# Rotational Joint Redesign

## MECH 497 – Value Engineering

VORTEX

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# Executive Summary

## Introduction and Objectives

Vortex International is a worldwide leader in creating fun and safe aquatic play solutions. In some of the aquatic structures they offer to their clients, there is a rotational joint which provides an interface between the top and the bottom part of a feature; hence, it increases the play value of the feature.

This rotational joint initially costs about $443.84 to manufacture, and about 300 units are manufactured each year. In this sense, the main objectives that Vortex wants to achieve are:

- Decreasing the manufacturing cost
- Fulfilling all the required functions
- Reducing wear rate.

## Solution

The solution proposed is a two-staged tapered bushing; the first stage is installed in the outer pipe and locked into place by installing the second stage of the bushing, and hence, expanding the first stage. A C-clip is opened to allow the top feature to be inserted in place, and then the C-clip is released to lock the top feature in place and prevent vertical movement while allowing rotation.

The cost of manufacturing the new rotational joint is estimated to be $270.60, which represents a reduction in cost of 39%.

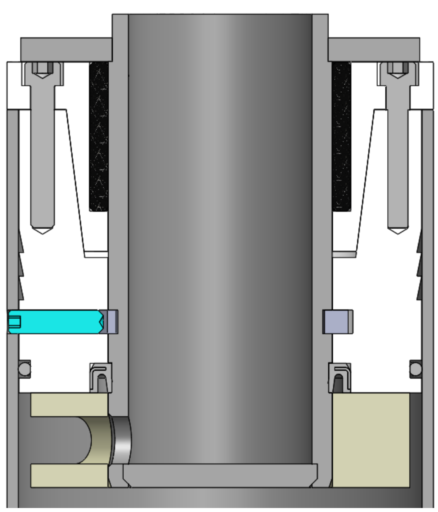


*Figure 1 Proposed Conceptual Design*

# Acknowledgements

We would like to thank our advisors, Mrs Lucie Parrot, Professor Vince Thomson and Professor Zsombor-Murray as well as the Vortex International team, Michel Corbeil and Michael Durand, for their support, guidance, and wisdom throughout our project.

# Introduction

## Client Profile

Vortex Aquatic Structures International is a Canadian company founded in 1995 in Montreal, QC. They are a worldwide leader in creating innovative and lively aquatic play solutions with around 7 500 installations in more than 50 countries.

They have different ranges of products that can accommodate various client needs, both technical and fun-wise, with their own specific aquatic feature choices as well as different water circulation systems.

*Figure 2 Vortex Splashpad*

Producing a value engineering study on a product has as a purpose to increase the value of the product to the company, and hence, to the client, either by increasing the satisfaction produced by the product, or by decreasing the cost associated with manufacturing the product, or both, as described by the following equation:

*Equation 1 Value of a product or process*

$$Value = \frac{Satisfaction\ of\ Needs}{Cost\ of\ Resources}$$

The value engineering process is divided in three main parts.

The first part is the Information gathering, which was conducted to better understand the context of the product, the reasons why it exists, the reasons why it brings value to the company, the ways in which it can be used, the functions it must fulfill, and the potential points of improvement. It can be further divided as follows:

1. Problem Definition
2. Organization of the Work
3. Cost and Function Analysis.

The second part of the value engineering process is the creative and brainstorming process. This is the part where we used various techniques to generate many creative ideas, by brainstorming with the client and by taking existing concepts and ideas and expanding them. This phase is:

4. Brainstorming and design phase.

The third phase is the evaluation phase. In this phase, we look at the designs from the creative point-of-view and evaluate if they are legitimate conceptual designs. This phase is further divided into:

5. Evaluation phase
6. Development phase.

In the project, the creative process and the evaluation process were very iterative in order to develop an overall best solution by joining various concepts.

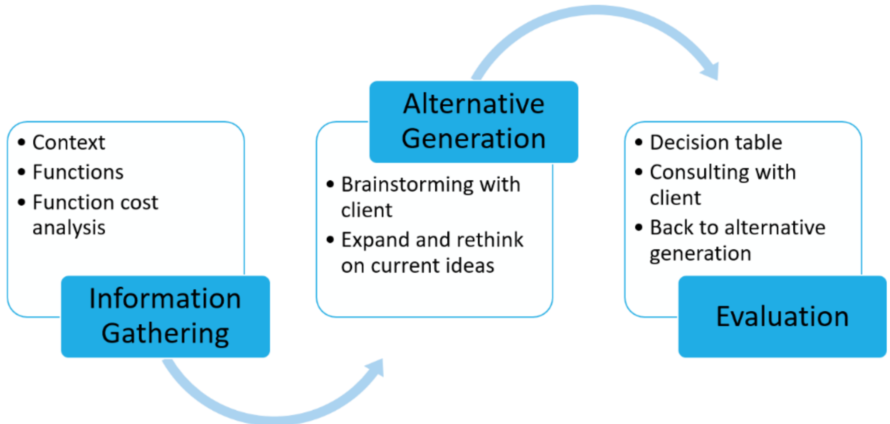



*Figure 3 VE Process*

## Resources

During the project, the following stakeholders participated as active resources to find an improved design solution.

*Table 1 Human Ressources for the Project*

| Name | Role | Contact Information |
|---|---|---|
| Michel Corbeil | Client | - |
| Michael Durand | Client | mdurand@vortex-intl.com |
| Min Jiang | Team Member | min.jiang@mail.mcgill.ca |
| Zawad Hassan | Team Member | zawad.hassan@mail.mcgill.ca |
| Louisa Oualim | Team Member | louisa.oualim@mail.mcgill.ca |
| Catherine Pronovost | Team Member | catherine.pronovost@mail.mcgill.ca |
| Vincent Ng | Team Member | vincent.ng2@mail.mcgill.ca |
| Lucie Parrot | Advisor | lucie@martin-parrot.com |
| Vincent Thomson | Advisor | vince.thomson@mcgill.ca |
| Paul Zsombor-Murray | Advisor | paul@cim.mcgill.ca |

## Context Overview

It is important to start by understanding in which context the studied rotational joint is used. The rotational joint studied in the scope of this project is a joint that allows rotation of the top of various aquatic features, as shown in the image below.

*Figure 4 Example of Vortex features using a rotational joint*

The rotational join provides an interface between the top feature, which provides play value, and the bottom of the feature which is fixed to the ground. The user would be able to grab onto the top feature and apply a torque to make the top feature rotate.

## Current Product Description

Below is an image of the assembly for the rotational joint currently in production. The different components are identified on the assembly, and a description of the different component is available below.

