Whirlpool Duet Washing Machine Water Recycling and Reduction Project

Final Report
ME 450 Team 12
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TABLE OF CONTENTS

EXECUTIVE SUMMARY

Motivation In an effort to improve the eco-efficiency of Whirlpool fabric care appliances, Whirlpool Corporation, manufacturer and marketer of major home appliances, is interested in developing a more water efficient washing machine. Thus, they asked our team to explore solutions to reduce the water usage of the Whirlpool Duet front loading washing machine by 75% without significantly increasing energy usage and cost.

Specifications In order to deliver a product that meets all of our sponsor's requirements as well as perceived consumer requirements, we developed several design specifications to help guide our design process. The main three specifications that we were trying to meet are: The system reduces the water consumption of the Duet by 75%, the filtration cycle takes place in 11.5 minutes, and the water is cleaned to a level between 5 and 20 nephelometric turbidity units.

Concept Generation Several preliminary concepts were generated and then compared to determine which would be the best design for the system. Using a systematic approach, we determined that a system involving continuous filtration from a tank would be best. This design included adding 2 pumps, a storage tank, 2 filters (polypropylene and activated carbon), and valves to direct the water to the appropriate components.

Final Design Our final design consists of two pumps, a water tank, two filter housings, and a valve. All the components are connected by pipes with clamps. The whole system is located in the pedestal, provided by Whirlpool, under the washer. The washer is kept the same and will be connected with our design to achieve the goal. The continuous filtering method is used for the final design. An electronic control of the system is required for the system, but was not designed because it was outside our scope.

Fabrication Plan For this design, the fabrication plan for individual components only involves the assembly of the storage tank because other components such as the pump and valves are pre-manufactured. The system level fabrication plan involves integrating the components by connecting them with tubing and joints, positioning them to maximize space efficiency, and setting up the system for partial manual control.

Test Results We had one main test to determine if our design worked and if our system was viable. This test involved running the system with dirty wash water to determine how clean we could get it in 11.5 minutes. Upon testing, we objectively determined that the water was clean enough to use in the subsequent rinse cycles

Cost Analysis To determine the economic feasibility of our system a detailed cost analysis was performed. We wanted to determine if the cost of electricity and maintenance on the system could be offset by the money saved by conserving water, and to see what the break even point would be. Summing the savings and costs, we determined that the system actually costs the user approximately $32.79 per year. At the current price of water, the user will never break even with our system. This analysis does not, however, take into account the intangible cost savings of reducing environmental impact in the form of water savings.

Design Critique We performed a critique of our final design to determine if there were any places we could make improvement. Three improvements that we found were that the stability of the system needs to be investigated further due to the vibration caused by the operation of the pumps, the cooling analysis could be further researched to have more feasible results, and the continuous filtering methods could be changed to filtering water only once which will increase the efficiency of the filtering by not having filtered and dirty water mixed.

Conclusion We determined that our system met the top three design specifications of water reduction, filtration time, and water cleanliness level. In addition, we managed to fit it all within the space available while keeping the energy consumption under 10% of the original washer. Although some modifications could be made to further optimize our design, it has proved the concept that a wash water recycling system is a viable solution for significant water savings.

INTRODUCTION

In an effort to improve the eco-efficiency of Whirlpool fabric care appliances, Whirlpool Corporation, manufacturer and marketer of major home appliances, is interested in developing a more water efficient washing machine. Thus, they asked our team to explore solutions to reduce the water usage of the Whirlpool Duet front loading washing machine by 75% without significantly increasing energy usage and cost. Collaborating with Team 30, another ME450 team, we continued the design process started by two fall 2007 ME450 teams of conceiving and building a prototype of a filtration system that recycles rinse water for reuse rather than disposing it after each cycle. Our team was responsible for the design of the overall system while Team 30 was responsible for the design of the filters. This poster outlines the process and results of the design and fabrication of our prototype.

PRELIMINARY RESEARCH

General Principle of Front Loading Washing Machine [1]

Parts of a Front Loading Washing Machine: The most important parts of a washing machine are inner drum and outer drum. The inner drum is the one you can see when you open the door or the lid. You push your clothes inside the door from the front and the whole drum rotates. The drum has lots of small holes to let water in and out and paddles around the edge to slosh the clothes around. The outer drum is the bigger drum outside the inner drum. Its job is to hold the water while the inner drum rotates. Unlike the inner drum, the outer drum has to be completely water-tight.

Besides the two drums, there are lots of other components. There's a thermostat (thermometer mechanism) to test the temperature of the incoming water and a heating element that warms it up to the required temperature. There's also an electrically operated pump that removes water from the drum when the wash is over. There's a mechanical or electronic control mechanism called a programmer, which makes the various parts of the washing machine go through a series of steps to wash, rinse, and spin your clothes. There are two pipes that let clean hot and cold water into the machine and a third pipe that lets the dirty water out again. All these pipes have valves on them.

How Washing Machine Works: All the important parts of the washing machine are electrically controlled, including the inner drum, the valves, the pump, and the heating element. You put your clothes in the machine and detergent either in the machine itself or in a tray up above. You set the program you want and switch on the power.

There are basically three steps in a wash cycle: washing, rinsing and spinning. There is usually 1 complete fill/drain for the washing step and 3 complete fills/drains for the rinsing step. During the washing step, the programmer first opens the water valves so hot and cold water enters the machine and fills up the outer and inner drums. The water usually enters at the top and trickles down through the detergent tray, washing any soap there into the machine. The programmer switches off the water valves. The thermostat measures the temperature of the incoming water. If it's too cold, the programmer switches on the heating element. When the water is hot enough, the programmer makes the drum rotate back and forth, sloshing the clothes through the soapy water. The detergent pulls the dirt from your clothes and traps it in the water. The programmer opens a valve so the water drains from the drums. Then it switches on the pump to help empty the water away. After the washing step, the washing machine begins rinsing. The programmer opens the water valves again so clean water enters the drums. The programmer makes the drum rotate back and forth so the clean water rinses the clothes. It empties the drum and repeats this process 2 times to get rid of all the soap. When the clothes are rinsed, the programmer makes the drum rotate at high speed—around 80 mph (130 km/h). The clothes are flung against the outside of the drum, but the water they contain is small enough to pass through the drum's tiny holes. This is how spinning gets your clothes dry. The pump removes any remaining water and the wash cycle comes to an end.

Layout and Analysis of Existing Duet System

With the basic understanding of how a front loading washer works, we could then analyze the system we were provided by Whirlpool. This section of the literature search provides research on the Duet system and how it works and is designed.

Consumer Services Manual: This manual outlined many of the technical specifications of the Duet washing machine. It gave all of the dimensions, power inputs, temperatures, wiring diagrams, and component descriptions. It also gave detailed descriptions of all of the washer subsystems and what components were involved and how they all functioned. Based on this manual, we could put hard numbers to many of our requirements by using the existing system as a benchmark. [2]

Duet Washer Schematics: These schematics allowed us to examine several subsystems to see how components connected and where we might be able to modify the washer to include our system. Areas of special interest were the drain and pump system and the washer tub and basket system. These schematics may also be used should we decide to disassemble the washer to examine its components first hand. [3]

Washing Machine Benchmarking and Patents

Washer Benchmark: We needed to have a competitor's product which we can compare to our washer system to use as a benchmark and see how well our system is performing. We decided to use Aeg L88810 Front load washer as a benchmark. This German company's product is listed as the most water efficient washer on the British market. [4] Its water consumption is 39 liters for 6 Kg load size, [5] compared to the Duet's 60 liters for a slightly larger load size of 9 Kg.

Patent of Recirculation Pump System for a Washer: A 1994 Whirlpool Corporation patent describes a washing machine recirculation and draining system which includes two bottom drains in a wash tub, the drains connected by a tubing manifold having a reversible pump. A two-way valve opens one drain and closes a drain line during recirculation; the pump first rotating in one direction to pump wash water through a recirculation line. For draining, a second two-way valve opens the second drain and the first two-way valve closes the first drain and opens the drain line; the pump then rotates in the other direction to drain the tub out through the drain line. [6]

Patent of System and Method for Economically Viable and Environmentally Friendly Central Processing of Home Laundry: A 2006 Shell Corporation patent describes an economically viable process and system for centrally processing multiple loads of laundry with minimum environmental impact. This is a system and method of laundering whereby successive loads of laundry may be washed while continuously providing effective soil removal comprising at least partially recycled wash water from at least one previous wash cycle. The method of using the same water comprises of filtering wash water with at least one filter to form wash retentate and wash permeate. The use of wash permeate in successive washes provides for reuse of chemicals and water recovery. A similar arrangement may be used with regard to the rinse water. Advantageously, one embodiment of the invention provides for the use of rinse retentate as make up water in the wash loop which increases water recovery and chemical recovery. Ultimately, the invention can reduce the production of gray water and recover chemicals used in the laundering process. [7]

Metrics of Wash Quality

In order to determine the effectiveness of the filtration system after the prototype has been created, a method of quantifying the quality of the washing process needs to be established. It was determined that the two most useful ways of doing this would be to measure the cleanliness of the water after it passes through the filtration system and the cleanliness of a load of clothes after they have gone through the complete washing process with the filtration system in place. The cleanliness of the water would be compared to that of the water entering the washer from an external source and the cleanliness of a load of clothes would be compared to that which the current, unmodified washer produces.

Cleanliness of Water: Methods for quantifying the cleanliness of water were researched and many different ways were discovered. The Pacific Northwest Pollution Prevention Resource Center (PPRC) [8] lists a variety of methods to detect the presence of bacteria, chemicals, and solid particles in water. However, many of the methods such as optically stimulated electron emission, direct oxidation carbon coulmetry, x-ray photoelectron spectroscopy, and ultraviolent spectroscopy, while very accurate, require equipment that is expensive and not readily available. Other methods, like magnified visual inspection and the water break test, are much simpler to perform, but only produce "pass/fail" results (i.e. The water is either contaminated or it's not). This is not useful because it would make it difficult to analyze and compare test results against each other for effectiveness. Also, the water may not necessarily need to be completely free of contaminants to be considered acceptable. The PPRC also suggests gravimetric measurements which involve removing solid particles from the water through filtration, solvents, or drying the water out over a surface and weighing them on a highly sensitive scale. This was considered as a viable option.

Another method that was researched was measuring the turbidity of the water. Turbidity is the amount of suspended particulate in a fluid that causes a decrease in the passage of light. Turbidity can be measured in nephelometric turbidity units using a turbidimeter. Measuring turbidity is simple, requires accessible equipment, and is accurate enough that the effectiveness of the filtration system can be closely monitored by comparing test results. This method was considered the most useful out all that were researched. Therefore, it was concluded that measuring turbidity, perhaps in conjunction with the gravimetric measurements, is the best way to measure the cleanliness of water in this system.

Cleanliness of Clothes: After much research, it was discovered that little has already been accomplished in the way of quantifying the cleanliness of clothes. The most relevant method found is the "PBIS" method that was adopted by the Australian Standards Committee in February 2005 [9]. This method is described in the summary report prepared by Energy Efficient Strategies as follows:

"Assessment of the rinse performance of a clothes washer is based upon the measurement of the apparent mass of retained marker (PBIS) in the load at the completion of the program.

The marker is dosed into the wash program in proportion to the rated load. A standard soil removal test is then conducted. At the completion of this test (following weighing of the load) the load is placed in a spin extractor and a sample of rinse liquor recovered. Using UV spectrophotometry the concentration of retained PBIS is then determined by comparison with measurements from solutions of known PBIS concentration (noting that background levels of PBIS in the supply water are accounted for in the procedure).

The rinse performance is then determined from the concentration of PBIS in the extracted rinse liquor multiplied by the mass of retained moisture in the load measured at the end of the program."

This method was determined to be highly accurate because it is supported by an abundant amount of research and testing and was adopted by the Australian federal government. However, it requires the use of a spin extractor and a UV spectrophotometer, both of which are expensive and not readily accessible.

It was decided that, since the goal of the filtration system is to output clean water and because of a lack of a feasible method to measure the cleanliness of clothes, this project will focus on measuring the cleanliness of the water to determine the quality of the wash process with the filtration system in place.

PROJECT REQUIREMENTS AND SPECIFICATIONS

Project Requirements and Specifications: In order to deliver a product that meets all of our sponsor's requirements as well as perceived consumer requirements, we developed several design specifications to help guide our design process. We then translated these general requirements to actual engineering specifications to which we feel our design must adhere. To develop these requirements, we analyzed our existing wash system and tried to incorporate the apparent requirements used in its design, as well as try to anticipate what requirements the customer would have for this product. We then chose reasonable numerical values for each requirement when the numbers were not explicitly given. The numbers were chosen based on our research and engineering judgment and meetings with Whirlpool. The level of importance was determined by judging what we thought Whirlpool and the end user would view as the most important specifications. Table 1 lists the requirements and specifications in order of importance.

Requirement	Engineering Specification
Reduce Water Consumption by 75%	Total usage is 15L
Complete Filtration in Same Amount of Time as Drain Cycle	Less than 11.5 minutes
Rinse Water is Equally Clean	5-20 NTU
Filters are Robust and Don't Require Maintenance	6 month lifespan
System Allows for Hot and Cold Rinse	104°F/77°F
System Minimizes the Increase in Energy Required	18.2 kWh/year
System Fits into Washer Pedestal	14" x 27" x 30.3"
System is Not Overly Expensive	Less than $170
System Requires Minimum Existing Hardware Change	Less than 5 parts
System Adds a Minimum Number of New Moving Parts	Less than 5 parts
System is Robust	11 year lifespan
Easy to Fix and Maintain	Components accessible
Easy to Manufacture	2.5% additional manufacturing time
No Leaks	0 drips/load

Table 1: Customer requirements with corresponding engineering specifications, listed in order of importance.

The following is a description of each requirement and how we arrived at the corresponding engineering specification.

- **Reduce Water Consumption by 75%** The highest level specification and the most important to our sponsor is the requirement that out system reduces the water consumption of the Duet washing machine by 75%. This was the only constraint that the sponsor has communicated to us so far and is directly related to the design problem. As such, our design must accomplish this goal. In terms of engineering specifications, this translates to a reduction in water usage from 60 Liters to 15 Liters. It is also important to note that no product currently on the market comes close to using this small amount of water. The closest benchmark we have to our proposed system is a usage of 39 L, so our design will be a significant improvement on the next best washer design.

