MECH 4860

# Multi-Barrier Machine Chiller Loop
# Final Design Report

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# Executive Summary

The team was tasked with redeveloping the multi-barrier cooling system at Winpak Winnipeg to reduce shutdowns and downtime of the three multi-barrier machines used to produce plastic packaging. The current setup has each multi-barrier machine connected to its own chiller, meaning that when a chiller fails, the multi-barrier machine must cease operation.

Three concepts were developed by the team, including a single loop system, an interconnected system, and a backup chiller system. The concepts were compared using a series of weighted decision matrices, and the single loop system was selected for recommendation. The new single loop system increases system reliability by allowing all three multi-barrier machines to continue operation in the event of a single chiller failure.

The new single loop system has all three chillers supplying cold fluid to the communal cold pipe, which then splits into three smaller pipes, each one supplying a set of heat exchangers for a multi-barrier machine. The three sets of heat exchangers return the hot fluid to the communal hot pipe, which splits into three smaller pipes, each one returning fluid to a chiller. In the case of a single chiller failure, this system will continue working as two chillers have the required cooling capacity to cool three multi-barrier machines.

The design meets or exceeds all specifications and constraints given by the client, such as the requirement for the design to meet code using black iron schedule 40 pipes, meets ISO standards, and other requirements set out in the needs and constraints section of the report.

With a safety factor of 1.25, 103.9 ft of head is required at the chiller one pump, 68.9 ft of head at the chiller two pump, and 79.4 ft of head at the chiller three pump. By analytical calculations, it was determined that an additional 0.64 tonnes of refrigeration is required to offset the heat gained through the pipe. Each chiller should be capable of supplying 206.32 tonnes of refrigeration with the 80% chiller utilization assumption, and 257.9 tonnes of refrigeration with a safety factor of 1.25.

The design will effectively eliminate the downtime of a multi-barrier machine due to single chiller failure, which has historically been [redacted]. At a conservative estimate of [redacted] CAD per hour of lost revenue, this will save [redacted] CAD during a future chiller failure. The design may prevent the additional side effects of a multi-barrier machine being shut down abruptly such as lost energy, the generation of waste material, and possible damage to the multi-barrier machine due to overheating.

This report contains the introduction to the problem, the concept selection justification, in-depth research of academic literature and industry solutions, detailed design specifications, a bill of materials, and renders of the 2D AutoCAD drawing of the facility with the new single loop system implemented. Included with this report is a PowerPoint presentation of the project, an a poster presentation.

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# 1 Introduction

Winpak is a packaging company whose main purpose is manufacturing packaging machines and materials. Their products are commonly used for packaging perishable foods, beverages, pharmaceuticals, medical supplies and personal items [1]. There are twelve Winpak manufacturing facilities in North America, one being here in Winnipeg. Winpak's mission statement is "to design, manufacture, and supply the most sustainable packaging solutions that reduce food waste, extend freshness, and promote health."[1].

## 1.1 Objectives

Currently, each of Winpak's three multibarrier (MB) plastic film extrusion lines have a dedicated chiller to control temperatures during extrusion processes. The MB line uses three chilled rollers to cool extruded plastic film from over 200 °C to room temperature. The temperatures of the three rollers are 20 °C, 30 °C, and 60 °C. A failure in one chiller or loss of cooling capacity results in that line going down to restore optimal temperatures. Not only does a failure create material and energy loss, but the amount of lost production time is also costly. Each MB line is operational 24 hours per day and each line extrudes the equivalent of [redacted] of plastic per hour. Lead times to order replacement parts for the chillers have been [redacted] long. The lost production time can cost Winpak upwards of [redacted] of lost revenue if the MB rollers cannot be chilled for that time. The frequency of chiller failure is low at twice in the last five year period, but the importance of redesigning this system is large due to the high cost associated with chiller failure.

On average each chiller was assumed to provide 138 tons of refrigeration to each MB line. This assumption was made because Winpak was unable to acquire the drawings for the MB 2 and MB 3 lines. When the actual value of the cooling loads are available, Winpak will be able to easily find the new chilling requirement by following the steps outlined in Section 4.5.2 of this report. The process loop that chills the rollers can not be modified. The cooling loops are connected to the process loops via heat exchangers. Images of the facility and these features can be found in appendix E.

The desired state is a new cooling loop that can provide sufficient refrigeration to maintain the chilled roller temperatures for all three MB machines after a chiller failure occurs. To accomplish this, a new piping network must be designed that specifies pipe lengths, sizes, specifications, fluid flow capacities in GPM, and temperatures in supply and return lines. This system must be operational for all outside conditions and should include a method of regulating the usage of each chiller to ensure even running time. This new design will save Winpak a significant amount of money if a chiller fails in the future.

The remainder of this report discusses the problem analysis, concept development, concept analysis and selection, detailed design, and the future considerations that could be implemented to this project.

### 1.1.1 Expectations

Table I shows the Supplier Input Process Output Customer (SIPOC) table which gives a general outline of the processes required to complete this project. Additionally, it outlines all inputs and outputs of the processes as well as the suppliers and customers that correspond to the inputs and outputs, respectively. Beyond the main objectives, Winpak has requested additional deliverables that can be found in the output column such as the chilling capacity of the remaining two chillers if one fails, CAD drawings of the new cooling loop, and a bill of materials. The bill of materials will also include the costs of each of the components used in the final design.

TABLE I: SIPOC TABLE

| Supplier | Input | Process | Output | Customer |
|---|---|---|---|---|
| >Winpak | >Facility Access | >Tour facility | >Max chilling capacity | >Winpak |
| >U of M | >System operating conditions | >Calculate cooling loads | >Final Design | >U of M |
| | >Cooling loads | >Select concept | >Piping Network CAD Drawing | |
| | >Facility drawings | >Create piping network | >Bill of materials | |
| | >Autocad licences | >Draft 2D drawing | >Cost Analysis | |

## 1.2 Needs and Constraints

The main goal of the project is to design a piping network so that all multi barrier machines run on one cooling loop. The cooling loop must be able to perform cooling functions to all multi barrier machines even if one of the chillers is non-operational. Table II briefly outlines the needs of the customer to complete this goal. Winpak has reviewed this list, and a priority number has been assigned to each need.

TABLE II: NEEDS TABLE

| Client Needs | | Priority |
|---|---|---|
| 1 | The design must be a single common loop | 5 |
| 2 | The pipes must be insulated | 5 |
| 3 | The design must have built in redundancy | 5 |
| 4 | The design must include a 2D CAD drawing | 3 |
| 5 | The material of the pipes must be black iron | 4 |
| 6 | The cooling line must maintain setpoint temperature | 5 |
| 7 | The design must fit in the designated space | 4 |
| 8 | The design must be easy to access for maintenance | 5 |
| 9 | The system must be able to operate year-round | 5 |
| 10 | The design must meet ISO standards | 5 |
| 11 | The cooling loop GPM and Pressure must be maintained | 5 |
| 12 | The design must have bypass valve to isolate machine for maintenance | 5 |
| 13 | The design must have low cost to implement | 2 |
| 14 | The design must be easy to operate | 3 |

### 1.2.1 Constraints and Limitations

There exist some constraints and limitations for the project:

- Space around the machines is limited. Access for piping is restricted by racks, walls and overhead services.
- All designs must meet ISO standards.
- Project must be completed before December 8, 2022.

## 1.3 Technical Specifications

Table III outlines all relevant metrics related to the project. These specifications were developed by analysing the needs of the project and through conversations with the client. Each specification corresponds to at least one of the needs from Table II. The current target values are a combination of process benchmarks, piping network parameters, and technical estimations adapted from the current system.

TABLE III: TECHNICAL SPECIFICATION TABLE

| Specification | Corresponding Needs | Target Value | Unit of Measurement |
|---|---|---|---|
| Heat loss through pipes | 1, 2, 5, 6, 9, 10 | 1.2 | TR |
| Space used | 1, 4, 7, 8 | 100 | $ft^2$ |
| Piping lengths | 1, 2, 4, 7, 10, 13 | 800 | ft |
| Heat transfer | 1, 2, 3, 9, 10 | 120 | TR |
| Roller temperatures | 3, 9 | 20, 30, & 60 | °C |
| Pipe pressure | 1, 4, 5, 10, 11 | 60 | PSI |
| Pipe flow rate | 1, 4, 5, 10, 11 | 1278 | GPM |
| Supply temperature | 4, 6, 9, 10 | 45 | °F |
| Return temperature | 4, 6, 9, 10 | 55 | °F |
| Cost | 13 | [redacted] | $ (CAD) |
| Complexity | 1, 3, 4, 8, 10, 12, 13, 14 | Low | Subj. |

### 1.3.1 House of Quality

A house of quality seen in Figure 1.1 was developed in order to relate the needs from the customer to the technical specifications required for the project. The house of quality conveys the strength of the relationship between the needs and technical specifications, the direction of improvement for each metric, the correlation between each technical specification, and the relative weights of the needs and technical specifications. The relative weight of the needs have been calculated from the customers priorities. The relative weights of the technical specifications have been calculated using the relationships between the technical specifications and needs. Technical specifications have a higher importance rating based on the amount of correlations, the strength of the correlations, and the relative weight of each need that has been correlated to the technical specification.