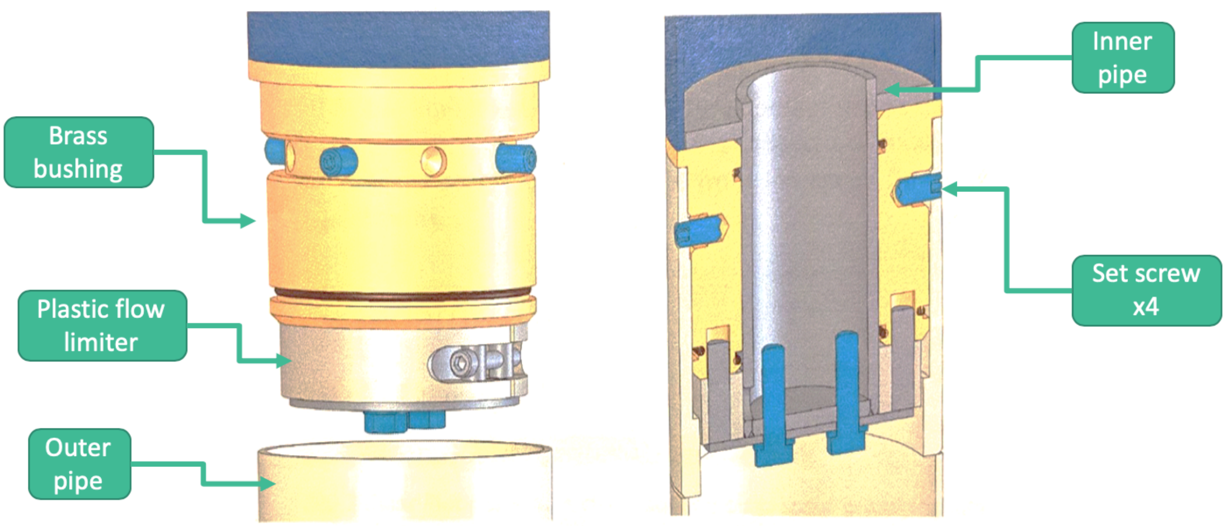



*Figure 5 Initial rotational joint assembly*

- **Outer Pipe:** Fixed to the ground. This piping provides support to the entire installed fixture and houses the entire rotational joint assembly.

- **Inner Pipe:** Steel piping, welded to the top fixture. Provides the top fixture with a component and axis about which it can rotate. Installed inside the brass bushing.

- **Brass Bushing:** Interface between the outer and inner pipe; provides a constrained environment inside which the inner steel pipe can rotate.

- **Plastic Flow Limiter:** Limits water flow out of the top fixture by either allowing or preventing flow based on the angle at which the top fixture is rotated. When rotated to an angle at which flow is desirable, a radially machined slot is aligned with the flow, allowing water passage.

- **Set screws:** Used to fixed the brass bushing to the outer pipe.

# Methodology

## Function Analysis

The function analysis phase is essential since it identifies opportunities for value improvement, solidifies understanding, engages communication and enhances objectives achievement. In this phase, the team first brainstormed about all the functions that the design wished to accomplish before classifying them. Below is a bullet point list of functions the team came up with during the brainstorming:

- Spray water
- Seal liquid
- Control fluid flow
- Control rotation
- Directing water
- Limiting spray zone
- Support top feature
- Protect user
- Prevents pinching
- Minimize maintenance (serviceable/easy to service)
- Adjust spray zone easily
- Resisting wear
- Move mechanism

## Environmental Analysis

The environmental analysis asks the VE team to consider the environment in which the product is to be used. For the rotational joint, and more generally, the aquatic features, it was possible to identify the idea map shown in the figure below.

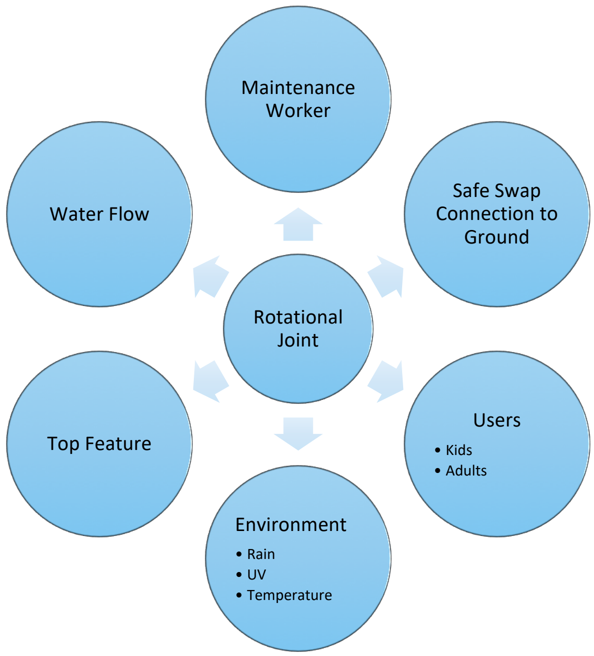



*Figure 6 Environment Function Analysis*

## Sequential Analysis

Sequential analysis involves determining the chronological steps associated to the use of the feature and identifying new functions that might not have been obvious at the beginning given the new insights.

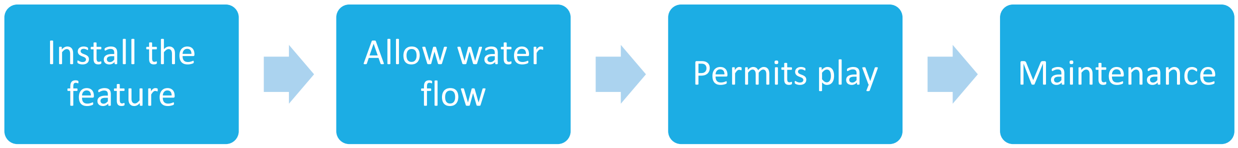



*Figure 7 Sequential Analysis of the Product*

## Fast Diagram

The functions can be organized in categories and ranked in order depending on the “how’s” (left to right in the FAST diagram) and the “why’s” (right to left). A FAST diagram summarizes the functions in this way.