- **Complete Filtration in Same Amount of Time as Drain Cycle** The next specification is that the system completes the filtration of the water in 11.5 minutes. In our design, the filtration will only take place between cycles, so it is important not to add undue time to the wash cycle. Our sponsor specified that we add less than 15 minutes to the total cycle run time. With 2 filtration cycles in one wash cycle and 4 minutes of drain time built into each wash/rinse cycle, this corresponds to a total system runtime of 11.5 minutes.
- **Rinse Water is Equally Clean** We also came up with the specification that the water exiting our filtration system and re-entering the washer be equally clean as the water that would be added by the washer without our filtration system. This is to ensure that the washer is still effective at cleaning clothes and is not simply saving water without cleaning the clothes. In order to get a quantitative measurement for water cleanliness, we will be employing a turbidimeter, which measures the amount of soil in the water by measuring the amount of light blocked by the suspended particles (turbidity). This would tell us how well our system was operating. We have decided that our system should clean the water to a level of 5-20 NTU (Nephelometric Turbidity Units), which is close to the level of turbidity in tap water.
- **Filters are Robust and Don't Require Maintenance** Another important specification we imposed was the fact that the filters must not require excessive maintenance. This is important because the consumer will not want to have to constantly have their appliance serviced or have to buy new filters often. We translated this requirement to engineering terms by determining that the minimum filter life should be at least 6 months if the filters are to be fully replaced and 3 months if they are to be cleaned by the user.
- **System Allows for Hot and Cold Rinse** The original Duet washer we are trying to redesign has two rinse temperatures. This practice is also common on most, if not all, washing machines sold by all manufacturers. We therefore decided that our system should be capable of supplying water at the two temperatures the Duet can run the rinse cycle. These temperatures are 104°F for the hot rinse and 77°F for the cold rinse. Since most washer models have this capability, we feel the Duet should have this capability too if is to compete.
- **System Minimizes the Increase in Energy Required** Whirlpool has asked us to design a system to increase the eco-efficiency of the system. Although their emphasis is on water conservation, they want us to minimize the amount of energy required to run this new system to try and keep its washers as energy efficient as possible. We have therefore specified that the system should not add more than 10%, or 18.2 kWh/year, to the overall energy consumption of the washer. This benchmark was determined from the Energy Star rating on the existing Duet supplied to us by Whirlpool.
- **System Fits into Washer Pedestal** Whirlpool has also placed the constraint that our system must fit inside the washer pedestal that was provided with the washing machine. This means it must fit in a volume no greater than 14" x 27" x 30.3". This is the volume of the inside of the pedestal with the included drawer removed. This is an ideal package for the system because it has the same footprint as the washer and has been designed to fit underneath the washer.
- **System is Not Overly Expensive** We also recognize that the system we design will not be purchased if it is not competitively priced. Whirlpool has specified that the final design of our system not cost more than $170. This is to ensure that the system will be an accessory that consumer will be able to afford.
- **System Requires Minimum Existing Hardware Change** Another specification we came up with is that our system should not require significant changes to the existing washer components or setup if possible. From an engineering standpoint, we have determined that a maximum of 5

components may be changed in the process of implementing our system. This will allow most of the current manufacturing of the Duet to remain the same.

- **System Adds a Minimum Number of New Moving Parts** Another specification we imposed on our design is that it did not add many new moving parts. Moving parts add to the maintenance that may be required on the system and also increases the number of places that failure can occur. Due to this, we have specified that no more than 5 moving parts may be used in our system in order to minimize these problems.
- **System is Robust** We also need the system as a whole to be robust in order to minimize customer maintenance and part replacement. We have specified that the system should last at least 11 years, which is the average lifespan of a washing machine. With this specification, we can be reasonably sure that the system will not need to be replaced as long as the washer is in operation.
- **Easy to Fix and Maintain** This requirement will determine the placement and accessibility of certain components of the system. We will use this specification to help determine where the higher maintenance components like filters and pumps will be placed. The engineering specification that corresponds to this requirement is that these higher maintenance components need to be placed in a location where they can be easily replaced or serviced. The existing washer seems to also follow this specification in that all of its major motors and pumps are easily accessible from the back of the machine.
- **Easy to Manufacture** Another requirement we thought Whirlpool would want imposed is that the system be easily manufactured. This requirement is ranked fairly low because we are trying to provide proof of concept, and the system can be made more manufacturable once the process is fully developed. The engineering specification we developed for this requirement is that the addition of this system shouldn't add more than 2.5% more manufacturing time to the entire washing machine manufacturing process.
- **No Leaks** We found that consumers would react unfavorably to a system that leaked water into their homes. Because of this, we imposed the requirement that there should be no leaks in our system. This requirement is ranked very low because for the actual production model, water sealing is a relatively minor task. We assigned the unit drips/load to this requirement to develop the engineering specification that the system should allow zero drips/load of laundry. The benchmark for this specification is the existing washer, which also allows zero drips/load.

GENERAL CONCEPT GENERATION

Brainstorming In order to generate concepts, our team brainstormed with each other and the members of ME 450 section 3. The ideas that were generated are listed below. These brainstormed ideas were used to create different design concepts that we later evaluated to determine our alpha design.

- Use fraction of clean/recycled water
- Different soaps
- Different filtering systems for different cycles
- Coagulant sponge
- Adding cycles between rinse cycles to clean filters
- Decrease number of cycles
- Combine cycles
- Don't use complete cycle drain
- Continual filtering after wash cycle

- Filter with flush back wash (monthly)
- Gravity/spin to force water without pump
- Use two-way valve with same pump
- Disposable filters
- Easy to clean filters
- Use final rinse to flush filters
- Change amount of water for cycles
- Use function of water with power rinse

The ME450 Whirlpool Washer Design Project began in the fall 2007 semester and previous teams had already selected what they determined to be the most feasible solution to reducing water usage in the Whirlpool Duet Washer by 75%. However, the teams this semester were not constrained to developing this previous design, so further concepts were generated. These preliminary concepts were produced through brainstorming sessions between members of Team 12 and Team 30 which are listed above. Due to the nature of this project, concept generation for a general design solution had to be determined relatively quickly and early on in the project. A more detailed concept generation process was held after the general design solution was chosen. The following is a detailed list of concepts considered.

Different Soaps: For this design, the idea was to change the types of detergent the washer used, increase the amount of detergent for each load, or both. Different types or amounts of detergent could clean the fabrics as effectively as before, but require less water to do so.

Cycle Change: By either increasing or decreasing the number of cycles the washer used, the amount of water could be reduced. The Duet Washer currently uses three cycles, but the fabrics may be cleaned just as effectively only using two cycles at an increased length of time. Similarly, the fabrics may be cleaned as effectively by using less water spread out over several more cycles.

Recirculation With Filter: Instead of draining and refilling the tub with fresh water each time, water usage could be reduced by reusing the same water for each cycle. After the water is drained at each cycle, soil, soap, and other contaminants would be removed by a filter and the water would be clean enough to be used again in another cycle.

Redesign Washer: Water usage could be reduced by inventing a new method of washing fabrics different from the current washer's method of sloshing them through water in a rotating tub. This new method would clean the fabrics as effectively, but require less water.

Alternative to Water: The washer, for the most part, would function almost entirely the same way it does now, but the fabrics would be cleaned with a fluid other than water. This would almost completely remove the need for water.

The "Cycle Change" and "Recirculation with Filter" concepts were combined and considered as a sixth concept.

GENERAL CONCEPT SELECTION PROCESS

Once preliminary concepts were generated, they were compared to determine which one would be chosen for the alpha design. The primary medium for choosing a concept was the Pugh Matrix. The Pugh Matrix for comparing general design solutions is shown in Appendix D.

The design criteria that each concept was subjected to are as follows: 1. Amount of water that could be saved 2. Time to complete the washing process 3. Energy required to operate 4. Space required to install system 5. Cost of system 6. Maintenance required to keep system functional 7. Robustness of system over a lifetime 8. Laundry cleanliness 9. Modifications needed to be made to the current washer 10. Prototyping time 11. Prototyping cost.

The most significant advantage to the "different soaps" concept was that it did not require the washer to function differently than it already does. As a result, this concept does not use additional space, energy, or time to function. Furthermore, it does not require additional maintenance and would likely not affect the lifetime of the washer. However, its disadvantages are that it would require a substantial amount of research, testing, and knowledge of chemistry to create or discover a detergent that could clean fabrics as effectively as the current washer while using less water.

Changing the number of cycles in the washer is advantageous because it does not require adding any components to the current washer system. Thus, it does not affect the space, energy, or robustness of the current system and does not require additional maintenance. Disadvantages to this concept are that the functionality of the washer must be modified and the laundry may not be cleaned as effectively.

An advantage to recirculating and filtering the water is it has the most potential to reduce water usage which is the most important design criterion. It also has a reasonable prototyping cost and time. The disadvantage to this system is that it requires additional parts which consume extra energy, space, and time and have issues of maintenance and robustness associated with them.

Redesigning the washer could be either advantageous or not depending on whether the new design took more space, time, and energy than the current washer. However, the primary disadvantages for this concept are a substantial amount of prototyping cost and time that would go well beyond the scope of this project.

Finally, the "Alternative to Water" concept would save the most water by far and would not require any additional space or energy and likely not any more time. The disadvantages to this concept are the amount of time to research and test the design would be much greater than that of the other concepts considered.

After comparing all the concepts using the Pugh Matrix and our best engineering judgment, it was decided that a combination of the "Cycle Change" and "Recirculation with Filter" concepts was the most feasible design. One major advantage this concept has over the others is that it has a better chance than most the others of achieving the goal of reducing water usage by 75%. Furthermore, the prototyping time and cost is comparatively low and within the scope of the project. This concept pushes the limits of some of the customer requirements and engineering specifications such as time, energy, space, and cost relative to the other concepts, but the design can still meet all of the design specifications.

FUNCTIONAL DECOMPOSITION

In order to better understand what functions our system was going to have to perform and how many components and steps the process would take, we performed a functional decomposition. This functional decomposition will allow us to optimally design each component individually as well as assemble them into a system that met all of the customer requirements as efficiently as possible. We defined the system function as a washer water recycling system that must reduce water usage of the washer by 75% by cleaning and reusing wash water in a timely manner while being easy to maintain by the user and causing no decrease in performance of the washer's primary functions. Using this functional description, we broke the system down into the functions and sub-functions that would accomplish these goals. The functions and sub-functions are outlined below.

1. Reduce Water Usage
    - a Re-circulate water
    - b Adjust cycles
    - c Adjust initial water input
2. Cleaning Water
    - a Take out dirt
    - b Take out chemicals
3. Process Occurs in a Timely Manner
    - a Regulate flow
    - b Provide pumping power
4. Easy to Maintain
    - a Components in easily accessible locations
    - b Dirt removal system cleans itself
5. Cause No Decrease in Washer Performance
    - a Hot/cold rinse

We then produced a flow chart that graphically illustrates all of the components that may be required in our system and kept track of the movement of all materials, energy, and signals through our system. It is shown in Appendix E.

GENERATED CONCEPTS

We analyzed the results from the functional decomposition and brainstorming sessions and generated five main design concepts: 1. "filter and tank", 2. "surrounding filter", 3. "fully continuous filter", 4. "distillation filter" and 5. "increasing cycles and water redistribution". All of the five concepts use the recirculation with filter design.

Concept 1: Filter and tank

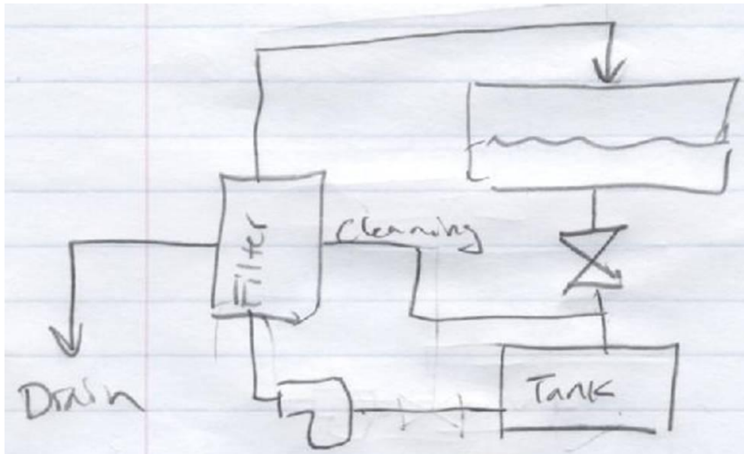

Figure 1: Filter and tank

As shown in Figure 1, we add a filter and a tank to the original washing system. Between each washing cycle, the dirty water from the last cycle first drains into the tank (valve is open). Then it is pumped through the filter and goes back into the tub for use in the next cycle. After the final cycle, the pump runs reversely. The water is pumped from the tub directly without draining into the tank (valve is closed) and goes through the filter in a reverse direction to clean the filter. The water drains directly after it leaves the filter.

Advantages: 1. Simple system and easy to build. This design keeps the features of the original system except adding a filter and a tank. 2. Keeps existing washing program. This design does not require changing the number of cycles of the original one. 3. Self cleaning filter. It does not require the customers to clean the filter frequently which is convenient.

Disadvantages: 1.More space filled. The tank occupies a large space. 2. More time spent. It takes extra time for the water to fill the tank.3. Requires a reverse pump. The self-cleaning filter requires a reverse pump which may increases the cost.

Concept 2: Surrounding filter

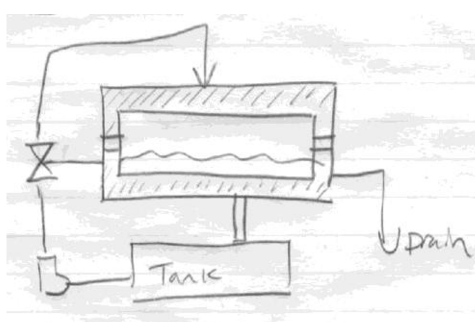

Figure 2: Surrounding filter

As shown in Figure 2, the shaded part represents the filter surrounding the tub. Between the cycles, the tub spins and forces the water through the filter. The filtered water drains into the tank and then is pumped back into the tub. (The valve closes the way to the pipe in the middle and so the water will go up the top pipe.) After the last cycle, the valve is opened. The water goes through the pipe in the middle and cleans the filter. The water drains directly after it gets out of the filter.

Advantages: 1.No filters in the piping system. 2. Self-cleaning filter.

Disadvantages: 1.Program redesign. Extra spin cycles should be added. 2. High energy cost. 3. Increase price. 4. Filter wear is increased.

Concept 3: Fully continuous filter (between cycles)

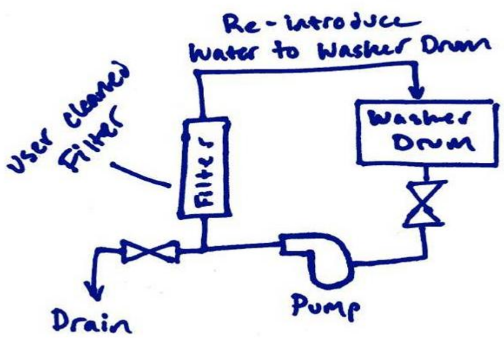

Figure 3: Fully continuous filter

As shown in Figure 3, the water drains from the tub between cycles. It is pumped through the filter and refills the tub. Since there is no tank, the filtering process and the draining process are running at the same time. The filtered water refills the tub before all the water from the last cycle drains from the tub, which makes the filtered water mix with the dirty water. In order to keep the effectiveness of the filtering, more cycles are added for the filtering process. The filter here is not self cleaning so the users must clean it themselves.

Advantages: 1.Saves space. 2. Simple system. The only change to the original structure is the added filter. 3. Use the original pump instead of a reverse pump.