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Figure 1.1: House of Quality

## 1.4 Assumptions

With the current data available and collected there was a number of assumptions that needed to be made:

- The cooling requirement of the MB machines is 80% of the associated chiller's capacity. This entails that the maximum cooling requirement for MB 1 is 128 TR, MB 2 is 132 TR, and MB 3 is 152 TR.
- The measurements taken at site are plus or minus 5 to 10 feet. This number is from the laser measuring device used and the access points to measure from.
- The pressure drop across the heat exchangers is 15 psi.
- The flow rates in each MB line are the same as MB 1, which is 425 gpm.

- The pipes used in the MB 2 and MB 3 lines are the same as the MB 1 line which are schedule 40 black iron pipe with a six inch diameter.
- Additional assumptions made for the heat gain through the pipes are detailed in section 4.5.1 of this report.

# 2 Concept Development

This section discusses the three concepts generated by the team.

## 2.1 Current System

In the current system, each multi-barrier extrusion machine has its own dedicated chiller. The main problem with the current system is the lack of redundancy. When one chiller fails, the entire line is inoperable as there is no way to continue cooling the multi-barrier machine. A representation of the current system can be seen in Figure 2.1.

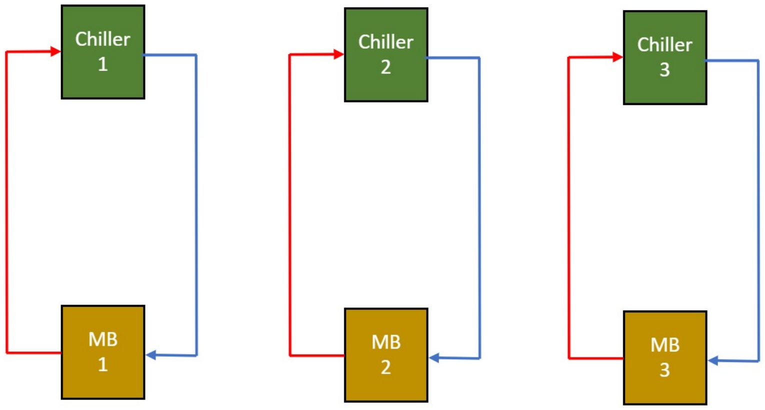


Figure 2.1: Current system

## 2.2 Concept One - Single Loop System

In the single loop concept, all three chillers are connected to a single common line which cools all three multi-barrier machines. Not all chillers need to be operating at all times, and operational time can be split among the chillers. A representation of the single loop system can be seen in Figure 2.2.

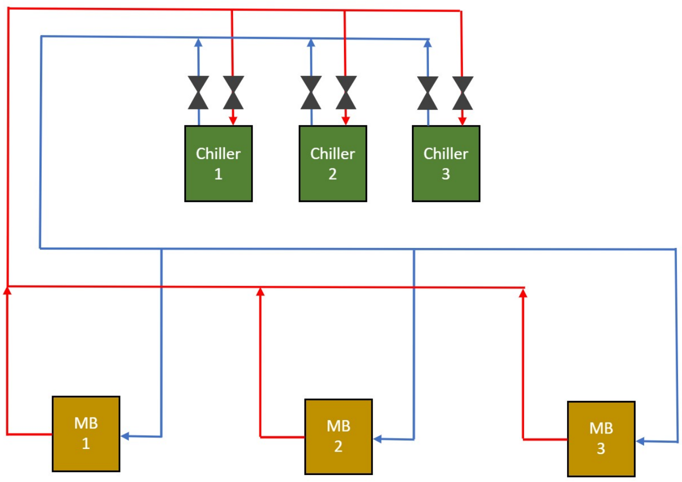


Figure 2.2: Single loop chiller system

## 2.3 Concept Two - Backup Chiller

In the Backup chiller concept, each multi-barrier extrusion machine has its own dedicated chiller, but a fourth additional chiller is on standby to connect to a machine in the case that its chiller fails. When one of the chillers requires maintenance or is out of service the fourth chiller can be operable to supply cooling to the line. This means that no downtime is required on the MB line when one chiller is out of operation. A representation of the backup chiller system can be seen in Figure 2.3. Figure 2.4 shows this system during normal operations and Figure 2.5 shows this system when a chiller fails.

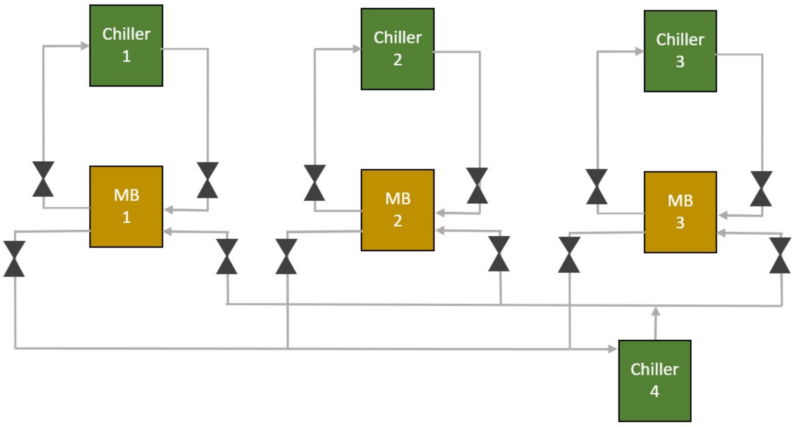


Figure 2.3: Full backup chiller system

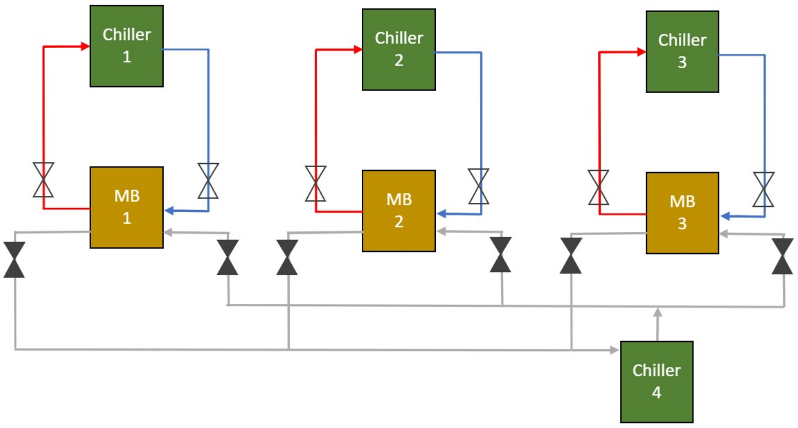


Figure 2.4: Backup chiller system running in normal operation

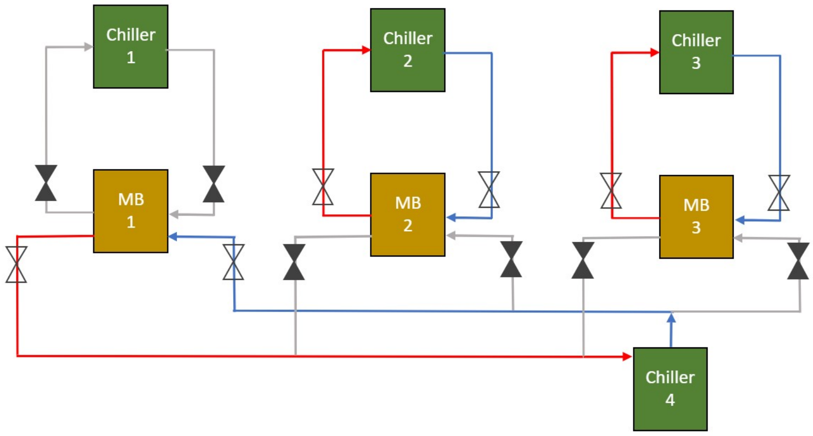


Figure 2.5: Backup chiller system running in alternate operation

## 2.4 Concept Three - Interconnected System

In the interconnected concept, each multi-barrier extrusion machine has its own dedicated chiller, but all three machines are linked through pipes. In normal operation, these linking pipes will be closed, but in the case that one chiller fails, the system can quickly convert to a single common loop system, where the two remaining chillers cool the common line to all three multi-barrier machines. A representation of the interconnected system can be seen in Figure 2.6.

