	1	0.378
	Total	7.867	2.267	7.810	12.400	19.200	22.000	11.924
	Average	1.311	0.378	1.302	2.067	3.200	3.667	

Table 9: Normalized Criteria Comparison Matrix for AHP

	norm[C] Matrix							
	Analytical Hierarchy Process	A	A	A	A	A	A	
B	**Engineering Charactersitic**	Collects Test Data	Provides Indication	Fixture Does Not Tip Over	Stores Data Related to Open/Close	Supplies Power to Test System	Can be Supported by Workstation	**Critical Weight {W}**
B	Collects Test Data	0.127	0.088	0.384	0.081	0.260	0.136	0.179
B	Provides Indication	0.636	0.441	0.384	0.242	0.260	0.227	0.365
B	Fixture Does Not Tip Over	0.042	0.147	0.128	0.565	0.156	0.136	0.196
B	Stores Data Related to Open/Close Failure	0.127	0.147	0.018	0.081	0.260	0.227	0.143
B	Supplies Power to Test System	0.025	0.088	0.043	0.016	0.052	0.227	0.075
B	Can be Supported by Workstation	0.042	0.088	0.043	0.016	0.010	0.045	0.041
	Total	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Table 10: Consistency Checks:

Consistency Check						
Engineering Characteristics	**Weighed Sum Vector {Ws} = [C]{W}**	**{W}**	**Cons = {Ws}./{W}**	**Average Consistency (λ)**	**Consistency Index (CI)**	**Consistency Ratio (CR)**
Collects Test Data	1.482	0.179	8.259	7.600	0.320	0.256
Provides Indication	2.861	0.365	7.837			
Fixture Does Not Tip Over	1.730	0.196	8.838			
Stores Data Related to Open/Close Failure	1.054	0.143	7.343			
Supplies Power to Test System	0.483	0.075	6.408			
Can be Supported by Workstation	0.283	0.041	6.916			

Table 11: Criteria Comparison Matrix for Collects Data

[C] Matrix for Collects Data					
	Analytical Hierarchy Process	A	A	A	
B	**Concepts**	ButterCookie	MysteryBox	MegaMaid	**Average**
B	ButterCookie	1.000	0.200	0.143	0.448
B	MysteryBox	5.000	1.000	0.333	2.111
B	MegaMaid	7.000	3.000	1.000	3.667
	Total	13.000	4.200	1.476	6.225
	Average	4.333	1.400	0.492	

Table 12: Normalized Criteria Comparison Matrix for Collects Data

norm[C] Matrix for Collects Data					
	Analytical Hierarchy Process	A	A	A	
B	Concepts	ButterCookie	MysteryBox	MegaMaid	Design Alternative Priorities {Pi}
B	Scan Wars	0.077	0.048	0.097	0.074
B	Aerial Tracker	0.385	0.238	0.226	0.283
B	Scan-E	0.538	0.714	0.677	0.643
	Total	1.000	1.000	1.000	1.000

Table 13: Consistency Check for Collects Data

Consistency Check					
Weighed Sum Vector {Ws} = [C]{Pi}	{Pi}	Cons = {Ws}./{Pi}	Average Consistency (λ)	Consistency Index (CI)	Consistency Ratio (CR)
0.222	0.074	3.013	3.066	0.033	0.063
0.866	0.283	3.062			
2.008	0.643	3.121			

Table 14: Criteria Comparison Matrix for Provides Indication

[C] Matrix for Provides Indication					
	Analytical Hierarchy Process	A	A	A	
B	Concepts	ButterCookie	MysteryBox	MegaMaid	Average
B	ButterCookie	1.000	1.000	1.000	1.000
B	MysteryBox	1.000	1.000	1.000	1.000
B	MegaMaid	1.000	1.000	1.000	1.000
	Total	3.000	3.000	3.000	3.000
	Average	1.000	1.000	1.000	