Disadvantages: 1.Filtering efficiency decreases. More cycles are added to keep the effectiveness of the filtering. 2. More energy cost. 3. More time spent.

Concept 4: Distillation

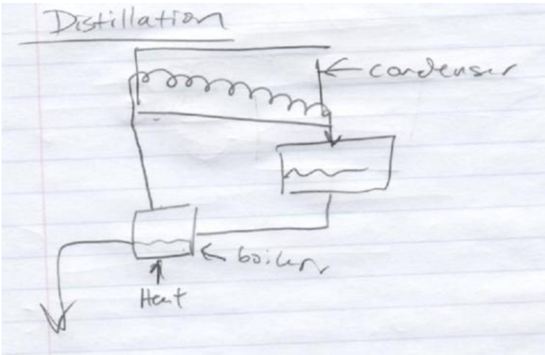

Figure 4: Distillation

As shown in Figure 4, between cycles the water drains from the tub into the boiler. The water is then boiled into a vapor. The steam goes up and is cooled through a condenser. It changes to liquid again when coming out of the condenser and refills the tub. After the final cycle, the water drains into the boiler, flushes the sediment out, and drains.

Advantages: 1.Very simple system. 2. Good filtering effectiveness. The evaporated water from distillation is very clean. 3. No pump is required.

Disadvantages: 1.Very high cost. 2. Too much time spent. 3. Too much energy cost.

Concept 5: Increase number of cycles and water redistribution

This concept uses the similar structure with that of concept 1. However, it makes further changes by increasing number of cycles and redistributing water in each cycle.

The original washing system has 3 cycles and uses approximately 20 liters (L) of water per cycle. Our design starts the washing cycle with less than 20 L of water, for example 3 L. After each cycle, it filters the water and adds 2 L more for the use of next cycle until the total water is 11 L. This process uses 5 cycles. We add 2 more rinsing cycle which uses the 11 L water. The total number of cycles is 7.

Advantages: Saves more water.

Disadvantages: 1. Decreases the washing effectiveness. It may be difficult to fully wash the clothes with less water per cycle. 2. More energy cost. 3. More time spent.

As shown in Table 2, the five design concepts vary based on four standards: changing cycles/not changing cycles, tank/continuous, self-cleaning filter/user-cleaning filter and pump/no pump. The details of each design concept are described below.

Classification		Design Concept				
		1	2	3	4	5
		Filter and Tank	Surrounding Filter	Fully Continuous Filter	Distillation Filter	Increasing Cycles
1	Changing Cycles		×	×		×
	Not Changing Cycles	×			×	
2	Tank	×	×		×	×
	Continuous			×		
3	Self-Cleaning Filter	×	×			×
	User-Cleaning Filter			×	×	
4	Pump	×	×	×		×
	No Pump				×	

Table 2: Classification of concept

COMPONENT CONCEPT SELECTION PROCESS

Once the component concepts were generated, it was discovered that many of the concepts could be combined with others. Therefore, the pump, filter, and method of recirculation components were separated and concepts for each individual component were compared through a Pugh Matrix. The Pugh Matrix for this selection process is shown in Appendix D. Once a concept was chosen for each component, they were all combined to form the chosen alpha design.

The design criteria that each concept was subjected to are as follows: 1. Time to complete process 2. Energy consumed 3. Cost of component 4. Space filled by component 5. Robustness 6. Modifications to washer necessary to implement 7. Prototyping time 8. Prototyping cost 9. User friendliness.

The first component reviewed was the method of recirculation. The two concepts generated for this component were continuously recirculating the water throughout the wash process or collecting it all in a tank at the end of each cycle then recirculating it all at once. The advantages to using a tank are it does not require as many modifications to the washer as the continuous filter does because the washer currently adds water at the end of each cycle, not continuously. The tank also may be easier to prototype because it requires fewer changes to the circuit board. The advantage to the continuous recirculation is it takes less space.

The next component is the method of cleaning the filter. The two concepts for this are a self-cleaning process and having the user clean the filter. The self-cleaning concept is desirable because it does not require any assistance from the user to stay functional. However, having the user clean the filter is advantageous in every other design criteria applied.

The third component is the method of forcing the water through the recirculation system. The two concepts are using a pump to move the water or somehow using the rotational energy of the tub spinning to move the water. The advantages for utilizing the rotational energy of the tub are it does not add any energy to the system and likely would be cheaper and take up less space. Advantages for using a pump are that it would likely recirculate the water faster and will take much less time and money to prototype.

After comparing all the concepts using the Pugh Matrix and our best engineering judgment, it was decided that a system with a tank, pump, and a filter cleaned by the user would be the most feasible design. This system can be realistically prototyped by the end of the project, requires the least modifications to the washer's current functionality, and is the most robust of all the possible combinations of components. Its disadvantages are that it requires maintenance by the user, takes up more space, and may take longer to complete a wash process.

THE ALPHA DESIGN

The alpha concept includes a filtration system, a tank, and a pump. The addition of a second pump and the cooling system was included through an overall system analysis and our engineering judgment. The filtration system with the pump and tank will be in the pedestal located under the washer, shown in the Fig. 5. The tank will be able to hold 32 liters of water with this dimension which exceeds the amount of the water for one load of wash or rinsing cycle for a normal load. The tank is bigger to accommodate extra water in the event the user washes a larger load of laundry than the "normal" load size. It will ensure that the system will not overflow and cause a flood of the user's laundry room. The filtration system is cylindrical with 0.23 meters in length and 0.064 meters in diameter.

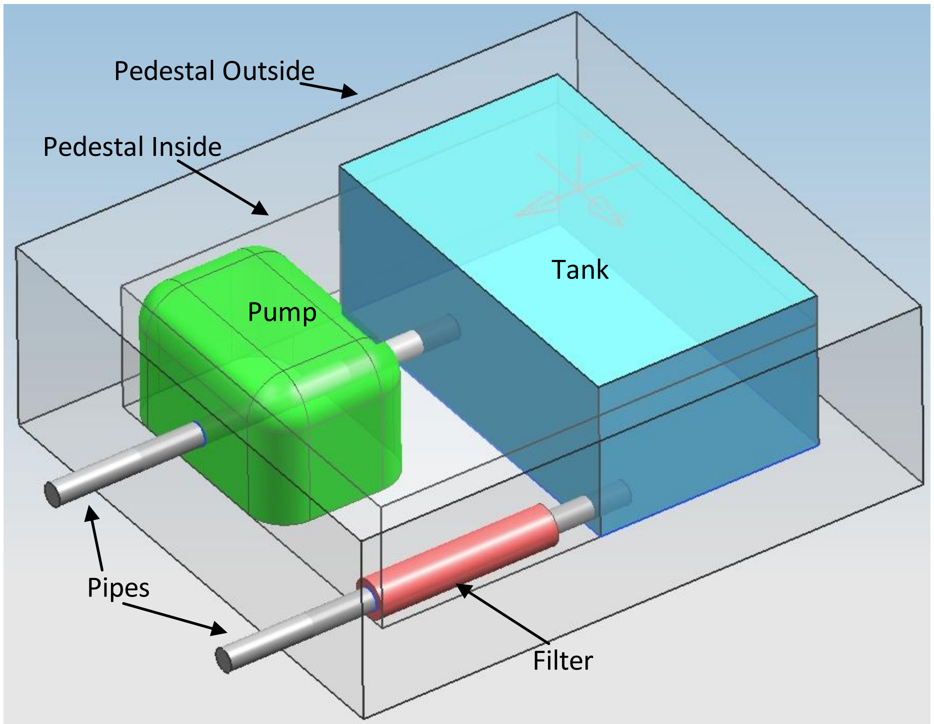

Figure 5: The schematic of the components in the pedestal

The operation process of this design comprises the following steps, as shown in Figure 6:

1. Filtration: After one wash or rinsing cycle, the laundary water will be drained into the filtration system using the pump in the washer.

2. Storage: The filtered water will be stored in the tank.

3. Recirculation: The other pump will deliver the filtered water back to the washer tub through the existing water inlets.

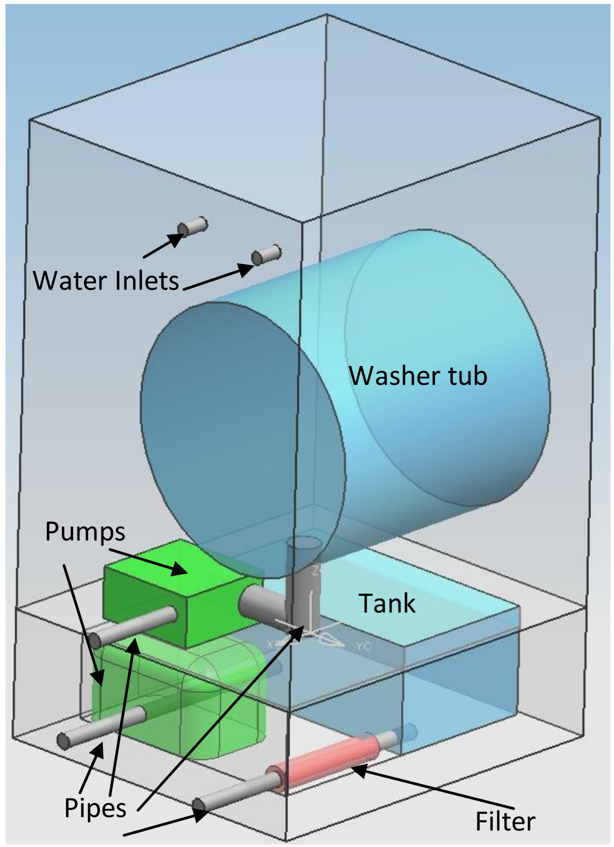

Figure 6: The schematic of the washer with the filtration and recycliation systems.

Normal wash cycles can include a warm wash cycle followed by a cold rinse cycle. Since we are recycling the water, we need to be able to cool the warm wash water down to use it in the cool rinse. To do this, we needed to add a cooling system to the filtration system. Also, since the rinse water is always cooler then the wash water, we only need to consider cooling and not heating. The cooling system now is similar to those in a refridgerator as shown in Figure 7.

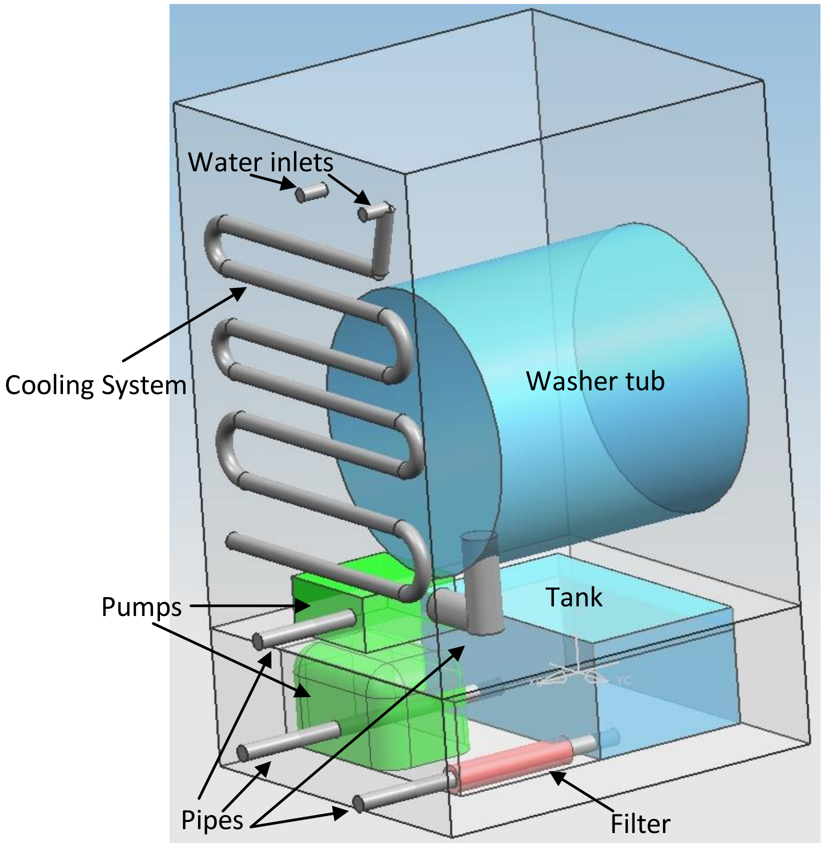

Figure 7: The schematic of the cooling system with washer.

The Alpha design is not the final design. This is simply the first concept chosen in the iterative design process. Further analysis and testing outlined in the parameter analysis section discusses why changes were made to this design.

ENGINEERING ANALYSIS

Thermal Analysis: For most of the washer settings, there is a cold rinse cycle following a warm washing cycle. Therefore, there exists a problem of how to cool the recirculated wash water between the wash and rinse cycles. We decided to cool the wash water through convection by passing it through a tube on the back of the washer which is exposed to the ambient. In order to determine the length of tube needed, a surface convection heat transfer model was made and is shown in Figure 8.

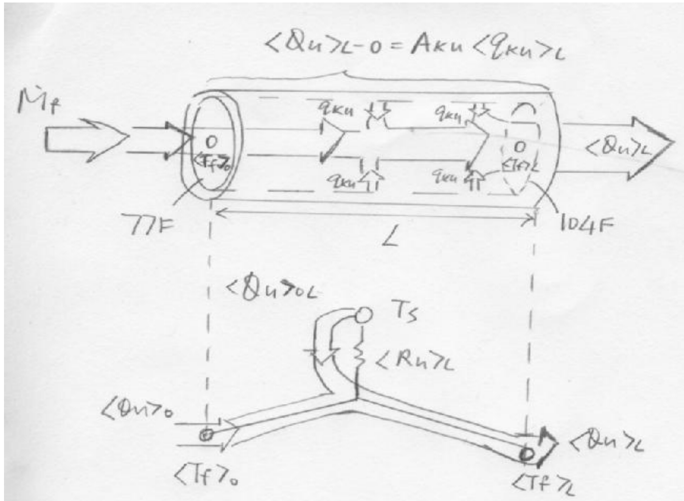

Figure 8: Thermal analysis heat transfer model.

We used the properties of water at room temperature to estimate the properties of the working fluid (wash water). We assumed that the tube was made of a type of metal with good thermal conductivity so that the temperature of the inner surface of the tube, Ts, is the same as the ambient temperature. Since the working temperature of the wash water ranges from 77 °F to 104 °F, we set the inlet temperature T_{fO} as 104 °F and the outlet temperature T_{fL} as 77 °F. We then set the flow rate $\dot{M}_f$ as 0.02 kg/s, which is the slowest possible flow rate found by dividing the total mass of water (15 L*water density) by the longest possible time it will take to finish the whole filtering process (11.5 min). We used the equation [10]

$$\epsilon_{he}=(T_{fO}-T_{fL})/(T_{fO}-T_s)=1-e^{NTU} \qquad \textbf{Eq. 1}$$

to estimate the length of tube L needed at different ambient temperatures. ϵ_{he} is the heat exchange effectiveness. NTU is the number of transfer units calculated by $NTU=\pi L \langle Nu \rangle_D K_f / \dot{M}_f C_{pf}$.. $\langle Nu \rangle_D$ is the Nusselt number which is equal to 3.66 in this situation. K_f and C_{pf} are the thermal conductivity and heat capacity of the working fluid respectively, and are equal to K_f = 0.6 W/m-K and C_{pf} =4182 J/Kg-K in this situation.