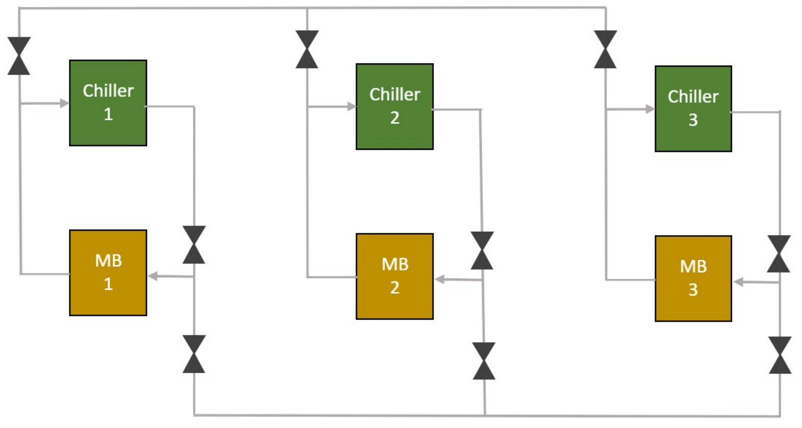


Figure 2.6: Full interconnected system diagram

Figure 2.7 shows the diagram of the interconnected system during normal operation. When all three chillers are operational, this configuration is used, which is identical to the current system in place.

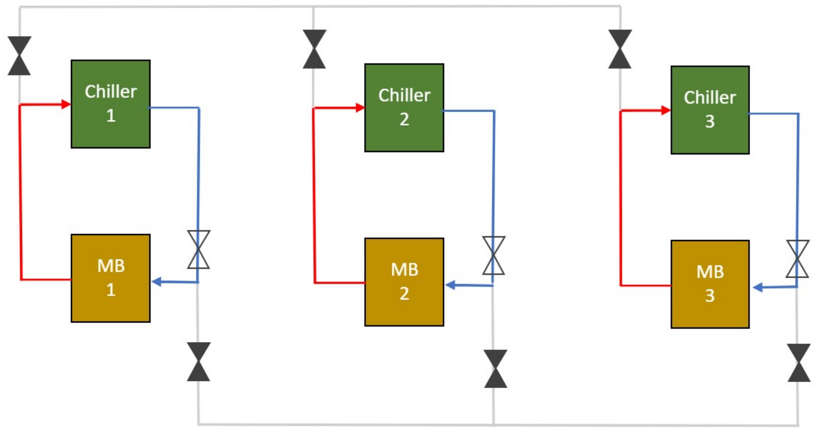


Figure 2.7: Interconnected system running in normal operation

Figure 2.8 shows the diagram of the interconnected system during a chiller failure, in this case chiller one has is non-operational. The valves are reconfigured, resulting in the system changing to the single loop configuration. In this case, chillers two and three are cooling fluid to all three multi-barrier machines.

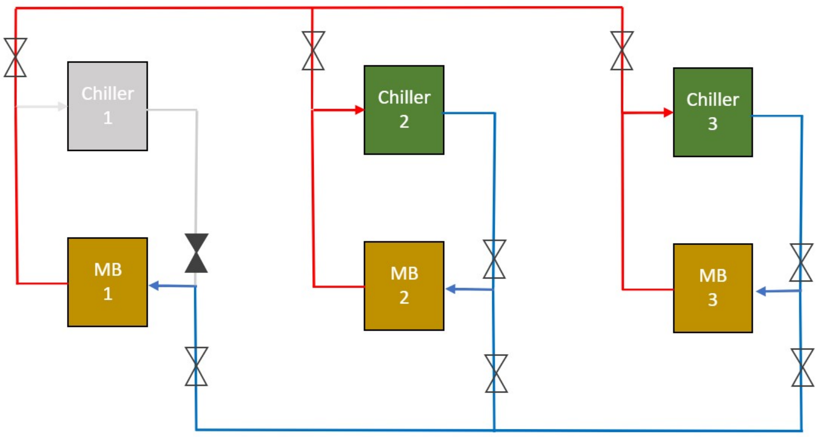


Figure 2.8: Interconnected system running in alternative operation

# 3 Concept Analysis and Selection

This section will analyze the three concepts and explain the decision process. A number of performance metrics have been generated and discussed to compare the three concepts. A weighted decision matrix is used to determine the best option. A criteria importance weighting table was generated and is used to assign weights to each of the performance metrics. Sensitivity analysis is also completed.

## 3.1 Performance Metrics

Seven performance metrics were created to score each of the models against each other. These metrics are:

- Pipes used
- Space Consideration
- Maintenance
- Cost
- Reliability and Redundancy
- Ease of Operation
- Ease of Implementation

Each of these metrics and their scores are discussed below.

### 3.1.1 Pipes used

This metric refers to the amount of piping used in the design. The single loop system uses a significant amount of pipes due to the long distance between multi-barrier 1 and the other two multi-barrier machines and chillers. The interconnected system uses the same amount plus the additional direct pipes between the chillers and the multi-barrier machine closest to it (although these pipes are already installed). Of the three concepts, the interconnected system uses the most. The backup chiller system uses the existing pipes between each chiller and machine, as well as the backup line from the north parking lot to the multi-barrier machines 2 and 3. The only additional piping required for this concept is between the roof and multi-barrier one.

### 3.1.2 Space Consideration

This metric refers the the space used by each concept. This metric does not take into account the space used by pipes, as that is covered in the previous metric. The single loop system uses the least amount of space as no additional chillers are needed, only a single reservoir is required. The interconnected system uses a medium amount of space. No additional chiller is required for the interconnected system, however three reservoirs may be required - one for each multi-barrier system. The backup chiller concept uses a significant amount of space, as an additional fourth chiller is required in an already space constrained facility. There is a possibility to place the fourth chiller on a platform above chiller one, but such a system would be difficult to achieve. Additionally, three to four reservoirs would be required.

### 3.1.3 Maintenance

This metric refers to the ease of maintenance of each of the concepts. The backup chiller concept is easy to maintain, as each piping loop is independent and can be shut down easily. The interconnected system is the next easiest to maintain, as each loop is independent under normal operation, and a conversion to the single loop system can be done if maintenance on a specific chiller is required. The single loop system is the most difficult to maintain, as pipes can not be isolated or shut down.

### 3.1.4 Cost

This metric refers to the cost associated with each concept. The single loop system is the least costly concept as no additional reservoirs or chillers are required compared to the current system. The majority of the cost for this concept would be the pipes and construction. The interconnected system is medium cost, as additional reservoirs would be required, but no additional chillers. The reservoirs, pipes, and construction would be the majority of the cost associated with this design. The backup chiller system is costly, as it requires up to four reservoirs, and an additional chiller with an approximate cost of [redacted].

### 3.1.5 Reliability and Redundancy

This metric refers to the reliability of each concept and the redundancy built into the system. The backup chiller concept is the least reliable, as it would not continue working in the event that two chillers fail. It only works as a stand in for one failed chiller. The single loop system and interconnected system are both reliable as they will continue working even with two failed chillers.

### 3.1.6 Ease of Operation

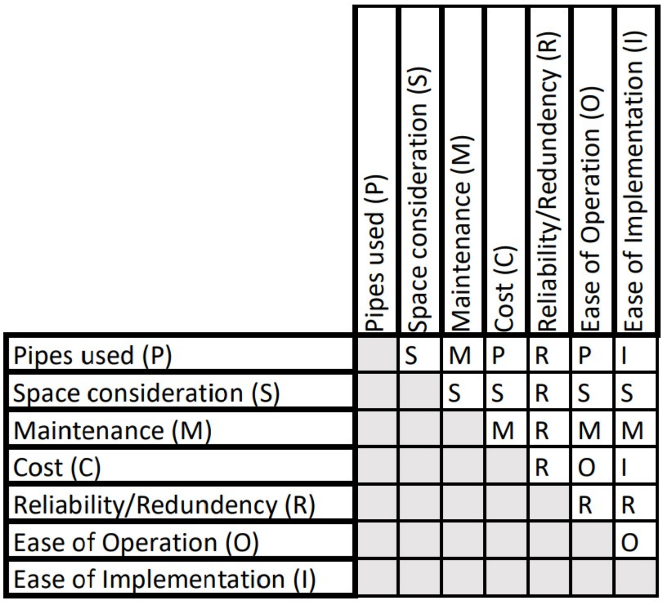
This metric refers to the ease of operating each design once implemented. The backup chiller and single loop system are both easy to operate. When a chiller goes down in the backup chiller concept, the main chiller for the loop needs to be closed off and the backup chiller loop opened to that multi-barrier machine. In the single loop system, the valves to the inoperable chiller simply need to be closed. The interconnected concept is more complex, as it requires the entire system to change configuration from three independent loops to a single loop system, requiring many valves to be opened or closed and chiller configurations changed.