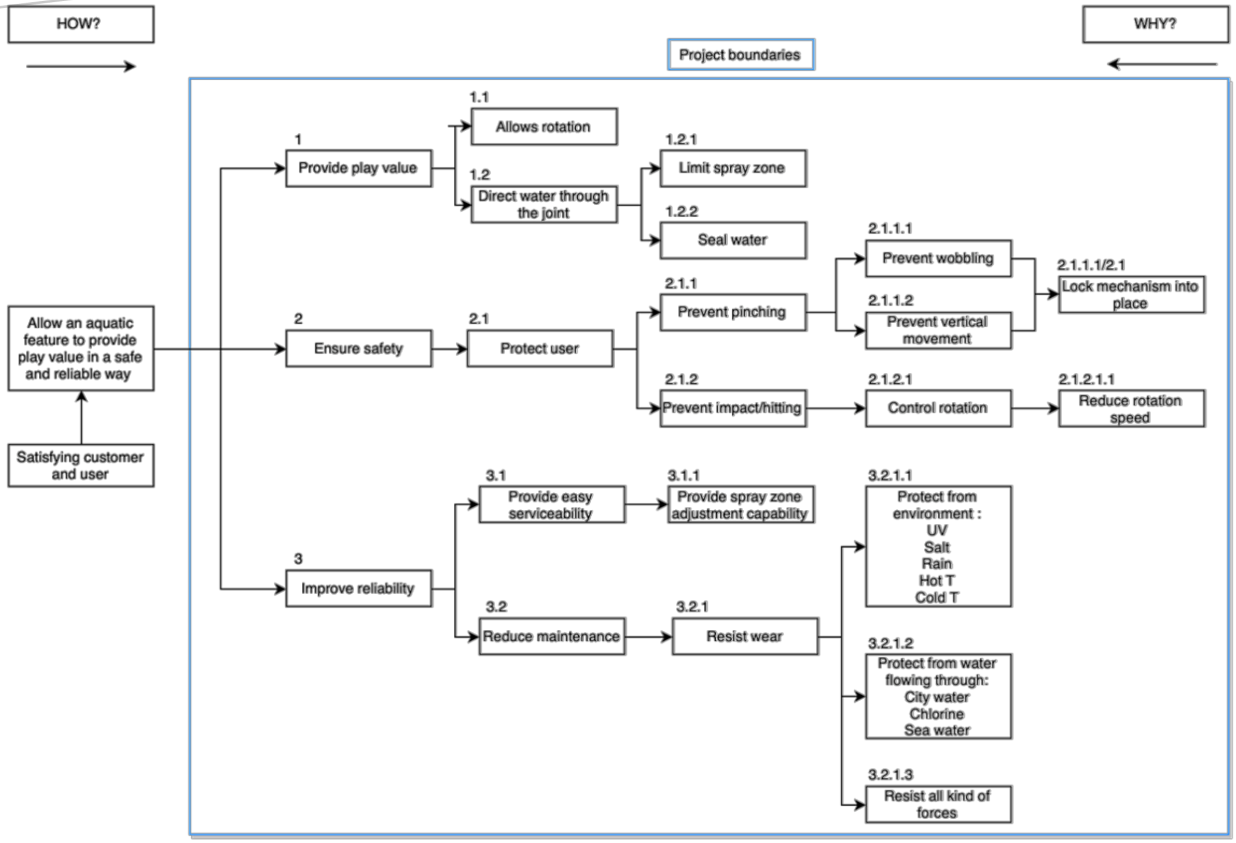



*Figure 8 FAST Diagram*

## Characterizing Functions

After identifying the functions, the next step consists of characterizing them. Each function is assigned a criteria, level and flexibility. The criteria describes how a function is measured. The level states the acceptable result for each criteria. Finally, the flexibility criterion indicates how flexible the level is.

- F0 = Not Flexible
- F1 = Little Flexible
- F2 = Some Flexible
- F3 = Very Flexible

*Table 2 Flexibility Table*

| Function | FAST Diagram | Performance Criteria | Level | Flexibility |
|---|---|---|---|---|
| Limit Spray Zone | 1.2.1 | Angle | ±10 degrees | F2 |
| Seal Water | 1.2.2 | Volume of leaking water | 0 | F1 |
| Lock Mechanism Into Place | 2.1.1.1/2.1 | Pull test | Less than 1/16" allowable | F0 |
| Reduce Rotation Speed | 2.1.2.1.1 | rotational speed | ASTM Standard | F2 |
| Protect from environment (UV) | 3.2.1.1 | Outsource - material test lab | 10 years warranty | F1 |
| Protect from environment (Salt) | 3.2.1.1 | Outsource - material test lab | 10 years warranty | F1 |
| Protect from environment (Rain) | 3.2.1.1 | Outsource - material test lab | 10 years warranty | F1 |
| Protect from environment (Hot Temperature) | 3.2.1.1 | Outsource - material test lab | 10 years warranty | F2 |
| Protect from environment (Cold Temperature) | 3.2.1.1 | Outsource - material test lab | 10 years warranty | F2 |
| Protect from city water flowing through | 3.2.1.2 | Outsource - material test lab | 10 years warranty | F1 |
| Protect from chlorine flowing through | 3.2.1.2 | Outsource - material test lab | 10 years warranty | F1 |
| Protect from sea water flowing through | 3.2.1.2 | Outsource - material test lab | 10 years warranty | F1 |
| Resist all kinds of forces | 3.2.1.3 | Pull test/measure deflection | Less than 1/16" allowable | F0 |

## Cost Analysis

The production costs for Vortex's current rotational joint were analyzed with respect to the functions of the joint and the components that the joint comprises. The charts below illustrate the cost distribution per function and per component.