From the analysis above, we obtained the relationship between the length of tube required L (m) and the ambient temperature T_s (°F) to be L= {ln[(104-Ts)/(77-Ts)]}/0.08 which is shown in Figure 9. We considered the ambient temperature ranging from -4 ° to 76 °F, just below what the wash water needs to be cooled to. The corresponding tube length ranges from 3.6 m to 41.7 m. As shown in Figure 9, for a normal ambient temperature of 60 °F, the length of tube should be 12 m which is too long to fit into our system. Since we already used the slowest flow rate possible to make this estimation, the real situation with a higher flow rate may require an even longer tube. Based on this analysis, we have determined that it is not feasible for us to include a cooling system in our final design.

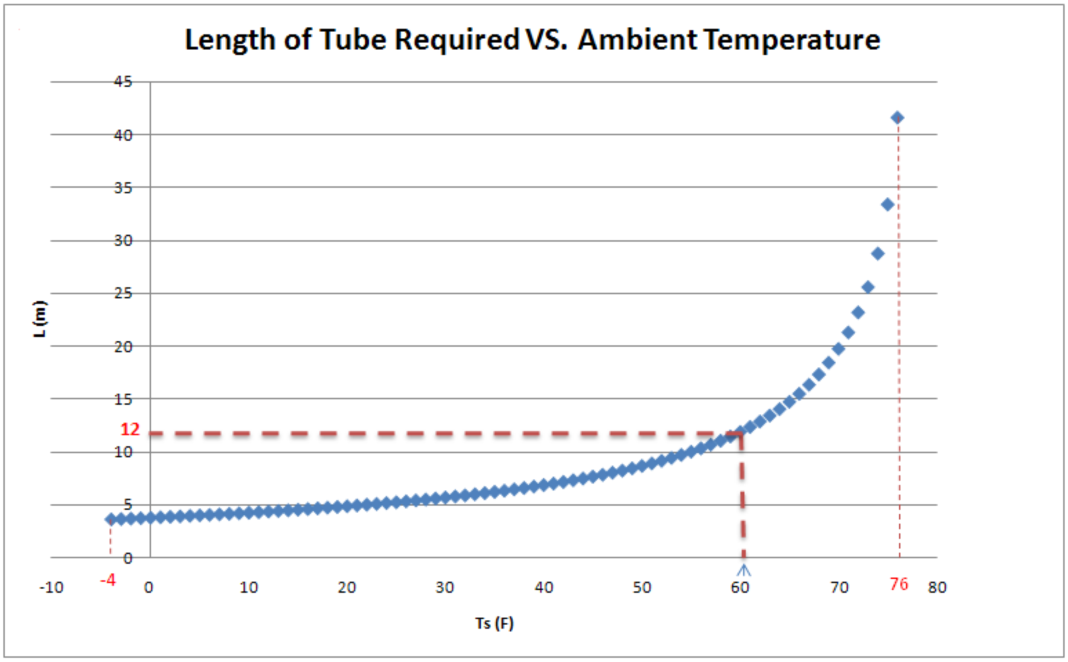

Figure 9: Tube length versus ambient temperature.

Fluid Dynamic Analysis: Since our system deals mostly with pumping water through pipes, tanks, and filters, a detailed analysis of the fluid dynamics of the system had to be undertaken. First, the losses associated with the piping and filters had to be taken into account in order to help determine what kind of pump energy must be given to the fluid in order for it to complete the circuit around our system. In addition, we needed to determine what kind of tube sizing and filter characteristics would allow us to have a flow rate high enough to complete our filtration in the specified time of 11.5 minutes or less. With these two analyses combined, a pump could then be chosen that will provide the proper pressure and flow rate without being overdesigned.

In order to determine what pressure loss we would experience across the filters, we conducted testing in Professor Skerlos' lab using a variable speed pump. We attached the pump to the filter system then varied the flow rate through the system and measured the pressure drop across the filters. Figure 10 shows the setup we used.

Figure 10: Filter test platform.

Using this setup, we could estimate how much power our pump would need to provide in order to force the water through the system with the appropriate flow rate. This testing yielded that the original washer pump was not powerful enough to force water through the system in a timely manner and a substantially more powerful pump would be required. These results directly influenced the arrangement of the components and slightly changed the process that was chosen in the alpha design. We have a high level of confidence in this analysis due to the fact that we directly tested our pumps with the actual filters and can expect the same behavior once they are placed in our system. Upon further testing, we determined that two pumps would be required to generate the pressure required to obtain the required slow rate. This will require that we place one pump before each filter to boost the pressure before each filter inlet.

The second fluid analysis we had to perform was to size the tubing and valve components. We wanted to have tubing that had a large enough diameter to allow the appropriate flow rate, but small enough to optimize the space constraints we had. In addition, we wanted to minimize the pressure loss associated with piping the water from component to component. To analyze this, we used equation 2 [11].

$$Q = \frac{\pi r^4 \Delta P}{8 \mu L}$$

Eq. 2

In equation 2, "Q" is the flow rate, which we held constant and was determined by dividing the amount of water we had to move by the maximum time we are allowed and multiplying that result by the density of water. The other parameters in the equation are "r" which is the radius of the pipe, ΔP which is the pressure drop across the pipe length, μ which is the viscosity of water, and L which is the length of the pipe. By assuming the maximum length of pipe in the system to be 12" we could choose a value for "r" that caused a minimal pressure drop. After this analysis, we determined that a tube with an inner diameter of 3/4" would be sufficient for our system. With these values, we only see a pressure drop of 2.97 E -4 PSI, which is negligible.

Power Analysis: The next step in the analysis, once we had found a pump that met our fluidic requirements, was to determine if we could meet our power usage specification. To do this, we simply calculated how much power the pump would consume and multiplied that by the average number of washes per year. This result would be the average power usage of our system per year.

To start, we made the assumption that the average consumer would operate the washer no more than 3 times per week. This multiplied by 52 weeks in a year resulted in 156 washer operations per year. We then found the pump power, which is 391W, and multiplied that by the total system runtime of 1380 seconds. After converting this to kWh, we multiplied the energy usage by the 260 washes per year to arrive at the result of 11.7 kWh/Year. This calculation is summarized in equation 3.

$$\frac{Power\ Usage}{Year} = Pump\ Power \times \frac{System\ Runtime}{Wash} \times \frac{Washes}{Year}$$

Eq. 3

Geometric Analysis: The final set of analyses that we needed to complete were geometric. This involved sizing the tank and arranging the components in such a way that allowed them all to fit into the pedestal while still being easily accessible to the customer for maintenance. To size the tank, we needed to make sure that it could hold at least 30 liters of water. We also needed to make sure we left enough room in the pedestal for the filter housings. The design we chose is shown in Figure 11.

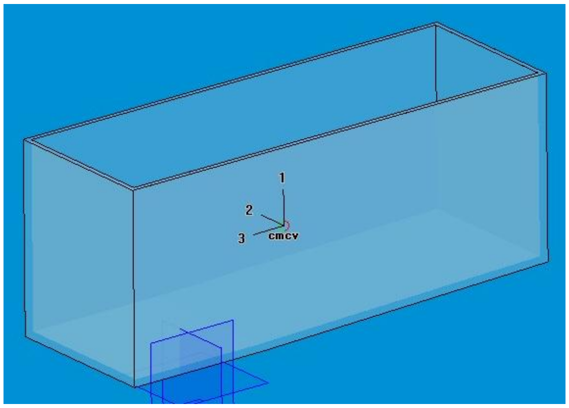

Figure 11: Final tank design.

The tank was designed as a mostly rectangular box with a slightly sloped bottom to facilitate good water flow to the pump. In addition, it is narrow and tall which leaves more room in the pedestal for the filter housings and pumps to be placed as necessary.

FINAL DESIGN DESCRIPTION

Our final design consists of two pumps, a water tank, two filter housings, and a valve. All the components are connected by pipes with clamps. The whole system is located in the pedestal, provided by Whirlpool, under the washer. The washer is kept the same and will be connected with our design to achieve the goal, shown in Figure 12 below.

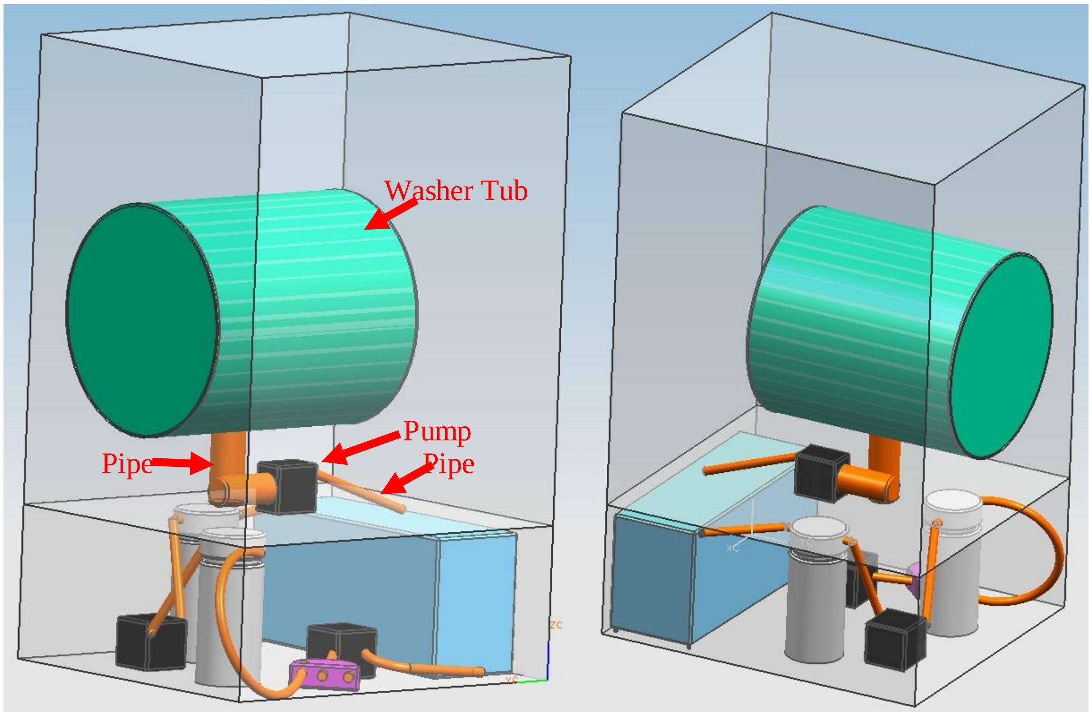

Figure 12: The final system placed underneath the washer.

Figure 13 shows the CAD mock-up for the final design. There are seven kinds of main components in the design and they are numbered and listed in Table 3. Minor parts such as bolts and nuts are not shown in the table and the CAD mock-up. All the dimensions of the parts are shown in Figure 13 in millimeters. The dimensions for the pedestal were provided by Whirlpool. The size of the tank was first determined by the amount of the washing water that would need to be stored under normal washing conditions, which is 20 liters. We designed the tank to be 32 liters to ensure that in the event they user washed a very large load, the tank could still accommodate the volume of water that would be introduced to the system. The height and the length of the tank are constrained by the dimensions of the pedestal, and the width by the volume of the tank. Besides the consideration of the volume for the tank, we also designed a slope on the bottom of the tank by installing two bolts at one side of the tank and making one side slightly shorter than the other. This is shown in Figure 14. This design assures the water will flow toward the other side of the tank and be sucked by the pump through the pipe connecting the tank. The dimensions of the two filter housings were provided by team 30, the other team researching the filters.

For the consideration of the accessibility of the filters, team 30 designed different filter housing in their final design, which is not shown here. The dimensions of the new filter housing will not exceed the current one by much and the pressure requirements for the filters won't change due to the housing change, which means the functionality of the system won't be affected.

The dimensions of the pumps are fixed by the manufacturer. Due to the complex geometry of the pumps, they are simplified by cubes here. The valve shown in the CAD is an estimation of a real one. Since we will have an electronic valve instead of the manual valve for the final design the real dimensions for the final valve are not known. The space taken up by the valve in the CAD model should be similar to that of an actual electronic valve. The diameters of all the pipes are the same, ¾", the lengths of which will be varied by the positions of the different components.

The pumps and the filter housings are bolted to the bottom of the pedestal. This guarantees that during the operation, the main parts of the system won't vibrate in the pedestal, which will reduce the possibility of piping coming loose and leaking.

Part Number	Part Name	Qty	Material	Function
1	Tank	1	Polypropylene	Store the water
2	Filter	2	From Team 30	Clean the water
3	Pump	2	From Manufacturer	Provide the pressure
4	Valve	1	Polypropylene	Guide the water flow
5	Pipe	8	Polypropylene	Connecting all the components
6	Pedestal	1	From Whirlpool	The system housing
7	Clamps	13	From Manufacturer	Fasten the pipe and component connections

Table 3: Major components list

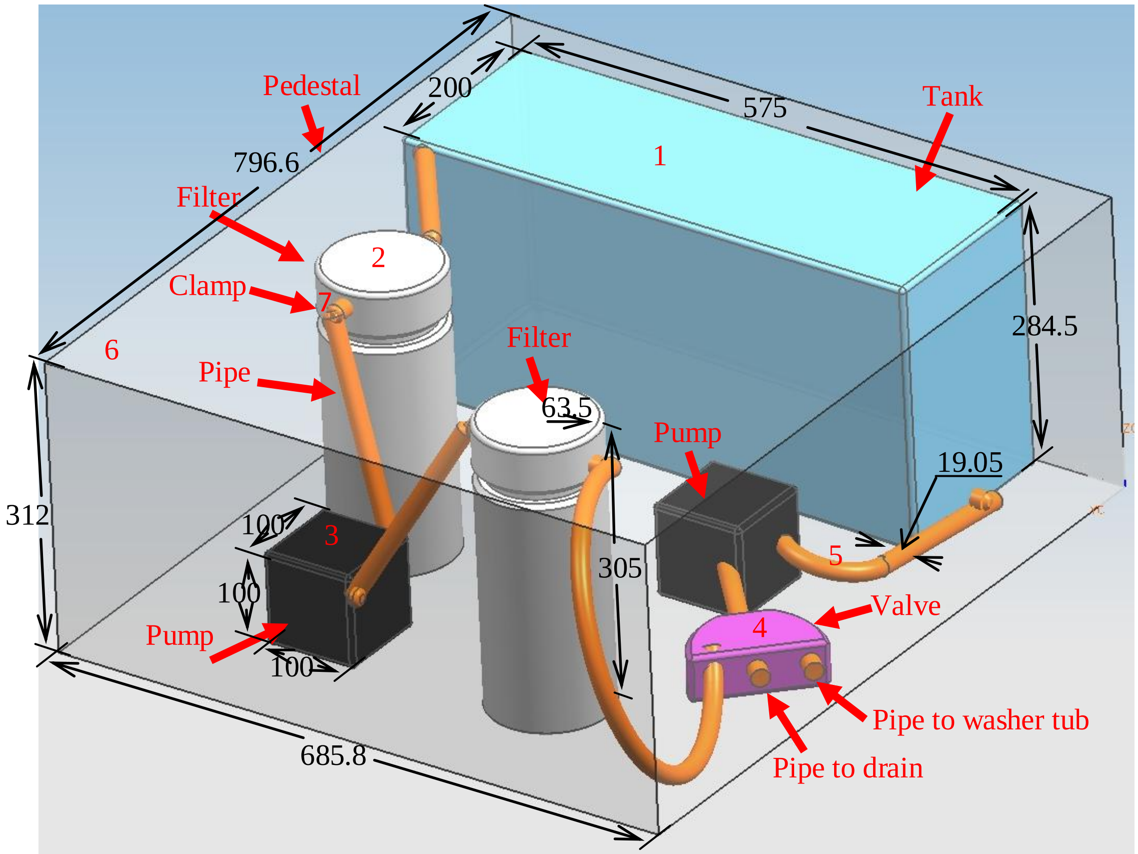

Figure 13: The final design in the pedestal with the unit of the dimensions in millimeter.