### 3.1.7 Ease of Implementation

This metric refers to the ease of implementing the concept in the facility. The interconnected system scores lowest on this metric as it is the most difficult to implement. It requires a complex piping network with numerous valves to ensure it will work when a chiller fails. The single loop system is the middle of the pack in this metric, as it will require a significant amount of new pipes, but not as much as the interconnected system. It also does not require as many reservoirs. The backup chiller is the easiest to implement as it does not require significant changes to the current active system, just the backup chiller and piping needs to be constructed.

## 3.2 Criteria Importance Weighting

The criteria importance weighting table is displayed in Figure 3.1. It was developed by analysing which of each pair of metrics was more important to the project. To determine which metric is more important the house of quality was consulted to incorporate the voice of the customer into the decision process. Each metric's relative weight was then calculated from the number of times it appears in the table. These weights are used in the weighted decision matrix.

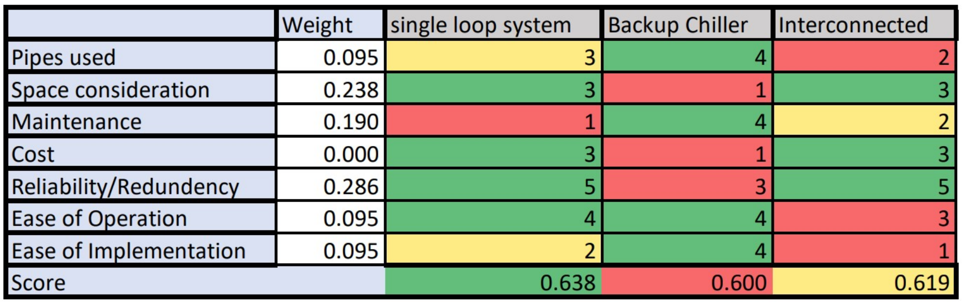


| | Pipes used (P) | Space consideration (S) | Maintenance (M) | Cost (C) | Reliability/Redundency (R) | Ease of Operation (O) | Ease of Implementation (I) |
|---|---|---|---|---|---|---|---|
| Pipes used (P) | | S | M | P | R | P | I |
| Space consideration (S) | | | S | S | R | S | S |
| Maintenance (M) | | | | M | R | M | M |
| Cost (C) | | | | | R | O | I |
| Reliability/Redundency (R) | | | | | | R | R |
| Ease of Operation (O) | | | | | | | O |
| Ease of Implementation (I) | | | | | | | |

Figure 3.1: Criteria importance weighting table

## 3.3 Weighted Decision Matrix

Figure 3.2 contains the weighted decision matrix. The weights from the previous section were used, and each of the three concepts was scored based on its performance in each metric on a scale from 1 to 5. Overall, the single loop system scored 0.638 out of 1.000, the backup chiller system scored 0.600 out of 1.000 and the interconnected system scored 0.619 out of 1.000. The single loop system scores the highest of the three concepts.

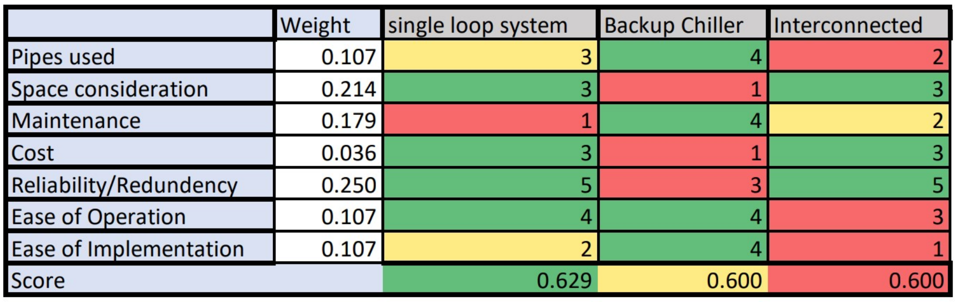


| | Weight | single loop system | Backup Chiller | Interconnected |
|---|---|---|---|---|
| Pipes used | 0.095 | 3 | 4 | 2 |
| Space consideration | 0.238 | 3 | 1 | 3 |
| Maintenance | 0.190 | 1 | 4 | 2 |
| Cost | 0.000 | 3 | 1 | 3 |
| Reliability/Redundency | 0.286 | 5 | 3 | 5 |
| Ease of Operation | 0.095 | 4 | 4 | 3 |
| Ease of Implementation | 0.095 | 2 | 4 | 1 |
| Score | | 0.638 | 0.600 | 0.619 |

Figure 3.2: Weighted decision matrix

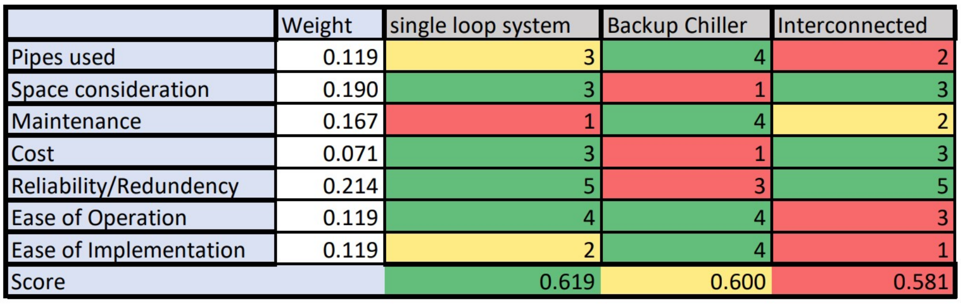
### 3.3.1 Sensitivity Analysis

For the sensitivity analysis, each metrics relative weight was brought closer to the mean by adding additional points in the criteria importance weighting table and recalculating the weights. Figure 3.3 shows the weighted decision matrix with an additional one point in each metric weighting, and Figure 3.4 shows the weighted decision matrix with an additional three points in each metric weighting. In the single additional point matrix, the single loop system scored 0.629 out of 1.000, the backup chiller system scored 0.600 out of 1.000 and the interconnected system also scored 0.600 out of 1.000. In the three additional point matrix, the single loop system scored 0.619 out of 1.000, the backup chiller system scored 0.600 out of 1.000 and the interconnected system scored 0.581 out of 1.000. The single loop system still maintains the highest score for both adjustments.



| | Weight | single loop system | Backup Chiller | Interconnected |
|---|---|---|---|---|
| Pipes used | 0.107 | 3 | 4 | 2 |
| Space consideration | 0.214 | 3 | 1 | 3 |
| Maintenance | 0.179 | 1 | 4 | 2 |
| Cost | 0.036 | 3 | 1 | 3 |
| Reliability/Redundency | 0.250 | 5 | 3 | 5 |
| Ease of Operation | 0.107 | 4 | 4 | 3 |
| Ease of Implementation | 0.107 | 2 | 4 | 1 |
| Score | | 0.629 | 0.600 | 0.600 |

Figure 3.3: Sensitivity analysis with +1 point for each metric



| | Weight | single loop system | Backup Chiller | Interconnected |
|---|---|---|---|---|
| Pipes used | 0.119 | 3 | 4 | 2 |
| Space consideration | 0.190 | 3 | 1 | 3 |
| Maintenance | 0.167 | 1 | 4 | 2 |
| Cost | 0.071 | 3 | 1 | 3 |
| Reliability/Redundency | 0.214 | 5 | 3 | 5 |
| Ease of Operation | 0.119 | 4 | 4 | 3 |
| Ease of Implementation | 0.119 | 2 | 4 | 1 |
| Score | | 0.619 | 0.600 | 0.581 |

Figure 3.4: Sensitivity analysis with +3 points for each metric

### 3.3.2 Selection

Based on the above analysis, the single loop system will be the selected design for further development. The single loop system is the overall best concept, as it scored the highest in space considerations, cost, reliability and redundancy, and ease of operation. Its only major downfall is the more difficult maintenance, but the pros of this system far outweigh the cons as seen in the weighted decision matrix final score of 0.638, compared to 0.619 for the interconnected system and 0.600 for the backup chiller system. Additionally, the single loop system maintains the best score throughout the sensitivity analysis adjustments.