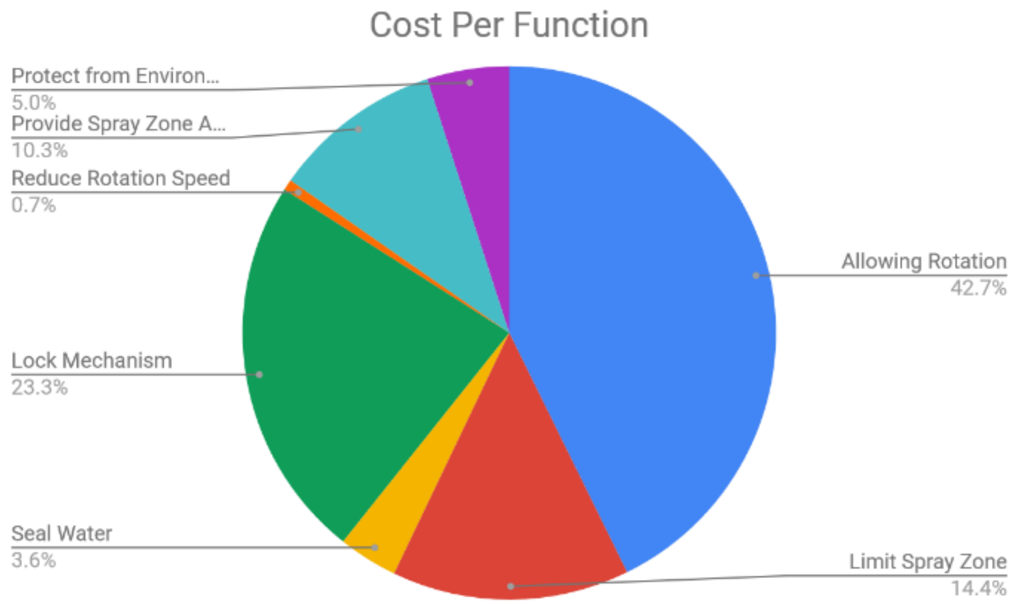



*Figure 9 Cost per Function Pie Chart*

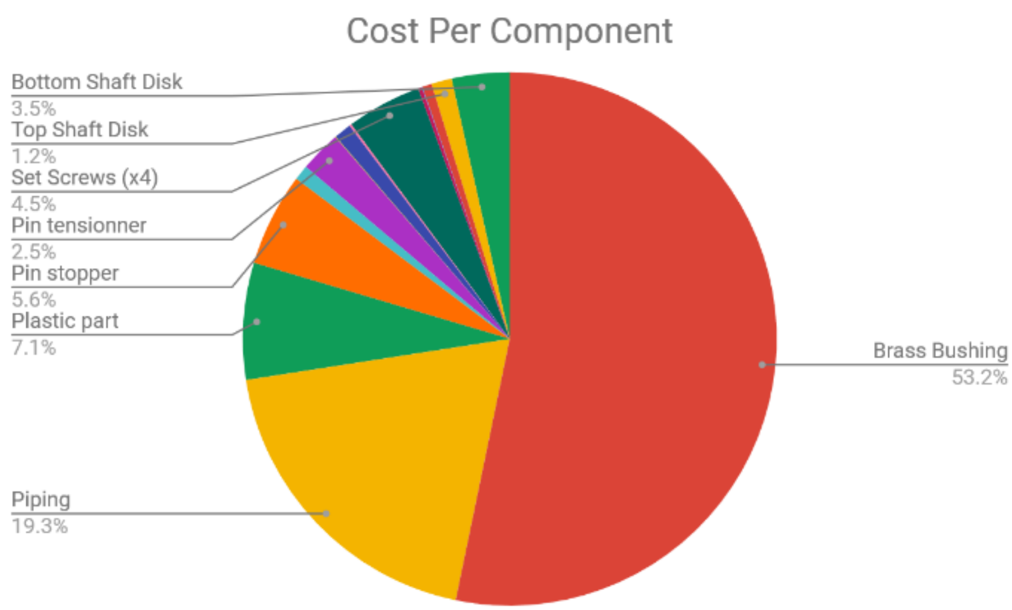



*Figure 10 Cost per Component Pie Chart*

These charts provide important insight as to where focus should be made to achieve cost savings. As expected, the function “Allowing Rotation” accounts for most of the cost; this makes sense, seeing as the product is a **rotational** joint. Other functions that make up a significant amount of the expenses include

“Locking Mechanism” and “Limit Spray Zone.” Increasing the percentage of the cost attributed to allowing rotation and spreading the cost more evenly amongst other function is not a goal per se, but would be beneficial to achieve.

Analyzing the cost distribution for the different components that comprise the rotational joint provides guidance regarding which components to prioritize in terms of finding alternate or more cost-effective solutions. The brass bushing accounts for over half the production costs of the joint; based on discussions with Vortex, the bushing clearly requires the most attention with respect to determining alternate solutions and finding ways to minimize cost. The next largest cost driver is the piping; since the piping is integral to the very shape and structure of the fixture, this is not a priority.

## Creativity Phase

Once all the functions and costs are properly analyzed, the creativity phase is used to generate a large quantity of ideas or alternatives to accomplish the functions identified in the previous phase. To generate as many concepts as possible, each individual had a brief moment to think about and to list their potential solutions separately. A brainstorm session was then held to combine and share the ideas. As a result, a total of 18 different concepts were proposed. The latter are listed below.

1. Regular taper-lock bushing
2. Added groves to brass bushing to limit wiggle
3. Add plastic spacer to brass bushing to limit wear
4. Tapered inner shaft with threads on the shafts and bushing
5. Threaded straight pipe with a threaded bushing
6. Water flow bushing with a vertical slot
7. Water flow bushing with a radial slot
8. Combined wear piece and water flow bushing with vertical slot
9. Intermediate water flow directing piece between shaft and wear piece
10. Combined wear piece and water flow bushing with radial slot
11. Straight or angled screws to lock against outer pipe
12. Single-screw taper-lock bushing
13. Magnetic bearings
14. Roller or needle bearings
15. Set screws and grooves on outer pipe
16. Set screws and grooves on inner pipe
17. Taper-lock bushings with flange or disks
18. Two-stage tapper lock bushing with C-clips

## Evaluation Phase

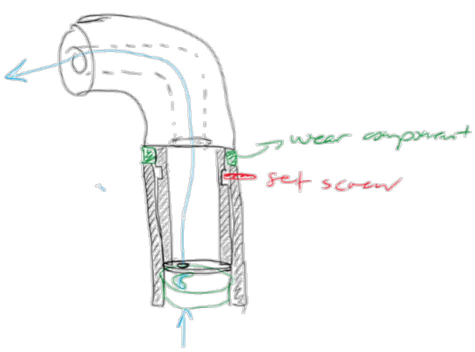
Following the creativity phase, the large number of proposed concepts needed to be filtered and narrowed down. As a result, a gut feel index was used to quickly evaluate the most feasible concepts by having the team members give a rating between 1 to 10 for each concept while considering the feasibility, complexity, cost, serviceability and ease of implementation. A rating of 1 was defined as nonsense and 10 was defined as a “champion” idea.

*Table 3 Gut Feel Index*

| | Idea | Gut Feel Index |
|---|---|---|
| 1 | Regular taper-lock bushing | 6 |
| 2 | Added groves to brass bushing to limit wiggle | 4 |
| 3 | Add plastic spacer to brass bushing to limit wear | 4 |
| 4 | Tapered inner shaft with threads on the shafts and bushing | 3 |
| 5 | Threaded straight pipe with a threaded bushing | 2 |
| 6 | Water flow bushing with a vertical slot | 7 |
| 7 | Water flow bushing with a radial slot | 8 |
| 8 | Combined wear piece and water flow bushing with vertical slot | 6 |
| 9 | Intermediate water flow directing piece between shaft and wear piece | 4 |
| 10 | Combined wear piece and water flow bushing with radial slot | 6 |
| 11 | Straight or angled screws to lock against outer pipe | 2 |
| 12 | Single-screw taper-lock bushing | 7 |
| 13 | Magnetic bearings | 1 |
| 14 | Roller or needle bearings | 2 |
| 15 | Set screws and grooves on outer pipe | 6 |
| 16 | Set screws and grooves on inner pipe | 7 |
| 17 | Taper-lock bushings with flange or disks | 8 |
| 18 | Two-stage tapper lock bushing with C-clips | 9 |

The concepts with the highest ratings were then chosen to be evaluated. To better evaluate and compare each solution, they were separated into two categories which are the ability to lock and rotate, and to limit water spray zone.