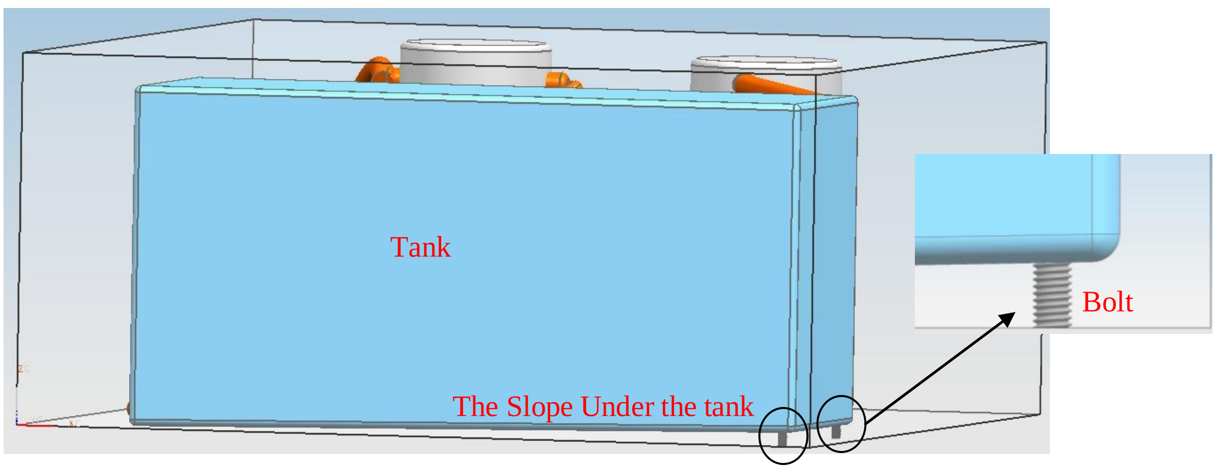

Figure 14: The slope under the tank assuring the flow of the water toward the other side with pipe.

The flow chart in Figure 15 illustrates the operation of the system. The continuous filtering method is used. An electronic control of the system is required for the system to control the valves and pumps and coordinate the system operation with the washing machine wash cycle.

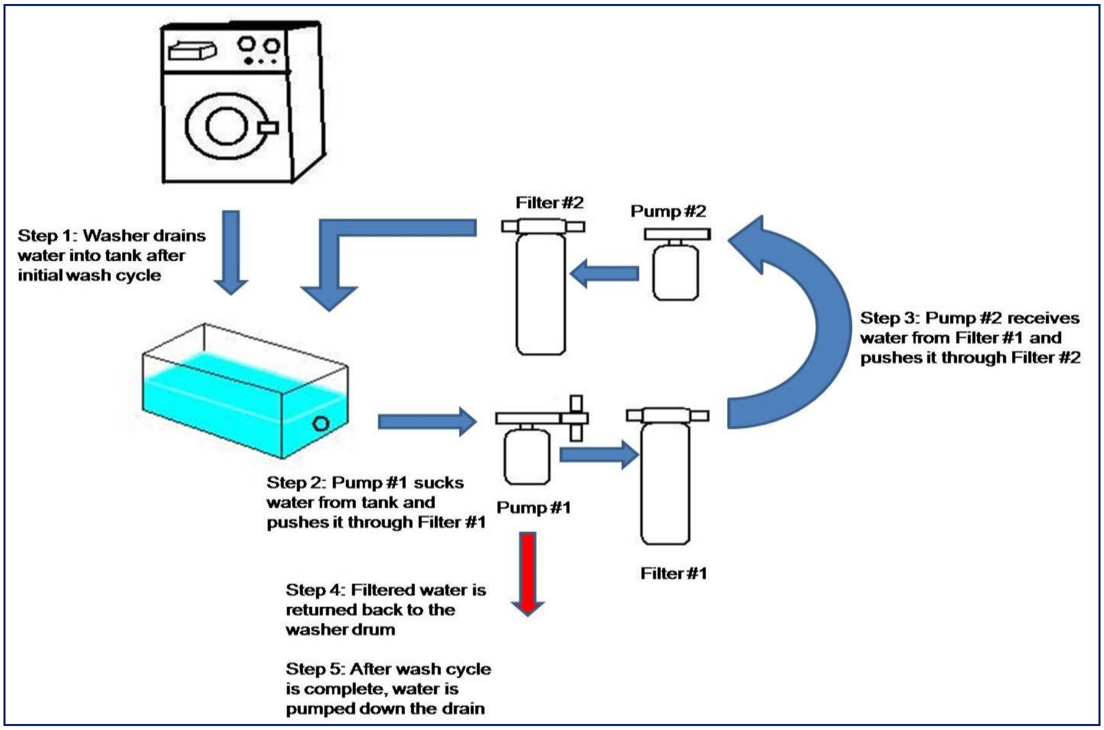

Figure 15: Flow chart of the system.

The prototype will be used to validate the final design by showing that it can meet several important customer requirements. The engineering specifications set for water cleanliness, power consumption, space constraints, number of existing hardware changes and additional moving parts, component accessibility, and leakage will be tested on our prototype. More importantly, we can measure the flow rate through the filters to determine if we can filter the water in the 11.5 minute time specification. By testing our prototype, we will also get an idea of the weaknesses of the design so that future improvements can be made.

There are five main differences between the prototype and the final design. First, the materials used will be different, especially for the tank. The tank is currently made of the Plexiglas pieces and angled aluminum bars; the final design for the tank will use injection molded polypropylene. Second, the manufacturing methods will be different for the tank. Injection molding is suggested instead of being assembled with Plexiglas pieces and angled aluminum bars with marine glue as sealant. Third, the main components of the design can be changed. The pumps used for the prototype are transfer pumps which are not specifically designed for pumping water through filters. We chose those pumps based on the pressure head and price considerations only. More appropriate pumps could be designed for the filters. Fourth, the control of the final design will be electronic instead of manual. This means the switching of the valves and turning on the pumps will be controlled by the washer circuit board. Fifth, the costs will be not same because the final design will be using different components, materials and manufacturing.

Due to the differences between the prototype and the final design, several things can't be validated by the prototype such as the feasibility of the material, the manufacturability, the control, and the cost. The electronic control which requires future investigation is out of the scope of this course.

By showing that the prototype met the engineering specifications through testing, the final design will be validated due to its similarity to the prototype. The control of the system should be similar to those of the other subsystems in the washer.

PROTOTYPE DESCRIPTION

The prototype system we will be building will contain all the main components of the final design with the exception of the cooling system and electronic control system. The prototype has been designed as a full mock up of the final design of the system. All of the components are represented with dimensions and power requirements that are very similar to what would be used in a final production model of our design. This will allow us to not only prove the concept of reducing the water usage of the washing machine by 75%, but also show the feasibility of the packaging and give a good representation of the manufacturing that would be required in the production model.

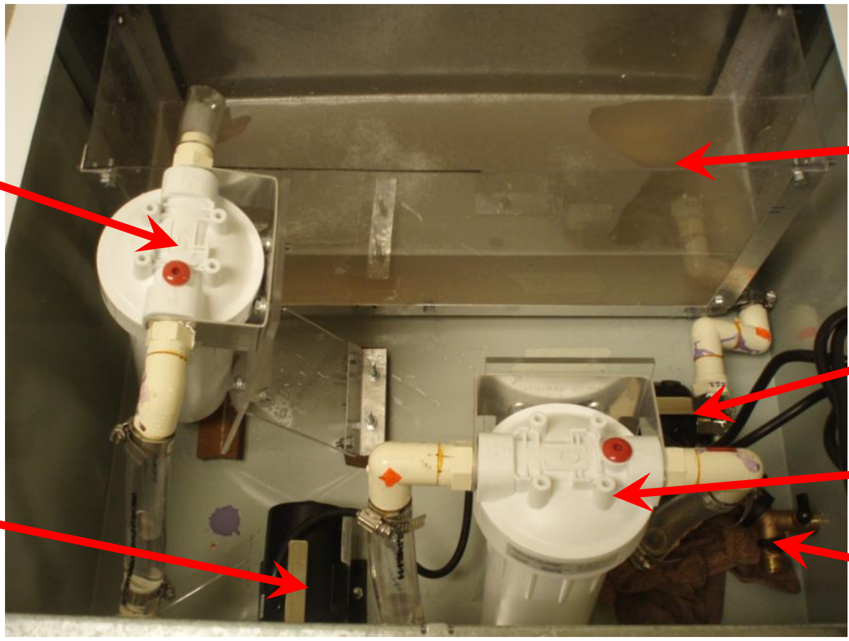

Figure 16: Photograph of final prototype

The first and only main component that we will be fabricating from scratch is the tank. In the final design, we required that a tank large enough to accommodate the entire volume of water and pump be included in the system in order to store the water that will be filtered. We have designed the tank with a very straightforward geometry so that we could construct it out of Plexiglas for simple manufacturing. This differs from what would be constructed for the final product, in which the tank would be made from an injection molded thermoplastic.

The next main components in the prototype are the pumps. In our prototype, we will be using two 115 volt 1.7 amp transfer pumps. These pumps can generate a maximum flow rate of 360 gallons/hour and a maximum rated pressure of 20.9 PSI. They will be placed in two spots in the system: the first between the tank and the first filter and the second between the two filters. The pumps will boost the water pressure to a level that will provide sufficient flow rate.

The next component in the prototype is the filters. Team 30 is providing the filters in their stock housings. They will be installed into our system and hooked up to our pump and tank via flexible tubing.

These may vary greatly in the final production model. First, the stock housing may be redesigned to be more space efficient. Second, the filters themselves may be redesigned to allow more flow and less pressure drop while still maintaining a similar cleaning capacity.

The final set of components in the prototype is the valves and tubing. These will be purchased from a hardware store and will all be stock sizes. The main difference between the prototype and the final design will be the valves. In the prototype, all of the valves will be manually operated, but in the final design, we have specified that the valves be electronically controlled by the washer’s circuit board and the entire system be integrated with the washer’s control system.

The prototype only needs to prove that a system of similar size and cost to the final design can clean and reuse washer water to complete the wash cycle. Individual components in the system are not as important as long as they can accomplish this goal. Even the arrangement of the components is not that critical as long as everything fits within the pedestal. We are aiming for our system to complete its filtration process in the maximum time allotted, however, the final design may be optimized later to produce the same results in much less time. Should the process take longer than our original specified time to produce water that meets our cleanliness standards, we will have still proven that the process is a viable solution to the water reduction problem, but the prototype might not contain a strong enough pump or optimal filters.

FABRICATION PLAN

For this design, the fabrication plan for individual components only involves the assembly of the storage tank because other components such as the pump and valves are pre-manufactured. The system level fabrication plan involves integrating the components by connecting them with tubing and joints, positioning them to maximize space efficiency, and setting up the system for partial manual control.

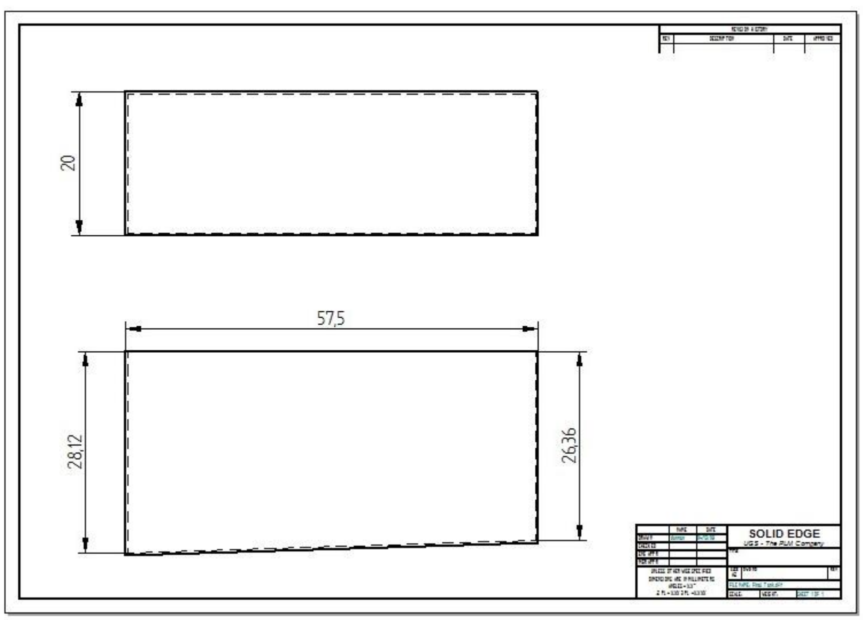

Figure 17: CAD drawing of the prototype tank.

The storage tank is fabricated out of Plexiglas and was put together using bolts, aluminum angle bar, and waterproof sealant. The Plexiglas has a thickness of 1/8 inch and was cut into 5 sides using a band saw and jigsaw. The dimensions of each side are shown in Figure 17. One of the 200 x 263.36 mm sides had a square hole 1 inch wide and high cut at the bottom center using a jigsaw. Each side was than fastened together by placing aluminum angle bar of thickness 1/8 inch at each point in the tank where two sides come together and fixing the angle bar to the Plexiglas with bolts and nuts. The angle bar is long enough to cover the length of each side and was cut using a band saw operating at 300 feet per second. The holes for the bolts in the Plexiglas and angle bar are 1/8 inch in diameter and were made using a hand drill. We were careful to drill the holes in the Plexiglas at a low speed because the Plexiglas may crack at higher speeds. Also, silicone-based marine glue was added in between where the angle bar and Plexiglas come into contact. The bottom of the tank was installed at a 10 degree incline so the lower end is on the same side as the square whole. This ensures the water in the tank collects at the outlet side of the tank. The top of the tank was left open. Finally, silicone-based aquarium sealant was applied on the inside and outside of the edges and corners of the tank to prevent leakage. It is strongly recommended that a silicone-based aquarium sealant is used because other sealants may not bond well with the Plexiglas surface. If this tank were to be mass-produced, it would be made out of a thermoplastic using an extrusion blow molding process.