# 4 Design Details

This section will discuss the detailed design. Contained in this section are the 2D models generated in AutoCAD, pipe height figures, pipe selection and sizing requirements, the calculations for pressure, heat transfer, and pipe losses, discussion of the variable frequency drive, the 3D models generated in Solidworks, and the failure modes and effects analysis.

## 4.1 Two Dimensional Drawings

The two dimensional facility layout was generated in AutoCAD which can be seen in Figure 4.1. In this layout, up is east. Light blue lines represent cold fluid lines, while pink lines represent hot fluid lines. The three chillers are highlighted in dark blue and the heat exchangers are highlighted in orange. The pumps for MB 1 are highlighted in green.

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Figure 4.1: Full AutoCAD Drawing

Figure 4.2 shows a close-up view of the single loop system. All three chillers supply cold fluid to the cold communal pipe from the south side. The communal pipe then splits into three smaller pipes which supply the heat exchangers for each multi-barrier machine. The heat exchangers return hot fluid to the north side of the hot communal pipe, which then splits into three and returns the fluid to the chillers.

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Figure 4.2: Close-up of the single loop system

Additional 2D drawings of the facility and pipe system are found in appendix A.

### 4.1.1 New pipes and existing pipes

Figure 4.3 shows which pipes are already existing and which are new. The new pipes that are required for the design are colored green, while the existing pipes are colored purple.

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Figure 4.3: New pipes and existing pipes

### 4.1.2 Pipe Heights

Figure 4.4 shows the height of all of the design pipes in feet to ensure there are no collisions or conflicts with the pipes.

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Figure 4.4: Pipe Heights in feet

## 4.2 Three Dimensional Model

Figures 4.5, 4.6, and 4.7 show the 3D model of the pipe network at the converging and diverging points. Multi-barrier machine one is on the main floor to the bottom left, while multi-barrier machine two is in the center right on the main floor and multi-barrier machine three is down the long corridor to the upper right. Chiller one is set up outdoors in the west parking lot, and the pipes going to it are near the center bottom of figure 4.5. Chiller two is on the second floor of the facility, its pipes are seen in the upper center, above the pipes to multi-barrier machine two. Chiller three is down the corridor to the upper right, in the same location as multi-barrier machine three. The pipes to each of these are labelled in the figures below.

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Figure 4.5: Isometric view of the pipes in the center of the system, facing northeast

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Figure 4.6: Isometric view of the pipes in the center of the system, facing east-northeast

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Figure 4.7: Bird's eye view of the pipes in the center of the system, up is east

## 4.3 Pipe Selection, Sizing, and Lengths

The pipes selected for the design are to match the current piping network in place. The pipes will be made from black iron and have a schedule 40 wall thickness. The nominal diameter of the existing pipe section is 6 inches so the new piping system will also have a nominal diameter of 6 inches as well. Both the supply lines and the return lines will converge before diverging again. To reduce the pressure losses in the two converged sections, the nominal pipe diameter will be expanded to 8 inches. Table IV summarizes the components in each section of the pipe network. A full bill of materials with the cost of all the new components can be found in appendix C. The total cost of all the components is [redacted]

TABLE IV: COMPONENTS USED

| Pipe Section | Length [ft] | Elbows | Tees | Reducers | Heat Exchangers | Valves |
|---|---|---|---|---|---|---|
| Chiller 1 Supply | 300.5 | 7 | | | | 1 |
| Chiller 2 Supply | 23.6 | 3 | | | | 1 |
| Chiller 1 & 3 Supply | 2.8 | | | | | |
| Chiller 3 Supply | 111.2 | 1 | | | | 1 |
| Communal Supply | 34.7 | | 4 | 2 | | |
| MB 3 Supply | 124.6 | 5 | | | 1 | 1 |
| MB 3 Return | 129.1 | 5 | | | | |
| MB 1 & 2 Supply | 1.4 | | | | | |
| MB 2 Supply | 77.4 | 5 | | | 1 | 1 |
| MB 2 Return | 87.9 | 6 | | | | |
| MB 2 & 3 Return | 1.3 | | | | | |
| MB 1 Supply | 41.1 | 4 | | | 1 | 1 |
| MB 1 Return | 36.1 | 3 | | | | |
| Communal Return | 32.9 | | 4 | 2 | | |
| Chiller 1 Return | 360.7 | 13 | | | | 1 |
| Chiller 2 & 3 Return | 4.7 | | | | | |
| Chiller 2 Return | 31.5 | 2 | | | | 1 |
| Chiller 3 Return | 120.9 | 4 | | | | 1 |
| Total | 1522.4 | 58 | 8 | 4 | 3 | 9 |

## 4.4 Pressure Calculations

The working fluid is used in this system is 50% glycol and 50% water. This ratio of glycol and water was determined based on the freezing point of glycol-water solutions. The freezing point of a 40% glycol by volume mixture is -23.5°C [2]. If the pipe section that is outside is isolated and the flow is stopped during the winter, the glycol-water mixture could freeze and cause excessive stress on the pipes, possibly causing a rupture. A 50% glycol and 50% water solution by volume has a freezing point of -36.8 °C, which will be able to withstand Winnipeg's winter climate. Using the fluid properties of the glycol-water mixture and the schedule 40 black iron pipe, the pressure losses were calculated in each portion of the piping network. Detailed calculations can be seen in appendix B.

An important design consideration is the flow rates that go to each MB line after the communal pipe section branches. In order to ensure the same flow rate goes to each MB line, the pressure drop in each branch must be the same. This can be ensured by using balancing valves in each branch leading to an MB line. A summary of the balancing process can be seen in Table V, and the process used to determine the position of each valve is shown in appendix B.

The vapor pressure of a 50% glycol 50% water mixture is 0.12 psi [3]. As long as the absolute pressure in the pipes is above the vapour pressure, the working fluid will not boil.

TABLE V: SUMMARY OF BALANCING VALVES

| | MB 1 drop [ft] | MB 2 drop [ft] | MB 3 drop [ft] |
|---|---|---|---|
| Before balancing valves | 37.21 | 41.43 | 42.29 |
| Balancing valve | 6.75 | 2.53 | 1.67 |
| After balancing valves | 43.96 | 43.96 | 43.96 |
| Number of turns from closed | 5.5 | 8 | 10 |

The pumps are to be located in the same pipe sections as the chillers. The pumps must be able to supply enough head to counteract the pressure drop for the communal supply and return lines, the pressure drop from the MB lines, and the pressure drop in each respective chiller line. The head required by each pump was calculated when all chillers are operational, and in each scenario where one of the chillers is nonoperational to determine the maximum head required. A summary of these calculations are shown in Table VI.

TABLE VI: HEAD REQUIRED FROM EACH PUMP

| | Feet of Head Required | | |
|---|---|---|---|
| | Pump 1 | Pump 2 | Pump 3 |
| Fully operational | 65.6 | 52.2 | 56.6 |
| MB 1 down | 0 | 55.1 | 61.3 |
| MB 2 down | 83.1 | 0 | 63.5 |
| MB 3 down | 80.0 | 54.3 | 0 |
| Maximum | 83.1 | 55.1 | 63.5 |
| Safety factor | 1.25 | | |
| **Total** | **103.9** | **68.9** | **79.4** |

The maximum pressure that can be withstood from the pipes is 2071 psi in the 6 inch pipes and 1829 psi in the 8 inch pipes [4]. The maximum pressure that can be withstood from the gate valves used to isolate each chiller is 125 psi [5]. The equivalent pressures in terms of head for a 50% glycol 50% water system are 4234 ft, 3739 ft, and 256 ft, respectively. The maximum pressure commanded by any pump is 103.9 ft with a safety factor of 1.25 applied, therefore the pressures in the pipes are within an acceptable range.

## 4.5 Heat Transfer Calculations

The cooling requirements for each MB line is assumed to be 80% of the associated chiller cooling capacity, both of which are shown in Table VII as well as the total requirement for all three MB lines.