*Table 4 Lock and Rotate Concept Generation*

| | |
|---|---|
|   | Set-screw guided rotation; A set-screw installed from the outer piping into the inside, slotting into a notch machined radially around the inner pipe, to guide rotation and hold the top fixture down with a single set of components (1 or multiple set screws) |

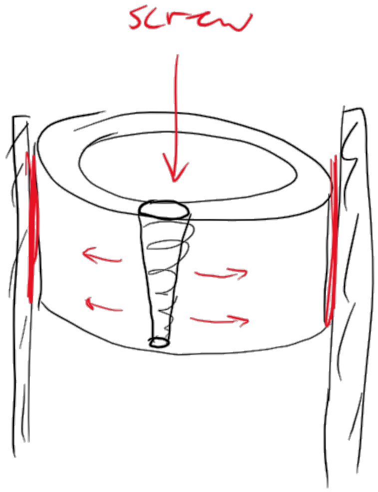
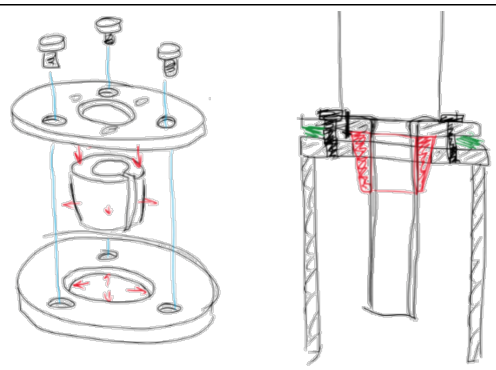
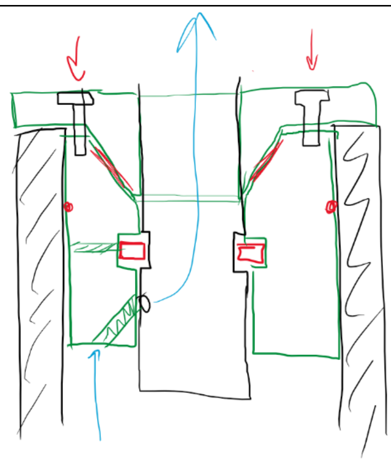
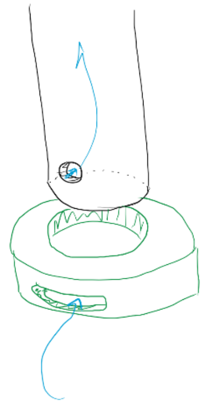
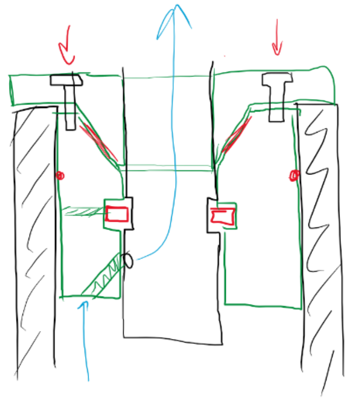
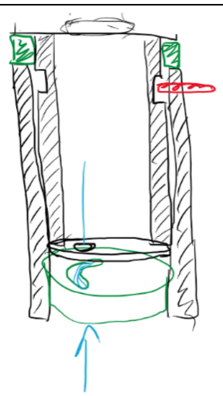
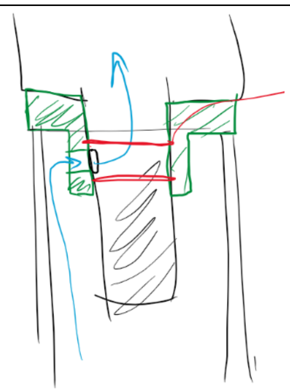
| | |
|---|---|
|  | Screw-bushing; driving screw into a threaded taper hole will force expansion of element against the walls of outer pipe, held in position via friction and expansive force. |
|  | Taper bushing with set screws; as the two flanges get screwed together, they will squeeze the taper bushing that is in between, which will cause the taper bushing to be tightened against the inner shaft, thus securing it. |
|  | Two stage taper bushing; screwing the top bushing half into the bottom bushing half will force the bottom bushing to expand outwards due to the tapered shape; the bushing will be held in place via expansive force. |

*Table 5 Limit Spray Zone Concept Generation*

| | |
|---|---|
|  | Plastic flow limiter with radially-machined slot; allow flow into the inner steel pipe, up and out of the top fixture when the machined slot is aligned with water flow, based on angle of rotation of top fixture. |
|  | Diagonally machined slot for water flow; water flows vertically up and into bushing, channeled diagonally into inner steel pipe, up and out of top fixture. |
|  | Plastic flow limiter with vertically-machined slot; allow flow into the inner steel pipe, up and out of the top fixture when the machined slot is aligned with fixed plate with hole, based on angle of rotation of top fixture. |
|  | Water flow through dedicated tubes vertically, into inner steel pipe and out. |

**Bushing selection**:

The following table was created to select an appropriate bushing for this application. The first section of this table is provided in SKF's bushing catalog and compares their bushings' suitability in different loading and operating environments. Highlighted in yellow are the conditions that align with the functions defined in this project - maintenance-free operation, dirty environments, corrosion-resistant, and heavy load. The second section gives the maximum inner diameter offered for each type of bushing. The joint design for this project uses an inner shaft of about 2.5in or 64mm. The last section more specifically addresses the chlorine and salt resistance of each type of material. Each type of bushing was then judged against these specified criteria – shown in red are the limiting factors that eliminated a particular bushing. For example, the solid bronze bushing was not suitable for "maintenance-free operation." The only option that remains is therefore the filament wound bushing.

*Table 6 Bushing Material Selection Table*

| | Solid Bronze | Sintered Bronze | Wrapped Bronze | PTFE Composite | POM Composite | PTFE Polyamide | Filament Wound |
|---|---|---|---|---|---|---|---|
| **Self-Lubricating Performance** | Not Suitable | Good | Not Suitable | Excellent | Good | Excellent | Excellent |
| **Maintenance-Free Operation** | Not Suitable | Good | Suitable | Excellent | Good | Excellent | Excellent |
| **Dirty Environments** | Good | Suitable | Excellent | Not Suitable | Suitable | Not Suitable | Good |
| **Corrosion-Resistant** | Good | Suitable | Good | Suitable | Suitable | Excellent | Excellent |
| **High Temperature** | Good | Not Suitable | Good | Excellent | Suitable | Suitable | Good |
| **Heavy Load** | Suitable | Not Suitable | Suitable | Good | Excellent | Suitable | Good |
| **Shock Loads/Vibrations** | Good | Suitable | Good | Suitable | Suitable | Not Suitable | Excellent |
| **High Sliding Velocity** | Not Suitable | Excellent | Suitable | Good | Good | Suitable | Not Suitable |
| **Low Friction** | Not Suitable | Good | Not Suitable | Excellent | Excellent | Suitable | Excellent |
| **Poor Shaft Surface Finish** | Good | Not Suitable | Suitable | Not Suitable | Suitable | Suitable | Suitable |
| **Small Operating Clearance** | Not Suitable | Suitable | Suitable | Excellent | Good | Suitable | Not Suitable |
| **Insensitive to Misalignment** | Good | Suitable | Suitable | Not Suitable | Suitable | Suitable | Good |
| **MAX ID Straight** | 250 | 100 | 100 | 200 | 150 | 30 | 200 |
| **MAX ID Flanged** | 250 | 100 | 100 | 35 | - | 25 | - |
| **Chlorine Water Resistance** | Ok | Ok | Ok | Yes | No | Yes | Yes |
| **Salt Water Resistance** | Yes | Yes | Yes | Yes | Yes | Yes | Yes |