The other components of the system consist of two filters provided by Team 30 and two Northern Tool Pony Pumps (Model # 50AC110B) [12]. The position of the filters, pumps, and tank within the pedestal is shown in Figure 13. To connect one of the pumps to the tank, a PVC elbow joint was first placed in the square hole of the tank and fixed in place with the marine glue. Another PVC joint was screwed onto the inlet of the pump and the two joints were connected with a polyurethane tube. The tube was fastened around the joints with hose clamps. Next, two Y-shaped garden hose valves were connected in series to the outlet of the pump to provide three possible paths of water flow. Each pump and filter were then connected to each other as shown in Figure 13 using the same PVC joints, polyurethane tubing, and hose clamps. Teflon thread seal tape was wrapped around the threaded parts of the joints to prevent leakage. Finally, the polyurethane tubing connected to the last filter extends over the top of the tank so water exiting the filter falls back into the tank. For mass-production, the tubing would be made via polymer casting from a type of thermoplastic. The joints would be sealed onto the tubing which could be screwed onto each component and fastened with hose clamps.

To operate the prototype, water can be put into the system by pouring it through the top of the tank. Once the water flows into the first pump, the pump can be turned on by plugging it in. Once the flow of water reaches the second pump, that pump may also be turned on. The system can run freely by itself at this point and may be turned off by unplugging both the pumps at the same time. The water in the tank can be drained by adjusting the valves and turning on the pump connected to the tank. For mass-production, the pumps and valves would be electronically controlled by the washing machine's circuit board to turn on and off or switch at the appropriate times.

VALIDATION RESULTS

We had one main test to determine if our design worked and if our system was viable. The first step was to introduce 15 liters of dirty wash water from the washing machine into the tank and let the system run for the prescribed 11.5 minutes. At that point, we switched off the system and took a sample of the water. We then continued to run the system to see how clean we could get the water with a longer time period. Originally, we were going to have access to a turbidimeter to determine the cleanliness of the water sample by measuring how turbid the water was. We did not, however, have access to this machine at the time of testing, so we objectively judged the relative cleanliness of the system. Figures 18 and 19 show the relative change in water quality before and after testing

Figure 18: Wash water before filtration.

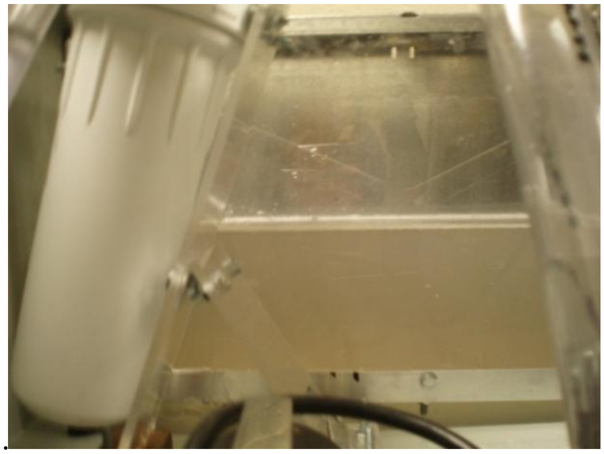

Figure 19: Wash water after filtration.

As you can see in the figures, the change in water quality is dramatic after the filtration cycle. Based on this objective test, we have determined that out system with Team 30's filters does a sufficient job of cleaning the water so that it may be used for laundry rinsing.

Much of the other validation was done through calculation and observation. We met the specifications for space constraints, power consumption, and washer water reduction in addition to the water cleanliness specification. These results were validated by observing that the components all fit within the washer pedestal, through a power analysis calculation, and by only allowing 15 liters of water to be introduced into our system during a normal wash cycle.

DISCUSSION

Design Critique The prototype shows that it works well and it meets almost all the customer requirements. However, some minor problems still exist and can be improved. First, we didn't analyze the stability of the system which could be a problem due to the vibration caused by the operation of the pumps. The system now works fine without too much vibration; however, some engineering analysis such as dynamics could be applied here and experiments with the system and the washer connected together could be implemented. Second, the cooling analysis could be further investigated to have more feasible results. We only analyzed the simplest surface convection situation for the cooling system and got not quite good results. More analysis about it using different heat transfer models could be done and more investigations about the existing cooling methods would be better. Third, the continuous filtering methods could be changed to filtering water only once. Since we worked with the other team for the project, we were constrained by the other team for the information needed. We were told by the other team that continuous filtering is needed for the final design. The test results of our prototype showed, however, that only filtering the water once seemed to be fine in terms of the cleanness of the water for the next rinse cycle. If this is the case, the final design could be changed with having the water from the tub drain into the first the pump of the system first. With only one time filtering, the filtered water goes into the tank and being sucked by the first pump to push it back into the tub. This design only requires one more two-way valve before the first pump with one pipe coming from the washer tub and the other from the tank, but it will increase the efficiency of the filtering by not having filtered and dirty water mixed.

Cost Analysis To determine the economic feasibility of our system a detailed cost analysis was performed. We wanted to determine if the cost of electricity and maintenance on the system could be offset by the money saved by conserving water, and to see what the breakeven point would be. Assuming 3 washes per week and normal wash conditions, the average user will save approximately 7000 liters of water per year. This comes to a total savings of 45 cents per year. [13] The filter cost $8 to replace and will need to be replaced every 6 months. This amounts to $32 per year in upkeep costs. The average cost of electricity in the United States is 10.64 cents/kWh, and our system uses 11.7 kWh/year, totaling $1.24 in electricity costs per year. [14] Summing the savings and costs, we determined that the system actually costs the user approximately $32.79 per year. At the current price of water, the user will never break even with our system. This analysis does not, however, take into account the intangible cost savings of reducing environmental impact in the form of water savings.

Materials Selection When selecting materials for the piping, the strictest constraints that were applied were resistivity to water, acids, alkalis, and organic solvents. This is important because of the high content level of chemicals in the water that will be passing through the tubes. Other constraints were for temperature to ensure the material could handle hot and cold washes and for shear modulus because the tubing should be flexible enough to bend slightly, but rigid enough to help keep the components in place. A chart showing shear modulus against price of the materials that passed the applied constraints is shown in Figure 20 in Appendix C1. From this, we decided the two best materials for pipes would be polypropylene (Copolymer, 40% calcium carbonate) and polypropylene (Homopolymer, low flow). The 40% calcium carbonate polypropylene was chosen because it is the cheapest material by a margin of about $0.23/lb that met the constraints, has a good shear modulus, and is recyclable. The homopolymer, low flow polypropylene was chosen because it is the next cheapest material, has a good shear modulus, and is also recyclable. The other three materials that are in our top five are polyethylene (High Density, Ultra High Molecular Weight), polypropylene (Copolymer, low flow), and polypropylene (Copolymer, UV stabilized).

When selecting materials for the tank, the same constraints for resistivity to water acids, alkalis, and organic solvents and temperature were applied. However, the constraint for shear modulus applied was much higher because a more rigid tank is desirable. A chart showing water absorption against price of the materials that passed the applied constraints is shown in Figure 21 in Appendix C1. Water absorption is an important aspect because we don't want to lose any water in the system. From this, we decided the two best materials for the tank are polypropylene (65-70% barium sulfate) and polypropylene (Homopolymer, 40% talc). These two materials were chosen because they are the cheapest, have low water absorption rates, and are recyclable. The other three materials that are in our top five are polypropylene (Copolymer, 40% talc), polypropylene (Homopolymer, 40% glass and mineral), and Polyamide (Nylon) Type 6/Polypropylene Blend (30-35% glass fiber).

Manufacturing Process Selection For selecting a process to manufacture the tubing, we applied constraints pertaining to the shape, thickness, and tolerances of the tubing. CES returned many different methods, so we plotted them on a chart showing tooling cost against capital cost. This is shown in Figure 22 in Appendix C1. We then investigated the most cost efficient methods to see which ones were primarily used for thermoplastics and had a reasonable production rate. Based on these criteria, we chose polymer casting. Polymer casting is one of the cheapest methods in regards to combined tooling and capital costs and shown by the chart and, according to CES, the method is already typically used for manufacturing tubes.

To select a process of manufacturing for the tank, we applied the same constraints as we did the tubing, but with the corresponding values for the tank. The results were also plotted on a chart of tooling cost against capital cost and this is shown in Figure 23 in Appendix C1. We investigated each option to see which methods are primarily used for thermoplastics and found that the extrusion blow molding process is the best option. CES notes that this method is typically used to manufacture bottles and tanks and can leave a small opening. The small opening would be useful as the outlet point for the tank. This method can also create a variety of shapes and our chart shows that it is relatively cheaper than many other methods with respect to tooling and capital costs.

Design for Assembly To help determine our design's assembly efficiency, we evaluated it using the Boothroyd-Dewhurst design for assembly method. Applying this method, we estimated the design assembly efficiency of this design to be 0.1. This is very low and indicates that some of the parts could be combined to make assembly simpler. We analyzed the components to determine the true minimum number of parts of our system, and then redesigned it accordingly. By combining the tubing from the tank to the pump and the tank, we eliminated one component. In addition to this, we combined the filters, the filter holders, and the tubing that connected the pumps to the filters into 2 components instead of several. With these design changes, we were able to increase the design assembly efficiency of our system to 0.43. The DFA tables are shown in Appendix C2.

Design for Safety We conducted the risk assessment for our prototype. The results are listed in the chart in Appendix C3.

As shown in the chart, the major risks include:

1. Mechanical: Machine instability the running of pump introduces vibration.
2. Electrical / electronic: Water / wet locations

   Water leaks from the pipes and wets the pumps.
3. Heat / temperature: Radiant heat

   When pumps run, they radiate heat.
4. Noise / vibration: Noise / sound levels > 80 dBA

   When the pumps run, they produce noise.
5. Fluid / pressure: Fluid leakage / ejection

   Water leaks from the slits at connections between pipes.

All the users are at risk and we did not encounter any unexpected risks. Comparing risk assessment and FMEA, we find that FEMA emphasizes Failure Modes & Effects Analysis and component failures while risk assessment emphasizes improper operation by the user.

Acceptable risk of certain kinds of hazards means that the severity of the failure is not high and the probability of failure is low. Zero risk means that the failure does not impact at all and the probability of the failure is zero. In the reality, zero risk does not exist. The distinction does not show up in our project.

Design for Environmental Sustainability The closest materials available in Sima Pro to the materials we selected using CES for pipes in our system are polypropylene injection molding E and Polypropylene resin E. We need 0.12 kg polypropylene injection molding E or 0.12 kg Polypropylene resin E in our final design. We compared these two materials and the results are shown in the graphs in Appendix C4.

For polypropylene injection molding E, the total mass of raw, air, water and waste emissions are 6681.5 g, 468.7677 g, 1.196221 g and 18.35814 g separately. For polypropylene resin E, the total mass of raw, air, water and waste emissions are 5232.591 g, 203.4072 g, 0.687528g and 2.931655g separately.

Polypropylene injection molding E has more mass emission of all the categories raw, air, water and waste than polypropylene resin E does.

Polypropylene injection molding E has bigger impacts than Polypropylene resin E does on the following EcoIndicator 99 damage classifications: Carcinogens, Resp. Organics, Resp. inorganics, and Climate change, Radiation, Ecotoxicity, Acidification/Eutrophication and Minerals.

Human health is most likely to be important based on the EI99 point value.

We conclude that polypropylene injection molding E has a higher EcoIndicator "point value". The life cycles of products made of polypropylene injection molding E and polypropylene resin E should be similar. So polypropylene injection molding E is also likely to have a bigger impact with the consideration of the full life cycle. Based on the analysis, the environmental impacts of polypropylene resin E are in a reasonable range. We don't think it is necessary to select different materials. Therefore, we decide to choose polypropylene resin E as the material to make the pipe.

RECOMMENDATIONS

Throughout the course of the design, manufacturing, and assembly process we came across a number of potential problems that could affect the final product. To minimize the effect of these problems when the final design is being built, we have compiled recommendations for how to handle them.

During testing of the prototype, vibrations from the motion of the washing machine tub rotating were not extensively tested. Such vibrations could cause components in the system to be jarred loose or increase the noise level of the system. Therefore, we recommend that special attention be given to the vibrations of the washer when the final product is integrated. If problems with this arise, we recommend that the bottom of the pedestal be made thicker so that components bolted into the bottom will be steadier when fixed into place. Another modification that we recommend be made to the pedestal is to take out any parts that were used to house the drawer that previously used to fit inside. They are no longer necessary, take up space, and have sharp edges that pose safety hazards to users that are changing out the filters. We also recommend that the pedestal be modified so the components of the system can be accessed from the front and that the pedestal remains detachable from the rest of the washer. This will make servicing components of the system much easier.

We also recommend that further research be done to address the space, cost, lifetime, and noise level of the pumps. The pumps currently chosen for the design are reasonably sized and priced to meet engineering specifications, but may have problems with corrosion from chemicals in the water and the amount of noise they produce. Further research into what other materials the pump can be made out of and acoustics surrounding the pump may solve these problems. We also recommend looking into finding a submersible pump that is reasonably priced and can generate enough pressure to produce an acceptable flow rate across the filters. A submersible pump could be placed in the tank which would save space and may reduce the noise level of the system.

For cooling the water between wash and rinse cycles, we recommend that more research be done for determining efficient methods of heat removal. As the thermal analysis on Pg. 17 shows, cooling the recycled water through unforced convection is not feasible. We recommend looking into forced convection with a fan or blower or different types of heat exchangers such as shell and tube or plate heat exchangers. Forced convection or certain types of heat exchangers will increase the energy usage, cost, and space taken up by the system so special attention should be given to these aspects when considering potential solutions.

Finally, to prevent sediment build-up in the tank and to increase the cleanliness of the recycled water, we recommend a small system level re-design to the current prototype. Instead of draining the dirty water from the tub into the tank, we recommend the water from the tub be drained directly into the first pump. This will allow the dirty water to be filtered before it reaches the tank and will keep sediment from building up on the sides. Also, since the filtered water won't be mixing with the dirty water in the tank, it ensures that all of the soap and particulate will pass through the filtration system at least once. Furthermore, connecting the first pump to the washer tub will eliminate the need for the existing washer pump that is used to drain the tub.

CONCLUSION

The main problem our system was designed to address was to find a way to reduce the water usage of the Whirlpool Duet washing machine by 75% without significantly increasing the usage of energy. Several design concepts were generated to solve this challenging problem but eventually, through a systematic comparison and elimination of designs, we arrived at a water filtration system as the method to achieve this water usage reduction. The system we designed is simple and robust, including a tank to store the water, two pumps to force the water through the system, and two filters of different materials to clean the water. All of this has been conveniently packaged in the original washer pedestal body to ensure minimal space usage and convenient placement of the system underneath the washing machine. This system achieves the quality of water after filtration that we were hoping to see while only increasing the energy consumption by 6.4% or 11.7 kWh/year. Upon testing, we determined that the system sufficiently filtered the water to a cleanliness level that was acceptable for laundry rinsing. With this system in place, the washer only draws 25% of the water from the tap and gets the rest from the filtration system it is attached to, effectively reducing its water consumption by 75%.