TABLE VII: MB LINE COOLING REQUIREMENTS

| | Chiller 1 | Chiller 2 | Chiller 3 |
|---|---|---|---|
| Capacity [TR] | 160 | 165 | 190 |
| Requirement [TR] | 128 | 132 | 152 |
| Total Requirement [TR] | 412 | | |

### 4.5.1 Heat Gain Through Pipes

In order to calculate the heat gain in the pipes, several assumptions must be made:

- The supply and return temperatures for all three chillers are the same as in the MB 1 chiller drawing (45°F and 55°F, respectively).
- The outside temperature on a hot summer day in Winnipeg is 90°F, and the temperature within Winpak's facility is 77°F.
- The surface temperatures of the piping insulation are 5 K cooler than the surrounding temperatures.
- The wind velocity where the pipes are located outside is 15 km/hr, and 0 km/hr inside Winpak's facilities.

Two inch thick fiberglass insulation was chosen with a k-value of 0.18 Btu-in/hr-ft$^2$-°F [6]. As mentioned in section 4.4, the working fluid is 50% water and 50% glycol by volume. Table IV summarizes the lengths in each pipe section. The pipes will be made from black iron and have a schedule 40 wall thickness. The nominal diameter of the pipes is 6 inches, except for the communal section which is 8 inches. The heat gain calculations were done for 3 sections of pipe: pipes located outside, 6 inch pipes located inside, and the 8 inch pipes used for the communal sections. The communal section is calculated separately from the other interior pipes because it will gain more heat due to the larger radius and higher velocity in the pipe. The changes in heat gain through the pipes are negligible when comparing between scenarios with nonoperational chillers and the three fully operational chillers scenario. A summary table is shown in Table VIII and detailed calculations can be found in appendix B.

TABLE VIII: HEAT GAIN IN EACH PIPE SECTION

| Pipe Section | Heat Gain [TR] |
|---|---|
| Outside | 0.16 |
| Inside | 0.45 |
| Communal | 0.03 |
| Total | 0.64 |

### 4.5.2 Chiller Specification

The total chilling requirement is the sum of the total cooling load from the MB lines as well as the heat gain through the pipes. The total cooling requirement must be supplied when any one chiller becomes nonoperational, therefore each chiller must output half of the total chilling requirement. This is summarized in Table IX.

TABLE IX: CHILLING LOADS

| Load | Heat Transfer [TR] |
|---|---|
| Cooling Requirement | 412 |
| Heat Gain | 0.64 |
| Total Chilling Requirement | 412.64 |
| 3 Operational Chillers at Maximum Capacity | 137.55 |
| 2 Operational Chillers at Maximum Capacity | 206.32 |
| safety factor | 1.25 |
| **Total Chilling Requirement for Each Chiller** | **257.9** |

## 4.6 Variable Frequency Drive

A variable frequency drive (VFD) is an electronic system that is used to control the speed of a motor that is typically connected to a pump. The main benefit of this control device is a reduction in system operating costs. This is achieved through a reduction in water consumption, a reduction in total power used, and soft start and stop of the equipment.

An experiment for the reduction in liquid mixture loss by using a VFD was conducted by E. Al-Bassam and R. Alasseri. Variable Frequency Drives were installed and monitored to see if they provide an improvement over a dual speed control. From this experiment there was a "13% reduction in water consumption compared to the dual speed" [7]. The reduction in the cooling liquid needed to be added would provide both overall time and cost savings.

A reduction in power required for a system provides both cost savings and a better overall system efficiency. For example in Kuwait "VFDs were used with both chillers and cooling tower fans which produce a reduction of 5.8%" [7].

The third benefit is the soft start and stop of the equipment. "A soft start and stop of the equipment will increase the lifetime of the equipment" [8]. With this solution there is a cost benefit of less maintenance and longer life of current equipment.

Overall, a VFD would be a valuable asset for this single loop system, as it provides cost benefits as well as controls the speed of the pumps. The VFD that controls the pump would command the amount of head according to Table VI. The VFD that controls the chiller would command the amount of cooling depending on the required load. If all three MB machines are running at maximum capacity, the VFD would command the amount of cooling according to Table IX.

## 4.7 FMEA

A failure modes and effects analysis (FMEA) was completed on the detailed design to identify any failure modes and actions to take. The risk with the third highest priority is if cavitation occurs in the pumps. To mitigate this risk a VFD should be used to scale up the required head if needed. The risk with the second highest priority is if the MB lines require more cooling then can be provided because of a new plastic material with a higher required cooling load. The recommended action is to monitor the temperature of the MB lines, and if the temperature in the MB line is too high then running the MB machine at a lower setting would be required. The risk with the highest priority is if a valve gets stuck in the open or closed position because there is either damage to the valve or a manufacturing defect. Use of an automatically controlled valve with actuators connected to a motor will mitigate this risk. The FMEA can be seen in Table X.

TABLE X: FMEA

| Process Input | Potential Failure Mode | Potential Effect | SEV | Potential Causes | FREQ | Current Controls | DET | RPN | Action Recommendations |
|---|---|---|---|---|---|---|---|---|---|
| Flow | Absolute pressure below vapour pressure | Cavitation to the pumps which may cause damage | 8 | Not enough pumping power | 1 | N/A | 5 | 40 | Variable frequency drives to ensure flow |
| Valve | Valve gets stuck in open/ closed position | Flow is unable to enter main cooling loop, limiting cooling capacity | 7 | Damage to valve or manufacturing defect | 2 | N/A | 5 | 70 | Computer controlled valves |
| Pipe | Burst pipe | Loss of refrigerant and water damage to surrounding area | 8 | Pipe size is incorrect | 1 | N/A | 2 | 16 | Use flow modelling software to ensure pipes can withstand pressure |
| Pipe Support | Pipe support fails and the pipe falls | Potential injury and system line shuts down | 10 | Weak bracing or damage to supports | 1 | Visual shop inspection | 3 | 30 | Perform support calculations to ensure the load can be supported |
| MB Lines | Requires more cooling then can be provided | MB lines overheat and require maintenance | 7 | New plastic material | 3 | Monitors on MB lines | 3 | 63 | Continuous monitoring of temperature on the MB lines |
| Pipe Freezing | Refrigerant freezes in pipes | No flow to the chiller and potential chiller damage | 6 | Sustained temperatures much lower than -36.8 °C when chiller 1 is down | 1 | N/A | 5 | 30 | Implement a heat trace system or insulate the pipes |

# 5 Future Considerations

With the design currently in place, each MB machine has its own dedicated chiller. Winpak has requested a design eliminate MB downtime when a chiller is nonoperational. Research was conducted to look into different concepts that have been implemented in other applications.

## 5.1 Distribution Headers

Distribution headers can be used to divide supply and return lines across all three chilling machines. Figure 5.1 [9] is a visual representation of the connection lines and how distribution headers can be used. One of the findings was that the "distribution headers can increase reliability and redundancy when used" [9]. Therefore distribution headers can be considered in future application.

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Figure 5.1: Research Design

This study also looked into having an additional chiller on standby as an alternative. In this study the "reliability with having an additional chiller was raised from 4.4262% to 43% with an availability of 99.883% at all cooling loads"[9]. From this study a spare chiller can be considered to have on standby in the future to increase availability. Finally the study concluded that "increase of availability due to distribution headers is only around 0.00008% which is much smaller than the 0.2% increase of availability brought by an additional water-cooled chiller or an extra chiller plant"[9].

## 5.2 Series Versus Parallel

A different study looked into series versus parallel circuits of chillers. One of the conclusions was that having two chillers in parallel whether identical or different resulted in a minimal change in the temperature of the water flowing out of the chiller [10]. In Figure 5.2 [10] "the overall chiller coefficient of performance (COP) is plotted versus the difference between the condenser water return temperatures for equal loading on each chiller" [10].

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Figure 5.2: COP and the difference on condenser water return temperature

Additionally, this study analysed series versus parallel chillers in operation. Figure 5.3 [10], shows the COP versus the relative load on the first chiller.

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Figure 5.3: COP versus first relative load

‟Although the chillers perform more efficiently in series rather than parallel, there are significant increases in water stream pressure drops across both the evaporators and condensers for the series arrangement"[10]. From this insight parallel arrangements are recommended for future consideration. From this study a conclusion was garnered that ‟The performance of multiple chillers is enhanced by orientation in series rather than parallel. However, the increase in pumping power requirements for series chillers offsets the chiller improvements and the overall performance for the two configurations is similar"[10].

## 5.3 Redundancy

A third study found that having "redundant cooling systems in a building helped to increase the availability of a cooling system from 98.50% to 99.99%"[11]. This study shows how important redundancy to a cooling system can be. Increasing the availability to 99.99% is almost the ideal case for any business.