# Final Design

### Tapered two-stage bushing

**Allow rotation:** The two-stage bushing design (shown in white) is 'self-fixing' into the outer pipe and both allows rotation of the inner shaft as well as a c-clip which locks the top feature into place vertically. The bottom half of the bushing is first inserted into the outer pipe. The top half is then inserted, and the 4 top bolts tightened. As these bolts tighten, the top half is 'pushed' downwards into the bottom half, and the taper effectively causes the bottom half to expand outwards. With friction, the bottom half is now gripping the outer pipe. The filament wound bushing selected from SKF is pressed into the top half of the tapered bushing and prevents any seizing or wear between the tapered bushing and the inner pipe.

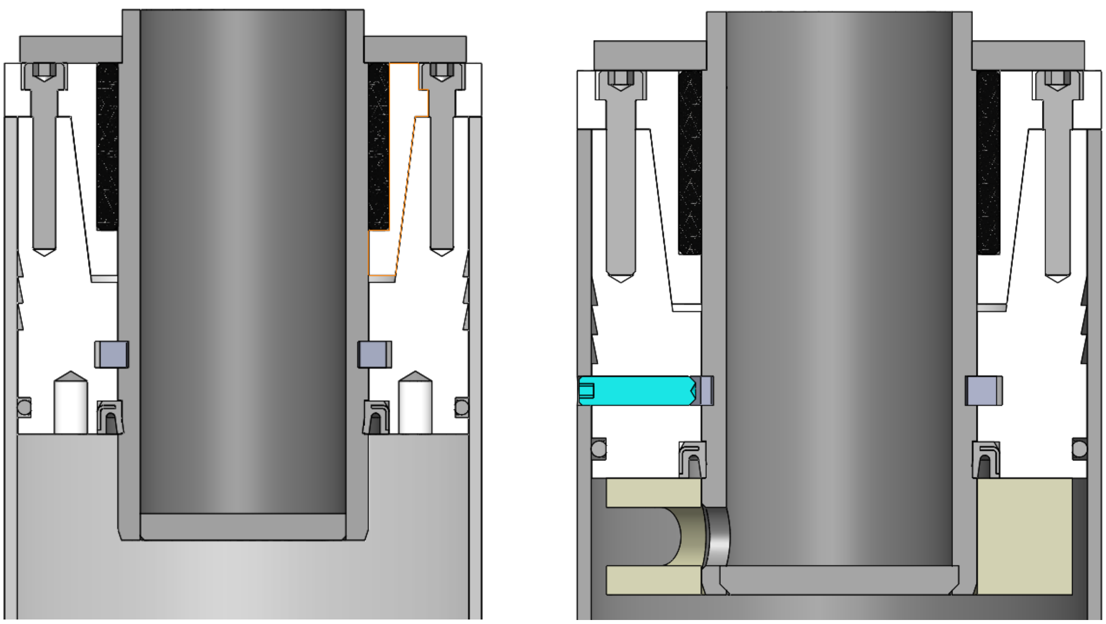


*Figure 11 Side View of Final Assembly*

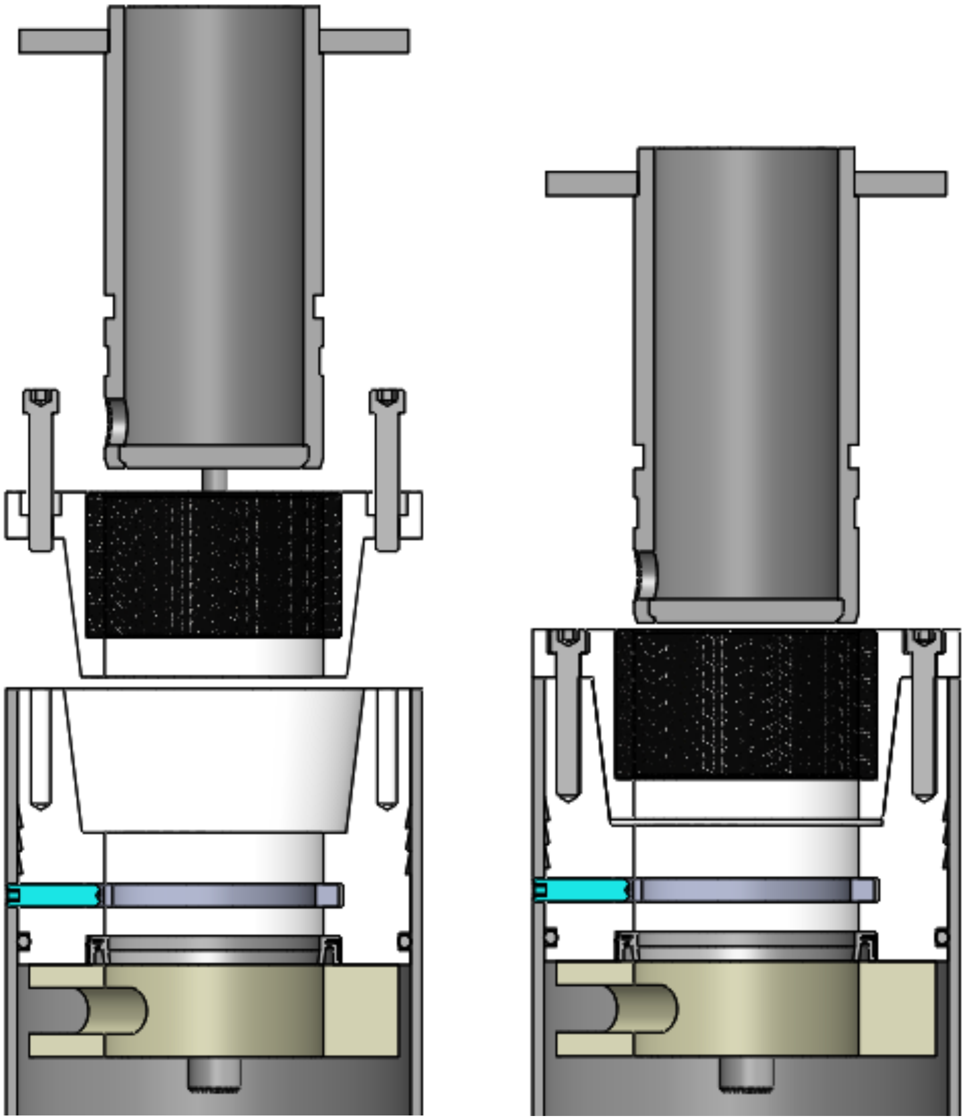


*Figure 12 Assembly of the Rotational joint in the feature*

**Lock mechanism:** The C-clip is pre-assembled into the bottom bushing. A set-screw accessed from the outside of the outer pipe can be used to open the C-clip; by driving the set-screw in, it pushes in the tapered ends of the C-clip which widens the inner diameter. With the C-clip open, the top feature can now be dropped into place. Backing out the set-screw then closes the C-clip which now clips onto the inner shaft. The set-screw can also act as a backup safety to prevent the whole joint from being lifted out of the outer pipe. Serrated edges can also be machined into the outside of the bottom taper to prevent this.

**Seal water:** To prevent water from leaking from around the outside of the joint, an O-ring is placed on the outside of the bottom tapered bushing. On the inside, a wiper seal is used. Wiper seals offer better sealing performance and wear resistance than O-rings. As water comes up against the seal, the rubber 'flaps' upwards and seals tighter, effectively blocking all water leakage. Placing this seal towards the bottom therefore protects the c-lip and filament bushing.

**Direct flow:** The chosen 'direct flow' solution was inspired by Vortex's original design. The original piece included pins and a screw to tighten it to the inner shaft. This version eliminates these fasteners. Since the wiper seal is located above the plastic part, it no longer needs to seal against water as tightly. The method of attaching the part is now to simply bolt it to the underside of the tapered bushing.