ACKNOWLEDGEMENTS

We would like to generously thank our sponsors Julie Martin and Boma Brown-West of Whirlpool Corporation for all of their help and support through the design process. We would also like to thank professors Gregory Hulbert and Steve Skerlos for their guidance and help along the way. Finally, we would like to thank Bob Coury for all of his help in manufacturing our prototype.

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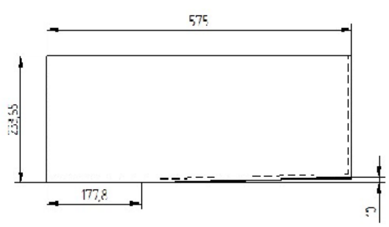
APPENDIX A: PROTOTYPE BILL OF MATERIALS

Item	Qty	Source	Catalog Number	Cost($)	Contact
Pony Pump Self-Priming	2	Northern Industrial	109730	99.98	NorthernTool.com
Plexiglas	2	HOME DEPOT	74507992342	29.98	
Angle gauge	4	HOME DEPOT	30699419500	17.92	
¾” Female Adapter	1	HOME DEPOT	12871625657	0.44	
¾” Male Adapter	1	HOME DEPOT	12871626036	0.32	
GE Clear Tube	1	HOME DEPOT	77027002843	3.72	
Silicone Sealant	1	HOME DEPOT	77027002812	3.72	
1in. Male Adapter	1	HOME DEPOT	12871626050	1.06	
¾”×10’ CPVC Pipe	1	HOME DEPOT	611942049806	5.38	
¾” CPVC Male	4	HOME DEPOT	39923107268	1.56	
¾” CPVC Elbow	8	HOME DEPOT	39923107701	2.72	
CPVC Female	4	HOME DEPOT	39923107220	3.84	
¾” CPVC Elbow	4	HOME DEPOT	39923107602	1.84	
¾” CPVC Elbow	4	HOME DEPOT	39923107480	0.96	
¾” Y Valves	2	HOME DEPOT	46878279315	15.74	
Marine Silicone Glue	3	ACE BARNES	12268	11.97	
¼” Threaded Bolts	44	Machine Shop		0.00	
¼” Threaded Nuts	44	Machine Shop		0.00	
Total				201.15	

APPENDIX B: ENGINEERING CHANGES SINCE DESIGN REVIEW #3

Engineering Change Notice

WAS:



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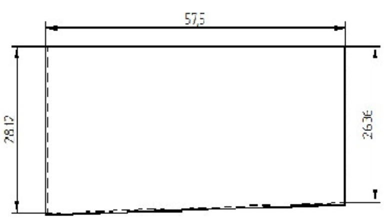
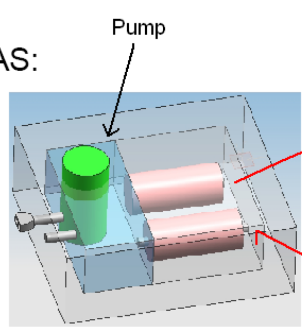


Notes:
Changed height dimensions of tank from 233.65 mm to 281.2 mm to handle a larger volume of water. Made sloping bottom one continuous piece.

ME 450: Team 12	
Project: Water Reduction	
Ref Drawing: Water Tank	
Engineer: Jeremy Kohlitz	4/1/2008
Proj.Mgr: G. Hulbert	4/1/2008
Mgmt./Sponsor: Whirlpool	4/1/2008

Engineering Change Notice

WAS:



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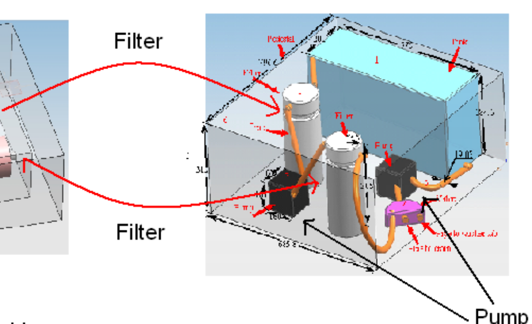

Notes:
Changed from 1 submerisble pump to 2 transfer pumps. Changed position and orientation of filters.

ME 450: Team 12	
Project: Water Reduction	
Ref Drawing: Water Tank	
Engineer: Jeremy Kohlitz	4/1/2008
Proj.Mgr: G. Hulbert	4/1/2008
Mgmt./Sponsor: Whirlpool	4/1/2008

APPENDIX C1: DESIGN ANALYSIS: MATERIALS SELECTION

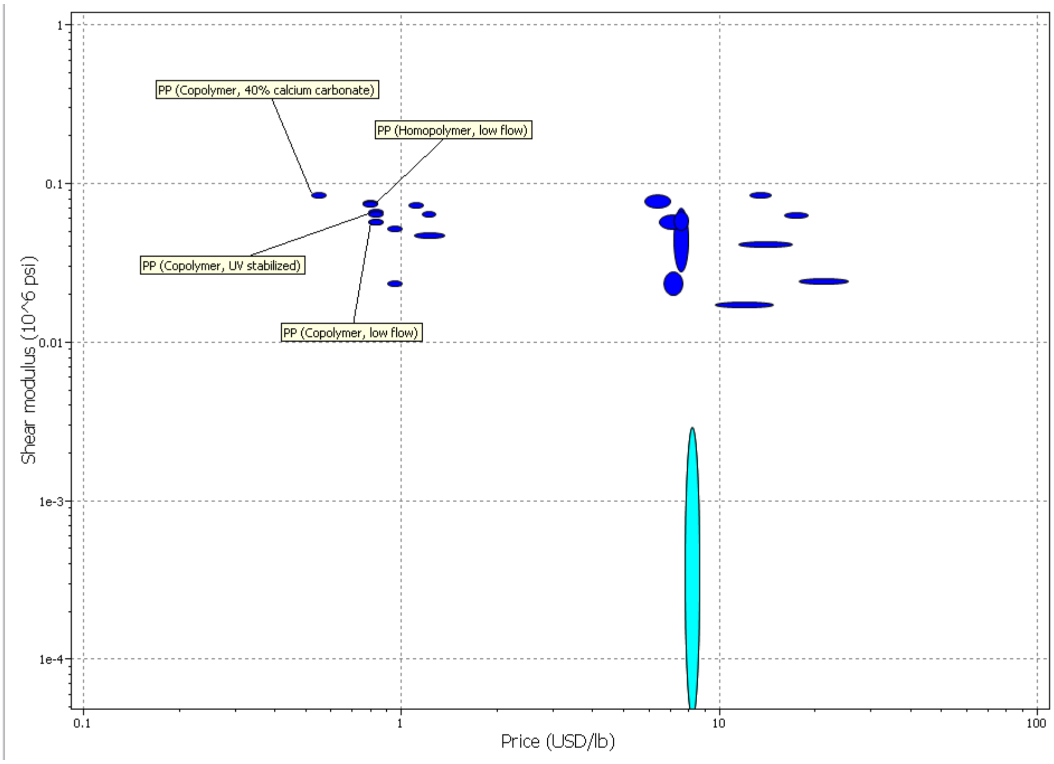

Figure 20: Material Selection for Pipes

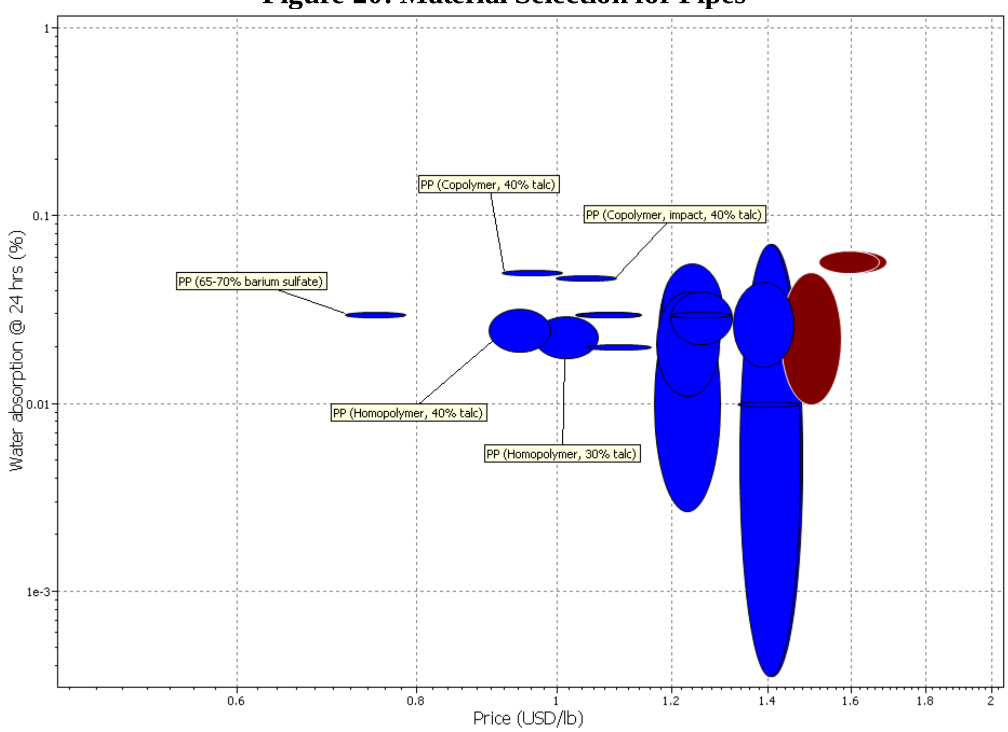

Figure 21: Material Selection for Tank

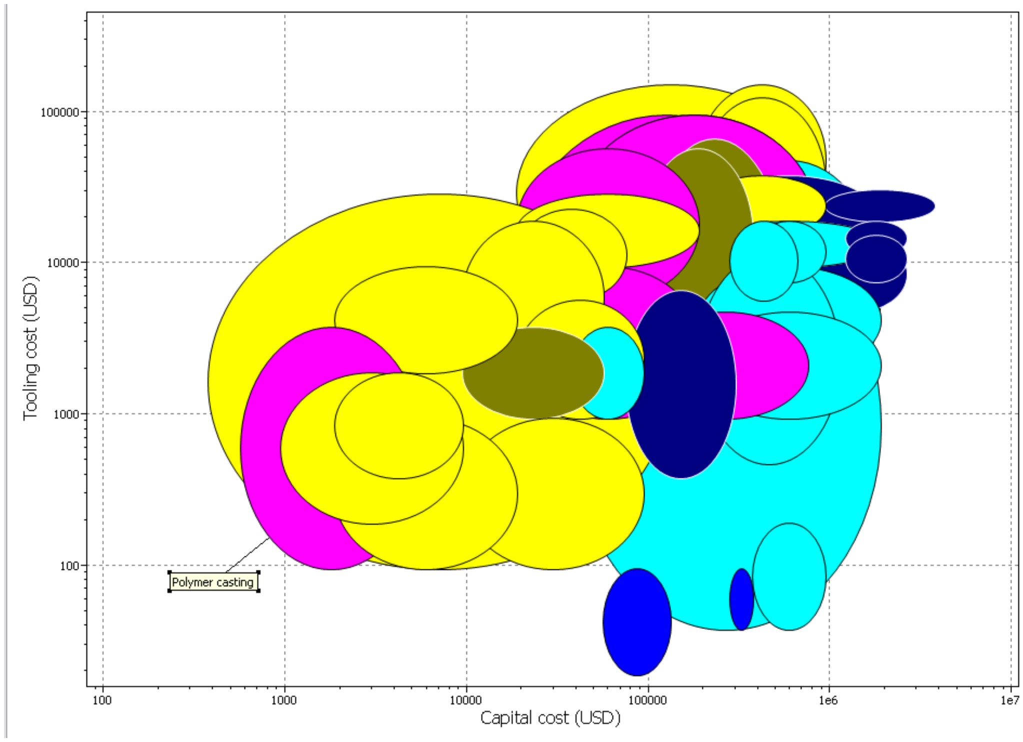

Figure 22: Process Selection for Tubing

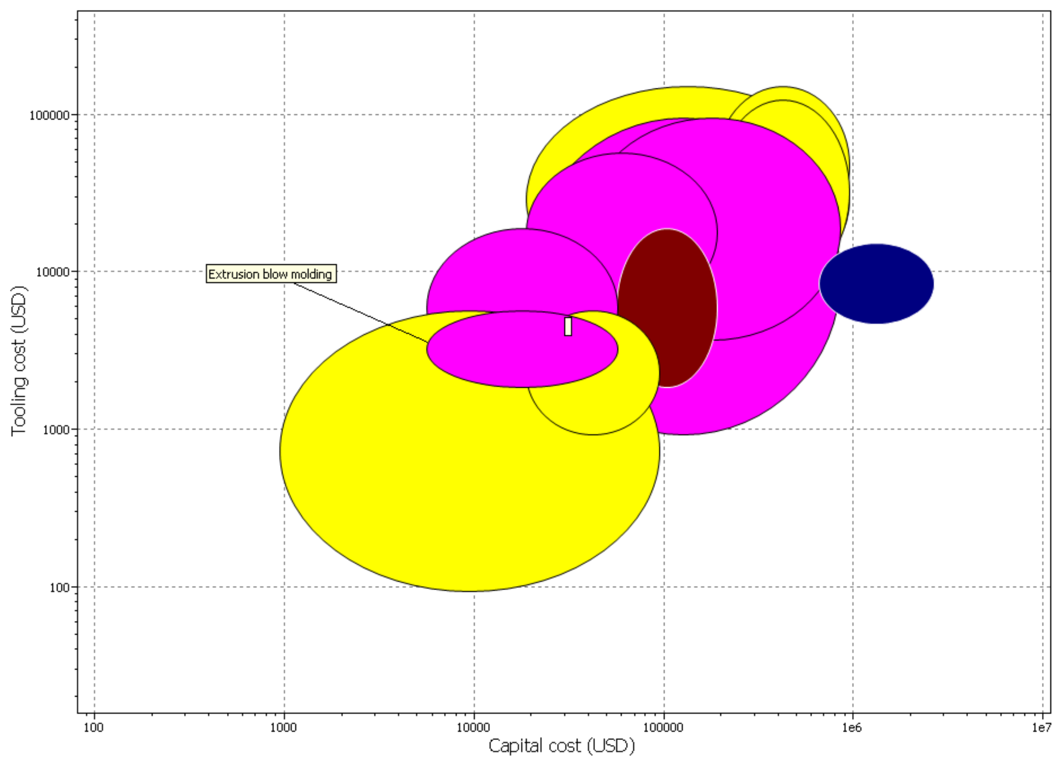

Figure 23: Process Selection for Tank

APPENDIX C2: DESIGN ANALYSIS: DESIGN FOR ASSEMBLY

Table 4: DFA table for original design

Manual Handling Time Per Part	2 Digit Manual insertion Code	Manual Insertion Time Per Part	Operation Time	Operation Cost	Figure for Estimation of Theoretical Minimum Part
3	00	1.5	4.5	1.8	1
5.6	01	2.5	8.1	3.24	0
5.6	11	5	10.6	4.24	1
5.6	01	2.5	8.1	3.24	0
5.6	00	1.5	7.1	2.84	0
5.6	01	2.5	8.1	3.24	0
5.6	11	5	10.6	4.24	1
5.6	01	2.5	8.1	3.24	0
5.6	01	2.5	8.1	3.24	0
5.6	00	1.5	7.1	2.84	0
6.75	01	2.5	9.25	3.7	0
			Total	**Total**	**Total**
			89.65	35.86	3
					Design Effectiveness
					0.100390407