## 5.4 Algorithm

The final source examined was on a control system for a cooling system. For the company of Pepco they supply cooling to a number of buildings and have numerous chillers in operation. After data collection analysis on their current system "An algorithm was created that can compute all possible chiller, pump and cooling tower sequencing permutations, modified flows, set points and load limits. These calculations find the combination of equipment and speeds that result in the lowest kW input and/or the lowest instantaneous cost of production"[12]. This is interesting as the optimal energy usage and power consumption can be reached. This algorithm takes into account many factors and can make "make real- time automatic adjustments to the system based on real-time building loads"[12]. The automatic adjustments include "modulate control levels to all VFDs, pumps and machines"[12]. The design then does not depend on human operation, and thus as mentioned can achieve the optimal state. In the closing statement of the article Pepco concluded that "Plant optimization where components work optimally as part of a networked, interrelated system has allowed us to reach a new level of plant efficiency"[12]. Data collection for this as well as the coding and creation of the algorithm is something that is out of the scope of time on this current project. The algorithm may be considered in future endeavours.

# 6 Conclusion

The team was tasked with the problem of redeveloping Winpak's multi-barrier machine chilling loop to reduce downtime due to a chiller failure. In consultation with the client, the team developed a problem statement for the project, and generated objectives, needs and constraints, and technical specifications for the project.

A number of possible solutions were brainstormed by the team and narrowed down to three concepts; a single loop system, a backup chiller, and an interconnected system.

These three concepts were developed further with diagrams and explanations. Seven performance metrics were used to compare the three concepts; piping, space, maintenance, cost, reliability and redundancy, operation, and implementation. A criteria importance study was conducted to determine the weights of each of these performance metrics in a weighted decision matrix. The weighted decision matrix determined that the single loop system was the superior option, with a score of 0.638, compared to a score of 0.619 for the interconnected system and 0.600 for the backup chiller. Sensitivity analysis were also performed and the single loop system was solidified as the best path forward.

The new single loop system works by using the three chillers to supply cold fluid to the communal cold pipe, which then splits into three smaller pipes, each one supplying a set of heat exchangers for a multi-barrier machine. The three sets of heat exchangers return the hot fluid to the communal hot pipe, which splits into three smaller pipes, each one returning fluid to a chiller. This system will continue working if one chiller fails, as two chillers have the required cooling capacity to cool three multi-barrier machines. This achieves the main goal of the project: to develop a system that will prevent downtime due to a chiller failure.

The design meets or exceeds all specifications and constraints given by the client, such as the requirement for the design to be a single common loop, have insulated pipes, have built-in redundancy, maintain setpoint temperature, easy to maintain, can operate year-round, and can maintain flow and pressure. The design meets code using black iron 40 pipes, and meets ISO standards. The design also meets the minor needs set out by the client such as cost-effective, with the final cost coming out to [redacted] CAD.

103.9 ft of head is required at the chiller one pump, 68.9 ft of head at the chiller two pump, and 79.4 ft of head at the chiller three pump. A factor of safety of 1.25 was used for the chilling load calculations. It was determined that there would be 0.64 tonnes of refrigeration required to offset the heat gained through the pipe. Not taking into account pipe losses, each chiller would need to provide 206.00 tonnes of refrigeration. With pipe losses, each chiller should be capable of supplying 206.32 tonnes of refrigeration with the 80% chiller utilization assumption, and 257.9 tonnes of refrigeration with a safety factor of 1.25.

The design will effectively eliminate the downtime of a multi-barrier machine due to single chiller failure, which has historically been [redacted]. At a conservative estimate of [redacted] CAD per hour of lost revenue, this will save [redacted] CAD during a future chiller failure. The design may prevent the additional side effects of a multi-barrier machine being shut down abruptly such as lost energy, the generation of waste material, and possible damage to the multi-barrier machine due to overheating.

The future considerations for this project include distribution headers, built in redundancy, and an algorithm. Each of these considerations would have a positive impact on the system and provide cost savings.

This report contains the bill of materials, AutoCAD 2D and Solidworks 3D renders, the design process, and detailed design. Detailed calculations, facility images, and the poster image are included in the appendices. Included with this report is an AutoCAD drawing of the facility with the new single loop system implemented, a piping network, a PowerPoint presentation of the project, an a poster presentation.

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# Appendix A - Additional Drawings

To increase clarity, Figure A.1 through to Figure A.5 show additional views of the design without the Winpak floor layout in the background. All dimensions listed are in inches.

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Figure A.1: Isolated system

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Figure A.2: Isolated system with dimensions

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Figure A.3: Close-up of single loop system with dimensions

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Figure A.4: Close up of the upper section with dimensions

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Figure A.5: Close up of the lower section with dimensions

# Appendix B - Calculations

## Pressure Calculations

The following sample calculations will be done for the chiller 1 supply line with all chillers fully operational. Fixed Parameters:

- Working Fluid: 50% propylene glycol, 50% water
- Working temperature: 50 °F
- Density: 67.7 lbm/ft$^3$ [2]
- Viscosity: 0.00375 lbm/ft-s [2]
- Interior Diameter: 6.065 in [4]
- Roughness: 0.05 mm [13]

The lengths, internal diameters, and flow rates are already known for each pipe section. The velocity of the pipes can be calculated using the flow rate and internal diameter. Subsequently, the Reynolds number can be calculated to determine the friction factor that influences the head loss.

$$V = \frac{4Q}{\pi D_i^2} = \frac{4\left(425\ gpm\ \left(\frac{ft^3/s}{448.83\ gpm}\right)\right)}{\pi\left(6.065\ in\left(\frac{ft}{12\ in}\right)\right)^2} = 4.72\ ft/s$$

$$Re = \frac{\rho V D_i}{\mu} = \frac{(67.7\ lbm/ft^2)(4.72\ ft/s)\left(6.065\ in\left(\frac{ft}{12\ in}\right)\right)}{0.00375\ lbm/fts} = 4.31 \times 10^4$$

$$f = \frac{1.325}{\left[\ln\left(\frac{e}{3.7D_i} + \frac{5.74}{Re^{0.9}}\right)\right]^2} = \frac{1.325}{\left[\ln\left(\frac{0.05\ mm\left(\frac{in}{25.4\ mm}\right)}{3.7(6.065\ in)} + \frac{5.74}{(4.31\times10^4)^{0.9}}\right)\right]^2} = 0.0226$$

$$H_L = f\left(\frac{L}{D} + \frac{L_e}{D}\right)\frac{V^2}{2g}$$

The length per diameter and equivalent length per diameter are determined from the layout of each pipe section:

- Length: 3605.8 in
- 6" Elbow equivalent length: 108 in [14]
- Number of elbows: 7

- 6” Gate valve equivalent length: 36 in [14]
- Number of gate valves: 1

$$H_L = (0.0226)\left(\frac{3605.8\ in + 7(108\ in) + 36\ in}{6.065\ in}\right)\frac{(4.72\ ft/s)^2}{2(32.174\ ft/s^2)} = 5.68\ ft$$

These calculations were carried out for each section of pipe with a unique velocity or interior diameter. The pressure loss across the heat exchangers was assumed to be 15 psi or 34.60 ft of head. The equivalent lengths for the elbows and gate valves were from [14] and the equivalent length per diameters for the tees and reducers were from [15]. A summary of all the pressure loss calculations can be seen in Table XI.

TABLE XI: PRESSURE LOSS IN EACH PIPE SECTION

| Pipe Section | Head loss [ft] | | | |
|---|---|---|---|---|
| | Fully Operational | MB 1 Down | MB 2 Down | MB 3 Down |
| Chiller 1 Supply | 5.68 | 0 | 11.87 | 11.87 |
| Chiller 2 Supply | 0.83 | 1.74 | 0 | 1.74 |
| Chiller 1 & 3 Supply | 2.01 | 1.19 | 4.27 | 1.19 |
| Chiller 3 Supply | 1.91 | 3.99 | 3.99 | 0 |
| Communal Supply | 2.85 | 2.85 | 2.85 | 2.85 |
| MB 3 Supply & Return | 40.36 | 40.36 | 40.36 | 40.36 |
| MB 1 & 2 Supply | 0.35 | 0.35 | 0.35 | 0.35 |
| MB 2 Supply & Return | 39.15 | 39.15 | 39.15 | 39.15 |
| MB 2 & 3 Return | 1.93 | 1.93 | 1.93 | 1.93 |
| MB 1 Supply & Return | 36.86 | 36.86 | 36.86 | 36.86 |
| Communal Return | 2.79 | 2.79 | 2.79 | 2.79 |
| Chiller 1 Return | 8.30 | 0 | 17.35 | 17.35 |
| Chiller 2 & 3 Return | 0.54 | 1.14 | 0.32 | 0.32 |
| Chiller 2 Return | 1.26 | 2.63 | 0 | 2.63 |
| Chiller 3 Return | 2.56 | 5.34 | 5.34 | 0 |

In order to ensure the same flow rate is going to each MB line, the pressure drop in each line must also be the same. This can be achieved with the use of balancing valves. Table V shows the necessary pressure drop caused by each balancing valve, and Figure A.6 [16] shows how the number of turns from closed was obtained.