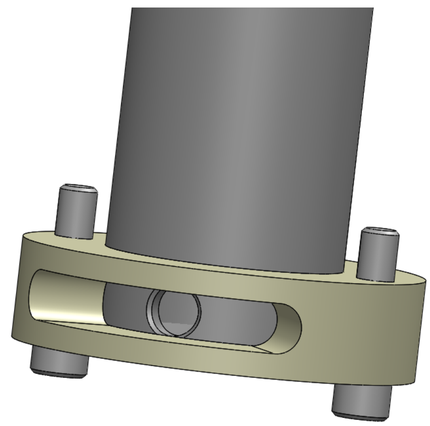


*Figure 13 Water Directing part*

# Cost Evolution

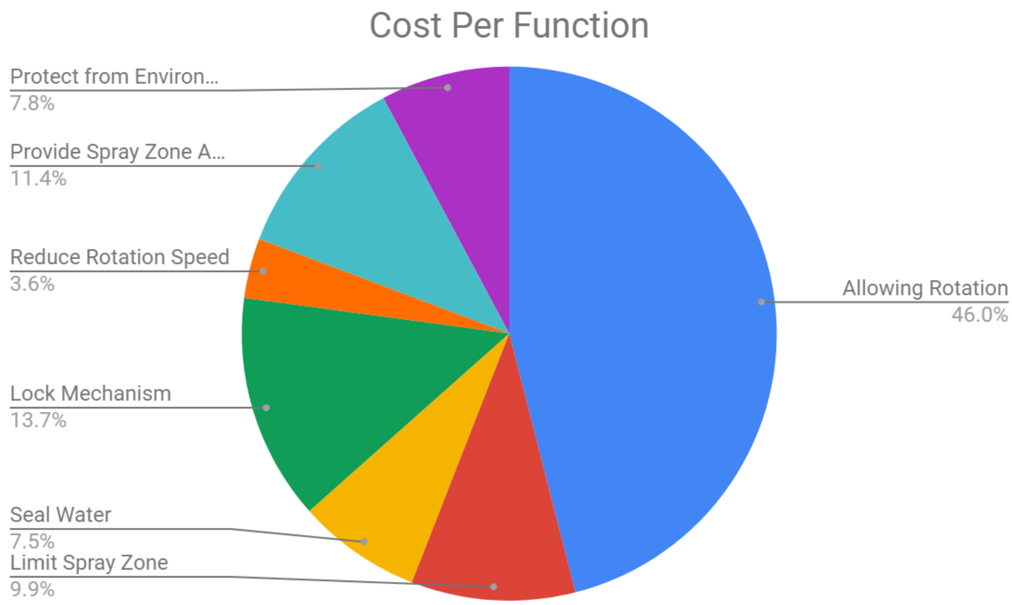



*Figure 14 Cost per Function of Proposed Design*

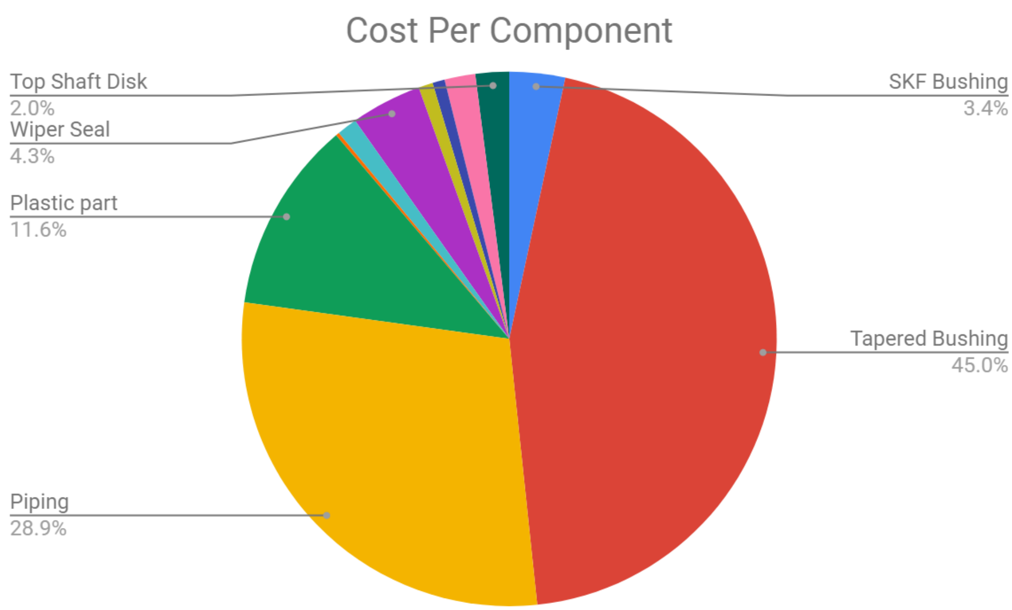



*Figure 15 Cost per Component of Proposed Design*

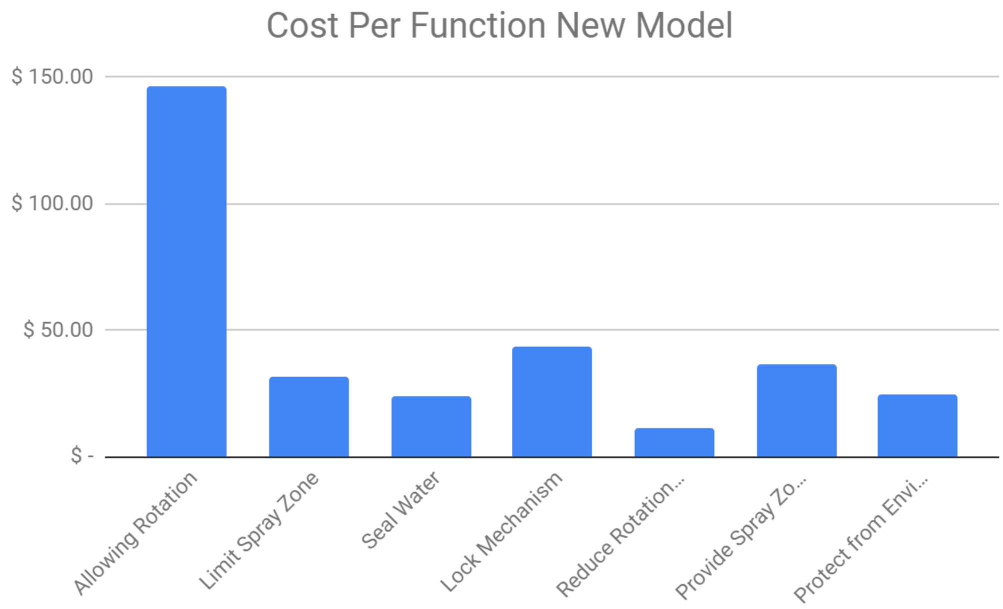



*Figure 16 Cost per Function of Proposed Design*

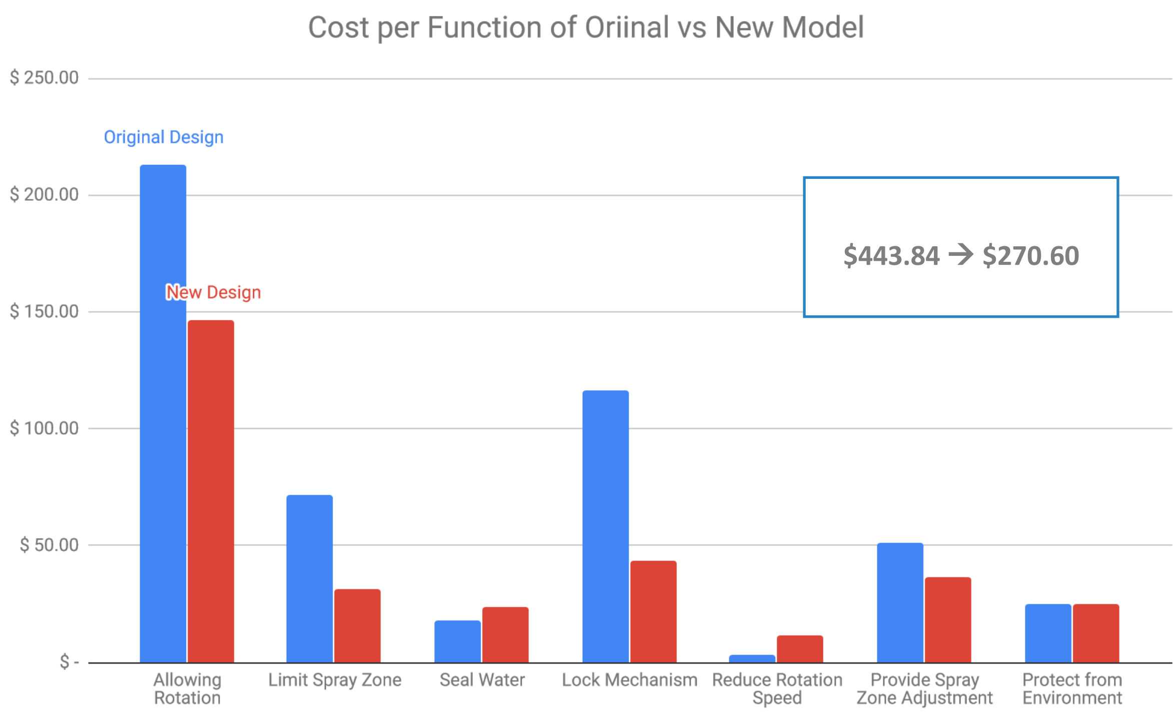



*Figure 17 Cost per function comparison between initial and proposed designs*

There is a significant price reduction regarding production costs between the currently implemented rotational design and the proposed solution. The production cost is decreased from \$443.84 to an estimated \$270.60 (resulting in a savings of \$173.24 per rotational joint). With an expected production of 300 rotational joints per year, the proposed solution yields a yearly savings of \$51 972.
When comparing the percent distribution of costs in relation to function, an increase in “Allowing Rotation” is noticeable, from 42.7 to 46 percent. Also, the percent distribution of the other functions is more equal, satisfying some concerns when analyzing the original cost distribution.

When comparing the costs related to components, the tapered bushing featured in the new design still encompasses most of the cost. However, the new two-staged bushing is estimated to cost \$115, compared to the old brass bushing costing \$183. Figure 16 illustrates on an absolute basis how much value is being saved per each function.

# Conclusion

The evolution of the current rotational joint utilized by Vortex to the proposed design solution presents several key benefits.

1) **Replacement of the brass bushing with a re-designed two-staged taper bushing.** With the inclusion of the SKF filament wound bushing, seizing of the bushing against the inner steel pipe is no longer a concern, and cheaper materials like stainless steel can be utilized. Moreover, less machining is required due to the expansive, tapered nature of the new bushing.
2) **Locking the top fixture with a single component.** With the incorporation of a C-clip to clamp the inner steel pipe, and with a single set-screw driven assembly and disassembly, the overall number of components has been reduced from 17 to 12 and servicing has been made faster and more effective.

Despite minor modifications regarding assembly to improved water sealing, **the radially machined slot in a plastic piece to direct water flow was maintained**.

The new model presents an overall **estimated savings of $173.24 per rotational joint** produced.

## Final Recommendations

**Finite Element Analyses:** Given the CAD files of the final solution proposal, conduct a Finite Element Analysis on the model in order to determine whether the model will perform as desired against the expected forces to be exerted on the fixture in use.

**Prototype Testing:** Produce multiple prototypes of the rotational joint in order to test real performance of the fixture against expected forces and to determine which materials are best.