APPENDIX C2: DESIGN ANALYSIS: DESIGN FOR ASSEMBLY

2 Digit Manual Handling Code	Manual Handling Time Per Part	2 Digit Manual insertion Code	Manual Insertion Time Per Part	Operation Time	Operation Cost	Figure for Estimation of Theoretical Minimum Part
91	3	00	1.5	4.5	1.8	1
83	5.6	11	5	10.6	4.24	1
91	3	00	1.5	4.5	1.8	1
83	5.6	11	5	10.6	4.24	1
91	3	00	1.5	4.5	1.8	1
				Total	**Total**	**Total**
				34.7	13.88	5
						Design Effectiveness
						0.432276657

Table 5: DFA table for re-design

APPENDIX C3: DESIGN ANALYSIS: DESIGN FOR SAFETY

designsafe Report

Application:	water recycling system	Analyst Name(s):	Mingming Yang
Description:		Company:	ME 450 Team 12
Product Identifier:		Facility Location:	
Assessment Type:	Detailed		
Limits:			
Sources:			

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users All Tasks	mechanical : machine instability The running of pump introduces vibration	Slight Remote Possible	Moderate	Fixing the pump on the pedestal with more and stronger screws.	Slight Remote Unlikely	Low	
All Users All Tasks	electrical / electronic : water / wet locations Water leaks from the pipes and wets the pumps.	Serious Frequent Probable	High	Using water proof pump and fixing the leaking problem.	Serious Remote Unlikely	Moderate	
All Users All Tasks	heat / temperature : radiant heat When pumps run, they radiate heat.	Serious Frequent Probable	High	Building a heat sink for the pump.	Serious Remote Unlikely	Moderate	
All Users All Tasks	noise / vibration : noise / sound levels > 80 dBA When pump run, they produce noises.	Serious Frequent Probable	High	Adding noise reduction device.	Serious Remote Unlikely	Moderate	
All Users All Tasks	fluid / pressure : fluid leakage / ejection Water leaks from the slits at connections between pipes.	Serious Occasional Possible	High	Using one tube made by good manufacturing technology instead of connecting several tubes.	Serious Remote Unlikely	Moderate	

Table 6: Design for safety results.

APPENDIX C4: DESIGN ANALYSIS: DESIGN FOR ENVIRONMENTAL SUSTAINABILITY

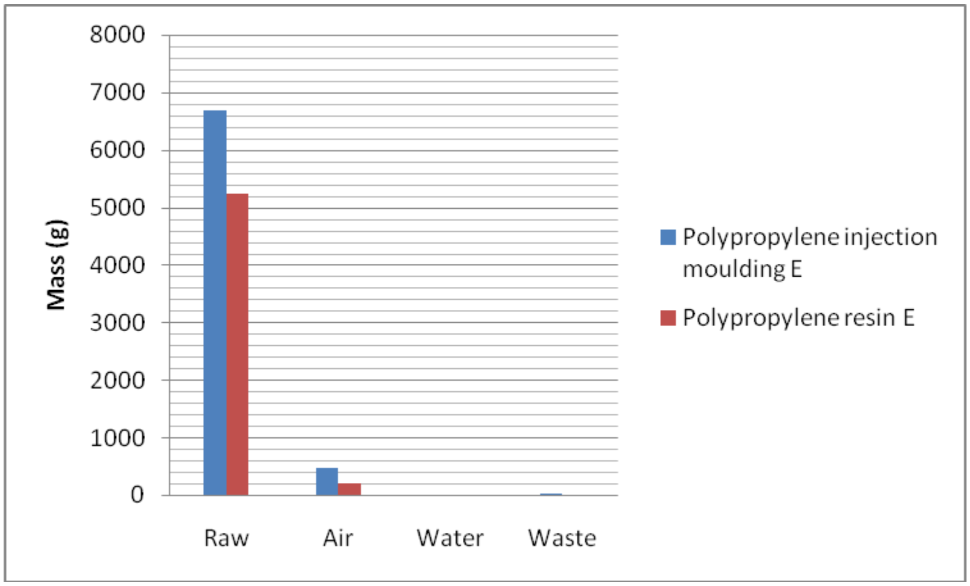

Figure 24: Emission of raw, air, water, waste plot.

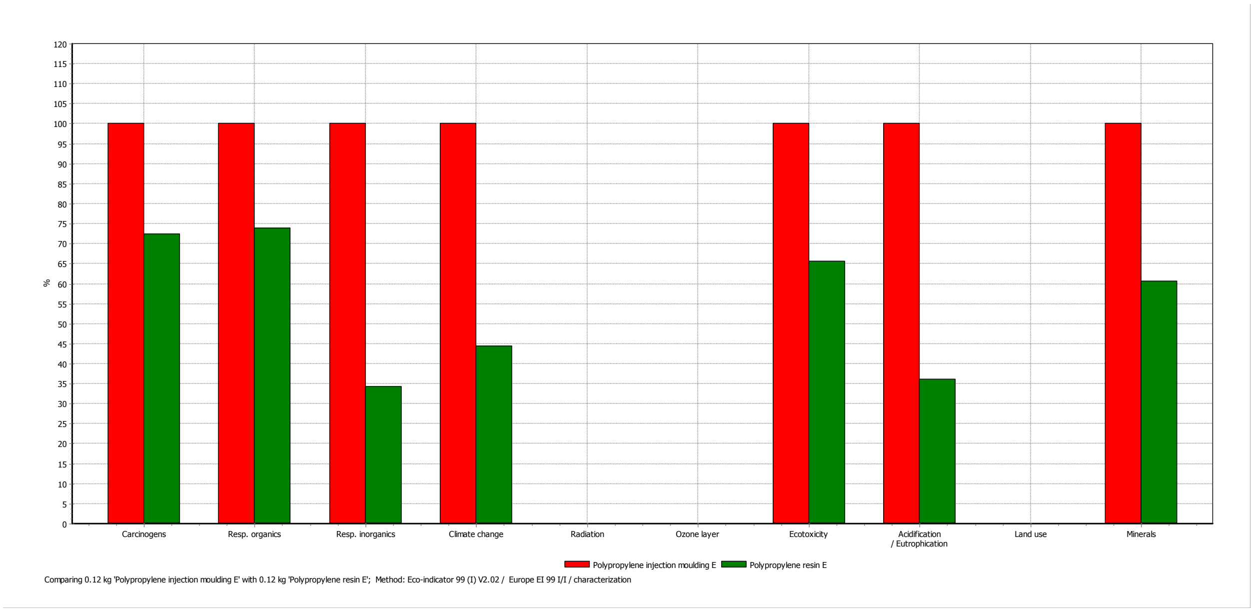

Figure 25: Relative impacts in disaggregated damage categories.

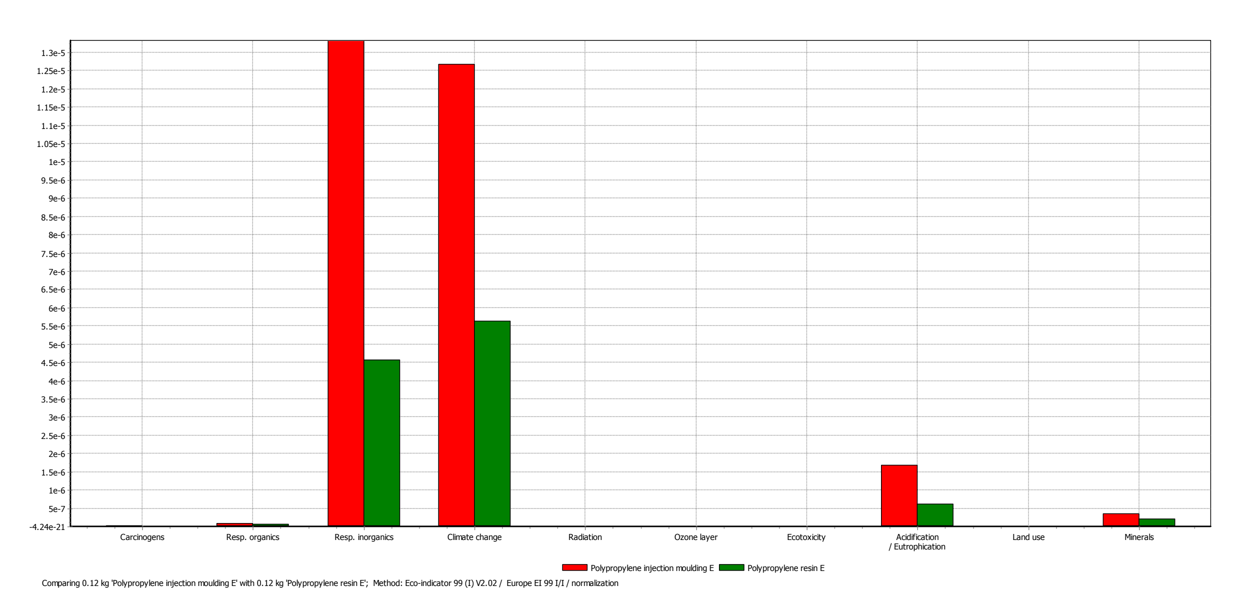

Figure 26: Normalized Score in Human Health, Eco-Toxicity, and Resource Categories.

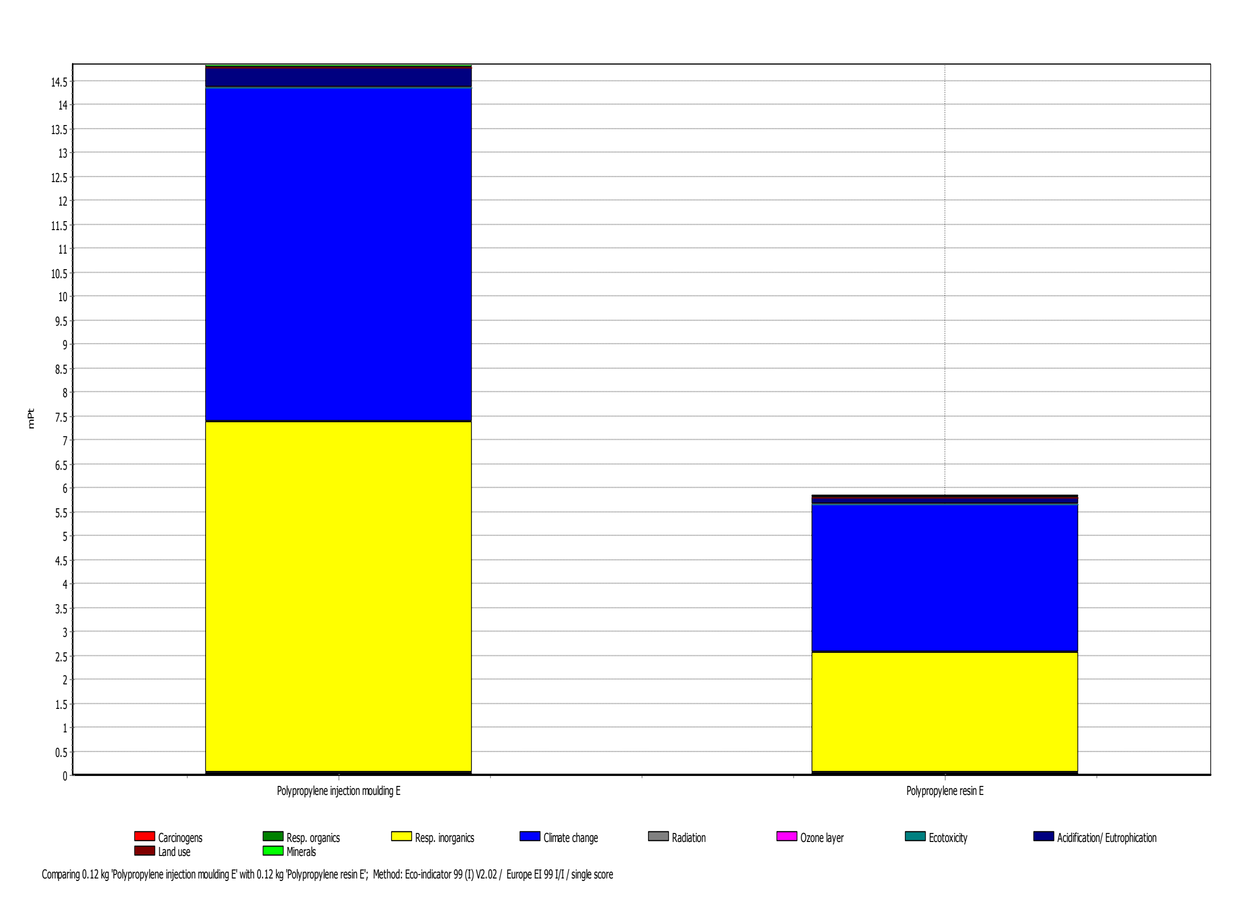

Figure 27: Single score Comparison in "points."

APPENDIX D: PUGH MATRICIES

Pugh Matrix for General Concept Selection

Design Criteria	Weight	Different Soaps (Datum)	Cycle Change	Recirculation with Filter	Redesign Washer	Alternative to Water	Combination of Cycle Change and Recirculation
Water Savings	4	0	+	++	+	++++	+++
Time	2	0	-	-	0	0	-
Energy	1	0	-	-	0	0	-
Space	2	0	0	-	0	0	-
Cost	2	0	+	+	0	-	+
Maintenance	1	0	0	-	0	0	-
Robustness	2	0	0	-	0	-	-
Laundry Cleanliness	2	0	-	0	0	-	0
Washer Functionality	3	0	-	-	---	-	-
Prototyping Time	2	0	++	++	-	0	++
Prototyping Cost	2	0	++	++	-	0	++
Total Points		0	6	9	-9	7	11

Pugh Matrix for Component Concept Selection

Design Criteria	Weight	Tank	Continuous	Self-Cleaning Filter	User Cleans Filter	Pump	No Pump
Time	2	-	+	-	+	+	-
Energy	1	0	0	-	+	-	+
Cost	2	0	0	-	+	-	+
Space	2	-	+	-	+	-	+
Robustness	2	0	0	-	+	0	0
Washer Functionality	3	+	-	-	+	+	-
Prototyping Cost	2	0	0	-	+	++	--
Prototyping Time	2	+	-	-	+	++	--
User Friendliness	3	0	0	+++	---	0	0
Total Points		1	-1	-5	5	8	-8

APPENDIX E: FUNCTIONAL DECOMPOSITION