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Figure A.6: Balancing valve sizing

## Heat Transfer Calculations

The amount of heat transfer through the pipes is dependent on the following equation.

$$q = \frac{2\pi L(T_\infty - T_i)}{\frac{1}{r_1 h_i} + \frac{\ln\left(\frac{r_2}{r_1}\right)}{k_p} + \frac{\ln\left(\frac{r_3}{r_2}\right)}{k_{ins}} + \frac{1}{r_3 h_o}}$$

The following assumptions are used to calculate the heat transfer:

- The supply and return temperatures for all three chillers are the same as in the MB 1 chiller drawing (45°F and 55°F, respectively).
- The outside temperature on a hot summer day in Winnipeg is 90°F, and the temperature within Winpak's facility is 77°F.
- The surface temperatures of the piping insulation are 5 K cooler than the surrounding temperatures.
- The wind velocity where the pipes are located outside is 15 km/hr, and 0 km/hr inside Winpak's facilities.

Separate heat transfer calculations were done for the outside pipes, the inside pipes with a 6 inch diameter, and the inside pipes with an 8 inch diameter. The sample calculations will be done for the outside pipes. Fixed Parameters:

- Working Fluid: 50% propylene glycol, 50% water
- Working temperature: 50 °F
- Density: 67.7 lbm/ft$^3$ [2]
- Viscosity: 0.00375 lbm/ft-s [2]
- Specific heat: 0.822 Btu/lbm-°F [2]
- Interior Diameter: 6.065 in [4]
- Pipe thermal conductivity: 28.9 Btu/hr-ft-°F [17]
- Insulation thermal conductivity: 0.18 Btu-in/hr-ft$^2$-°F [6]
- Fluid thermal conductivity: 0.234 Btu/hr-ft-°F [18]
- Velocity in 6 inch pipe: 7.08 ft/s

To calculate the convective heat transfer coefficient, the Prandtl and Reynolds number must be calculated in order to determine the appropriate Nusselt number correlation.

$$P_r = \frac{\mu C_p}{k_f} = \frac{(0.00375\ lbm/fts)(0.822\ Btu/lbm^{\circ}F)}{0.234\ Btu/hrft^{\circ}F\ \left(\frac{hr}{3600\ s}\right)} = 47.47$$

$$Re = \frac{\rho V D_i}{\mu} = \frac{(67.7\ lbm/ft^2)(7.08\ ft/s)\left(6.065\ in\left(\frac{ft}{12\ in}\right)\right)}{0.00375\ lbm/fts} = 6.74 \times 10^4$$

The Dittus-Boelter equation can be used because

$$0.6 \leq P_r \leq 160$$

$$10^4 \leq R_e$$

$$10 \leq \frac{L}{D_i}$$

$$N_u = 0.023 R_e^{0.8} P_r^{0.4} = 760$$

$$h_i = \frac{N_u D_i}{k_f} = \frac{(760)(0.234\ Btu/hrft^{\circ}F)}{6.065\ in\left(\frac{ft}{12\ in}\right)} = 351.4\ Btu/hrft^{2\circ}F$$

The following equation was found in the 2001 ASHRAE Fundamentals Handbook [19].

$$h_o = C\left(\frac{1}{D_o}\right)^{0.2}\left(\frac{1}{T_{avg}}\right)^{0.181}(\Delta T^{0.266})\sqrt{1 + 0.7935(V_{wind})}$$

The constant $C$ is determined depending on the shape of the shape and heat flow condition. The wind speed is taken as a low value because the pipes are shielded by the adjacent buildings.

$$\Delta T = T_{\infty} - T_s = 305.3\ K - 300.3\ K = 5\ K$$

$$T_{avg} = \frac{T_{\infty} + T_s}{2} = \frac{305.3\ K + 300.3\ K}{2} = 302.8\ K$$

$$h_o = 12\left(\frac{1}{270\ mm}\right)^{0.2}\left(\frac{1}{302.8\ K}\right)^{0.181}(5\ K)^{0.266}\sqrt{1 + 0.7935(15\ km/hr)}$$
$$= 1.35\ Btu/hrft^{2\circ}F$$

$$q = \frac{2\pi(258\ ft)(90^{\circ}F - 50^{\circ}F)}{\frac{1}{(0.253\ ft)(351.4\ Btu/hrft^{2\circ}F)} + \frac{\ln\left(\frac{0.276\ ft}{0.253\ ft}\right)}{28.9\ Btu/hrft^{\circ}F} + \frac{\ln\left(\frac{0.443\ ft}{0.276\ ft}\right)}{0.015\ Btu/hrft^{\circ}F} + \frac{1}{(0.443\ ft)(1.35\ Btu/hrft^{2})}}$$
$$= 1948\ BTU/hr = 0.16\ TR$$

This was repeated for the inside conditions with 6 and 8 inch pipes. A summary of the heat gain through the pipes can be seen in Table XII

TABLE XII: HEAT GAIN SUMMARY

| Heat Gain | Tons of Refrigeration |
|---|---|
| Outside | 0.16 |
| Inside 6” | 0.45 |
| Inside 8” | 0.03 |
| **Total** | **0.64** |

# Appendix C - Bill of Materials

The six inch pipes [20], the eight inch pipes [21], the elbows [22], the reducers [23], the flanges [24], the tees [25], and the gate valves [5] were sourced from Flocor. The Balancing valve was sourced from Danfoss [16]. The pipe insulation [6] and insulated pipe fitting covers [26] were sourced from Grainger. The bill of materials is shown in Table XIII with the prices in Canadian dollars.

TABLE XIII: BILL OF MATERIALS

| Item # | Item | Description | Vendor | Part # | Qty | Price/Qty | Price |
|---|---|---|---|---|---|---|---|
| 1 | 6” pipe | SCH 40 6 inch black iron pipe | Flocor | PST16 | 1140 | [redacted] | [redacted] |
| 2 | 8” pipe | SCH 40 8 inch black iron pipe | Flocor | PST18 | 68 | [redacted] | [redacted] |
| 3 | 6” Elbow | 6 inch standard long radius black iron pipe | Flocor | 90W6 | 38 | [redacted] | [redacted] |
| 4 | 6” Tee | 6 inch standard black tee | Flocor | RCW86 | 8 | [redacted] | [redacted] |
| 5 | 8” x 6” Reducer | 8x6 inch standard concentric black iron reducer | Flocor | TW6 | 4 | [redacted] | [redacted] |
| 6 | 6” Collar | 6 inch raised face slip on welding flange | Flocor | SO6 | 18 | [redacted] | [redacted] |
| 7 | Gate Valve | 6 inch flanged gate valve | Flocor | 452J6 | 6 | [redacted] | [redacted] |
| 8 | Balancing Valve | 6 inch flanged balancing valve | Danfoss | 065F8975 | 3 | [redacted] | [redacted] |
| 9 | Fiberglass Insulation | 2x36 inch fiberglass pipe insulation | Grainger | 4LFG5 | 380 | [redacted] | [redacted] |
| 10 | Fiberglass elbow cover | 6 inch fiberglass elbow cover | Grainger | 6TEF2 | 38 | [redacted] | [redacted] |
| 11 | Fiberglass tee cover | 6 inch fiberglass tee cover | Grainger | 6TED3 | 8 | [redacted] | [redacted] |
|  |  |  |  |  |  |  | [redacted] |

# Appendix D - Design Poster

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Figure A.7: Design Poster

# Appendix E - Facility

Figures A.8, A.9, and A.10 show some of the features inside of the facility.

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Figure A.8: Chiller One, outdoors in the west parking lot

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Figure A.9: Heat exchanger and pump for multi-barrier machine two

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Figure A.10: Pipes to MB machine one on the west side of the main transport corridor