Table 15: Normalized Criteria Comparison Matrix for Provides Indication

norm[C] Matrix for Provides Indication					
	Analytical Hierarchy Process	A	A	A	
B	**Concepts**	ButterCookie	MysteryBox	MegaMaid	**Design Alternative Priorities {Pi}**
B	ButterCookie	0.333	0.333	0.333	0.333
B	MysteryBox	0.333	0.333	0.333	0.333
B	MegaMaid	0.333	0.333	0.333	0.333
	Total	1.000	1.000	1.000	1.000

Table 16: Consistency Check for Provides Indication

Consistency Check					
Weighed Sum Vector {Ws} = [C]{Pi}	**{Pi}**	**Cons = {Ws}./{Pi}**	**Average Consistency (λ)**	**Consistency Index (CI)**	**Consistency Ratio (CR)**
1.000	0.333	3.000	3.000	0.000	0.000
1.000	0.333	3.000			
1.000	0.333	3.000			

Table 17: Criteria Comparison Matrix for Fixture Does not Tip Over

[C] Matrix for Fixture Does not Tip Over					
	Analytical Hierarchy Process	A	A	A	
B	**Concepts**	ButterCookie	MysteryBox	MegaMaid	**Average**
B	ButterCookie	1.000	3.000	0.333	1.444
B	MysteryBox	0.333	1.000	0.200	0.511
B	MegaMaid	3.000	5.000	1.000	3.000
	Total	4.333	9.000	1.533	4.956
	Average	1.444	3.000	0.511	

Table 18: Normalized Criteria Comparison Matrix for Fixture Does not Tip Over

norm[C] Matrix for Fixture Does not Tip Over					
	Analytical Hierarchy Process	A	A	A	
B	Concepts	ButterCookie	MysteryBox	MegaMaid	Design Alternative Priorities {Pi}
B	ButterCookie	0.231	0.333	0.217	0.260
B	MysteryBox	0.077	0.111	0.130	0.106
B	MegaMaid	0.692	0.556	0.652	0.633
	Total	1.000	1.000	1.000	1.000

Table 19: Consistency Check for Fixture Does not Tip Over

Consistency Check					
Weighed Sum Vector {Ws} = [C]{Pi}	{Pi}	Cons = {Ws}./{Pi}	Average Consistency (λ)	Consistency Index (CI)	Consistency Ratio (CR)
0.790	0.260	3.033	3.039	0.019	0.037
0.320	0.106	3.011			
1.946	0.633	3.072			

Table 20: Criteria Comparison Matrix for Stores Data Related to Open/Close Failure

[C] Matrix for Stores Data Related to Open/Close Failure					
	Analytical Hierarchy Process	A	A	A	
B	Concepts	ButterCookie	MysteryBox	MegaMaid	Average
B	ButterCookie	1.000	0.200	3.000	1.400
B	MysteryBox	5.000	1.000	3.000	3.000
B	MegaMaid	0.333	0.333	1.000	0.556
	Total	6.333	1.533	7.000	4.956
	Average	2.111	0.511	2.333	

Table 21: Normalized Criteria Comparison Matrix for Stores Data Related to Open/Close Failure

norm[C] Matrix for Stores Data Related to Open/Close Failure					
	Analytical Hierarchy Process	A	A	A	
B	**Concepts**	ButterCookie	MysteryBox	MegaMaid	**Design Alternative Priorities {Pi}**
B	ButterCookie	0.158	0.130	0.429	0.239
B	MysteryBox	0.789	0.652	0.429	0.623
B	MegaMaid	0.053	0.217	0.143	0.138
	Total	1.000	1.000	1.000	1.000

Table 22: Consistency Check for Stores Data Related to Open/Close Failure

Consistency Check					
Weighed Sum Vector {Ws} = [C]{Pi}	**{Pi}**	**Cons = {Ws}./{Pi}**	**Average Consistency (λ)**	**Consistency Index (CI)**	**Consistency Ratio (CR)**
0.777	0.239	3.250	3.306	0.153	0.294
2.231	0.623	3.579			
0.425	0.138	3.089			

Table 23: Criteria Comparison Matrix for Supplies Power to Test System

[C] Matrix for Supplies Power to Test System					
	Analytical Hierarchy Process	A	A	A	
B	**Concepts**	ButterCookie	MysteryBox	MegaMaid	**Average**
B	ButterCookie	1.000	0.200	0.333	0.511
B	MysteryBox	5.000	1.000	3.000	3.000
B	MegaMaid	3.000	0.333	1.000	1.444
	Total	9.000	1.533	4.333	4.956
	Average	3.000	0.511	1.444	

Table 24: Normalized Criteria Comparison Matrix for Supplies Power to Test System

norm[C] Matrix for Supplies Power to Test System					
	Analytical Hierarchy Process	A	A	A	
B	Concepts	ButterCookie	MysteryBox	MegaMaid	Design Alternative Priorities {Pi}
B	ButterCookie	0.111	0.130	0.077	0.106
B	MysteryBox	0.556	0.652	0.692	0.633
B	MegaMaid	0.333	0.217	0.231	0.260
	Total	1.000	1.000	1.000	1.000

Table 25: Consistency Check for Supplies Power to Test System

Consistency Check					
Weighed Sum Vector {Ws} = [C]{Pi}	{Pi}	Cons = {Ws}./{Pi}	Average Consistency (λ)	Consistency Index (CI)	Consistency Ratio (CR)
0.320	0.106	3.011	3.039	0.019	0.037
1.946	0.633	3.072			
0.790	0.260	3.033			

Table 26: Criteria Comparison Matrix for Can be Supported by Workstation

[C] Matrix for Can be Supported by Workstation					
	Analytical Hierarchy Process	A	A	A	
B	Concepts	ButterCookie	MysteryBox	MegaMaid	Average
B	ButterCookie	1.000	3.000	0.143	1.381
B	MysteryBox	0.333	1.000	0.111	0.481
B	MegaMaid	7.000	9.000	1.000	5.667
	Total	8.333	13.000	1.254	7.529
	Average	2.778	4.333	0.418	

Table 27: Normalized Criteria Comparison Matrix for Can be Supported by Workstation

norm[C] Matrix for Can be Supported by Workstation					
	Analytical Hierarchy Process	A	A	A	
B	**Concepts**	ButterCookie	MysteryBox	MegaMaid	**Design Alternative Priorities {Pi}**
B	ButterCookie	0.120	0.231	0.114	0.155
B	MysteryBox	0.040	0.077	0.089	0.069
B	MegaMaid	0.840	0.692	0.797	0.777
	Total	1.000	1.000	1.000	1.000

Table 28: Consistency Check for Can be Supported by Workstation

Consistency Check					
Weighed Sum Vector {Ws} = [C]{Pi}	**{Pi}**	**Cons = {Ws}./{Pi}**	**Average Consistency (λ)**	**Consistency Index (CI)**	**Consistency Ratio (CR)**
0.471	0.155	3.043	3.082	0.041	0.079
0.206	0.069	3.013			
2.477	0.777	3.190			

Table 29: Final Rating Matrix

[Pi] Matrix				
	Analytical Hierarchy Process	A	A	A
B	**Engineering Charactersitic**	ButterCookie	MysteryBox	MegaMaid
B	Collects Test Data	0.074	0.283	0.643
B	Provides Indication	0.333	0.333	0.333
B	Fixture Does Not Tip Over	0.260	0.106	0.633
B	Stores Data Related to Open/Close Failure	0.239	0.623	0.138
B	Supplies Power to Test System	0.106	0.633	0.260
B	Can be Supported by Workstation	0.155	0.069	0.777

Table 30: Alternative Value Chart

Concept	Alternative Value
Butter Cookie	0.235
Mystery Box	0.333
Mega Maid	0.432

References

There are no sources in the current document.